Approaching Complex Societal Problems Tied to Aviation

Elizabeth F. Rieken[1] and Eric R. Brubaker[2]
NASA Langley Research Center, Hampton, VA, 23681, USA

Rachel M. Best[3] and Kathleen H. Bond[4]
The Human Factor, Boston, MA, 02116, USA

Grace E. Burleson[5] and Timothy W. Simpson[6]
NASA Langley Research Center, Hampton, VA, 23681, USA

From climate change to health inequity, humankind faces complex societal challenges that aviation can both exacerbate and help to alleviate. In this paper we describe our approach to identifying and approaching complex societal challenges with existing or potential ties to aviation as part of the NASA Convergent Aeronautics Solutions (CAS) project. We detail three example challenges that we have done preliminary work on: enabling access to healthcare, supporting resilient rural communities, and ensuring supply chain wellness. Our approach to understanding and addressing such challenges involves iterative human-centered, systems-oriented, and futures-based design. We provide a discussion of cross-cutting characteristics of complex societal challenges that appear fruitful for aviation to address and detail the lessons we have learned thus far in approaching such challenges.

I. Introduction

From climate change to health inequity, humankind faces complex societal challenges that aviation can both exacerbate and help to alleviate. Take health inequity as an example. Studies have found that high exposure to aviation noise is associated with increased risk of cardiovascular disease [1], the occurrence of anxiety and depression [2,3] and other ailments, and that aviation and road noise exposure in the United States is highest among low-income communities and communities of color [4]. While these are examples of negative health outcomes associated with aviation, aviation can also help to enable access to healthcare. For example, organizations like Matternet and Zipline use autonomous drones to deliver medical supplies and increase access to diagnostics and lifesaving medical supplies, such as blood for transfusions performed at rural clinics. With societal problems like enabling access to healthcare, we take a broad and inclusive approach to identifying complex sociotechnical challenges and their potential ties to aviation [5].

In this paper we describe our approach to identifying, synthesizing, and prototyping solutions to address complex societal challenges with an aviation lens as part of the NASA Convergent Aeronautics Solutions (CAS) project. We detail three example challenges that we have worked on and our approach to doing so. These challenges are related to enabling access to healthcare, supporting resilient rural communities, and ensuring supply chain wellness. Our approach to understanding and addressing such challenges involves an iterative human-centered, systems-oriented, and futures-based design approach [5–12].

[1] Complex Systems Design Engineer, Engineering Integration Branch, Engineering Directorate, AIAA Member.
[2] Complex Systems Design Engineer, Engineering Integration Branch, Engineering Directorate.
[3] Founding Partner, The Human Factor.
[4] Partner, The Human Factor.
[5] Graduate Intern, University Space Research Association, University of Michigan.
[6] Engineering Integration Branch IPA, Pennsylvania State University, AIAA Associate Fellow.

CAS begins a new effort by (1) broadly mapping problem spaces, (2) conducting design research to synthesize new problem formulations, and (3) developing and prototyping concepts that address these problems. The focus of this paper is on step (2), the middle part of our front-end design process. This involves deeply exploring complex societal challenges, engaging stakeholders, understanding their points of view, mapping associated systems and leverage points, and synthesizing this understanding into problem formulations that point toward new opportunities for aviation. We close with a discussion of cross-cutting characteristics of complex societal challenges that appear fruitful for aviation to address. We also detail the lessons we have learned thus far in approaching such challenges.

II. Background

A. Addressing Complex Societal Problems

Complex societal problems, what some scholars call "wicked problems" [13], involve multifaceted and multi-stakeholder challenges characterized by complexity, uncertainty, and dynamism. Such problems, e.g., climate change and health inequity, are complex because they involve multiple domains (technical, economic, social, political, etc.) and are dependent on multiple interconnected stakeholder groups and industries. They do not typically have clear, single solutions but require a multitude of evolving interventions across disciplinary, organizational, and cultural boundaries. Aviation has long played a role in addressing and perpetuating complex societal problems, such as exacerbating versus mitigating the spread of infectious diseases or enabling high yield agriculture versus spreading algal blooms via the mass application of fertilizers. We foresee that the future of aviation is poised to play an even greater role in addressing and/or perpetuating complex societal challenges. Designing for collectively desirable futures will likely require new design tools, methods, and approaches in aviation.

Recent work has identified societal trends that influence the aviation industry, including issues of climate change and democratization [14], and there are a variety of non-aviation domains that aviation is poised to effect (e.g., healthcare, firefighting, policing, infrastructure maintenance). Tackling societal challenges that span domains requires adaptive problem-solving tools that consider problem scope and complexity [15]. Societal challenges can feel overwhelming due to their boundlessness—the seemingly infinite amount of information, stakeholders, and interests that may be involved [16]. Neglecting social and other non-technical aspects of sociotechnical problems can result in creating even more harm than good, making failures potentially catastrophic [17]. To mitigate such harm and prioritize socially beneficial outcomes, scholars recommend systems thinking approaches to consider the multitude of factors that influence problems and their potential solutions [18].

Systems thinking approaches encourage engineers to see beyond their perspectives and consult with the broader public [16], including a diverse range of stakeholders [19], i.e., individuals and organizations who may impact or be impacted by the issue at hand. Stakeholders often have differing interests, values, and objectives. Prior work in aviation design has found that stakeholders in complex or wicked problems have two important roles to play: (1) to articulate their viewpoint (e.g., provide context, needs, or metrics) and (2) to judge potential solutions [20]. It is the role of the design team to facilitate the engagement and collection of such stakeholder feedback, and those doing so may benefit from an *adaptive mindset* that encourages the exploration of contextual information and regular system and stakeholder feedback [21]. Scholars further distinguish *comprehensive* systems thinking to encourage broader inclusion of stakeholders and contextual aspects in addition to the technical elements of the immediate problem [22]. Indeed, going beyond just technical constraints and incorporating critical stakeholder perspectives has the potential to positively impact outcomes in the aviation industry and society more generally [10].

B. Our Approach to Identifying Complex Society Problems Tied to Aviation

At CAS, we have developed an approach to identifying complex societal problems that may offer opportunities for future aviation systems and solutions. Our design teams are composed of NASA researchers from diverse fields and design leaders and facilitators both within and outside of NASA. Our strategy is to use quantitative and qualitative evidence to find problem areas where leverage points exist for system-level impact via aviation. While there are many ways to approach the initial identification of areas to explore, CAS is using methodologies based in Strategic Foresight and Systems Thinking to discover high reach and impact problem areas at the convergence of social, economic, environmental, political, and technology trends. This first step identifies high-level problems worth further investigation. While much more could be said on this initial and critical part of our process, it is outside the scope of the current paper.

After identifying a high-level problem worth investigating, our next steps are to (1) frame the societal problem and (2) to develop preliminary concepts while potentially reframing the problem (see Fig. 1). Distinct from traditional engineering design which starts with technical requirements, we start by developing stakeholder maps, soliciting stakeholder needs, and identifying system-level leverage points using design methods from Human-Centered Design

[6, 10], Participatory Design [23,24], and Futures Design. We tailor our approach to each problem area because each has a unique context that may require different 'tools' and kinds of stakeholder engagement. Deep stakeholder engagement is a crucial element throughout our process and allows for the triangulation of needs across perspectives leading to unforeseen problem formulations and opportunities for aviation solutions. Additionally, we aim to move beyond the societal needs of today to imagine the needs and capabilities of future stakeholders one or more decades away. This helps us to imagine a future of aviation that may address the needs of future stakeholders and situations using futures-based design methods like backcasting, strategic foresight, and scenario planning. As problem formulations and opportunity concepts emerge, we solicit feedback from stakeholders to further reframe and refine the ideas. We also assess each concept's expected desirability, viability, and feasibility. By this point, the emergent problem formulations and opportunity concepts are deeply grounded in desk and field data.

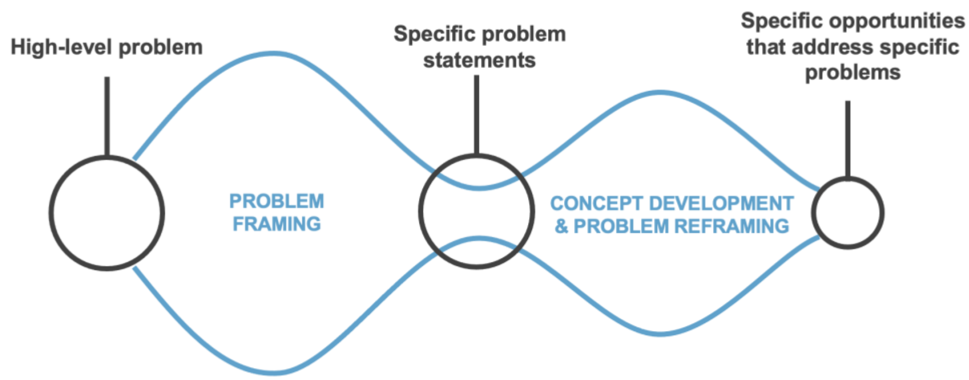

Fig. 1 Our approach to framing complex societal problems tied to aviation.

Our process is evolving as we continue to learn how to approach complex societal problems within the context of aviation and as a federal agency. Each of our problem explorations allows us to refine our approach and try new methods. By conducting targeted reflections and comparisons across each effort, and staying in conversation with the engineering design and innovation management communities, we will continue to mature our process.

III. Three Complex Societal Problems Tied to Aviation

We now offer three examples of how we approached complex societal problems with design teams. In these efforts, teams sought to formulate problem areas where aviation might play a role in pursuing a better future. Each effort started with a broad problem area that presented potential for a convergence of societal trends and technology capabilities and aimed to identify opportunities for transformative solutions based in aviation. The projects presented below explored the topics of fostering resilience in rural communities, enabling access to healthcare, and preventing disruption or disparity in the aviation supply chain.

A. Fostering Resilient Rural Communities

This effort considered the unique challenges that rural U.S. communities face in light of the trends indicating decline of geographically isolated communities. Approximately one in five Americans live in rural areas and these rural areas each have unique geography, people, and economic realities. Supporting resilient rural communities involves a complex network of stakeholders and needs involving considerations of infrastructure, economic development, environmental sustainability, and beyond. Initial desk research led the team to focus on exploring the problem of 'enabling rural production communities to thrive and become resilient outside of single industry infrastructure'. This problem exploration was conducted over 12-weeks with a team of four NASA researchers, one intern, and two design facilitators. The team used a combination of desk research on rural resilience and field research via stakeholder interviews to illuminate four rural community archetypes and "need areas" that surfaced across the research. Based on these themes, the team envisioned potential future states that represented the ways that aviation could engage to meet the stakeholder and system needs in a holistic way. By imagining future aviation states, the team was able to demonstrate how potentially transformative aviation solutions may arise out of a societal problem that does not have an obvious aviation connection.

B. Enabling Access to Healthcare

In this second effort, we examined the problem of ‘enabling access to healthcare as distance to care increases.’ Increasing access to healthcare is a salient and compelling challenge in the United States. It is also highly complex with many stakeholders, industries, systems, technologies, and sociopolitical considerations. We approached this topic in two phases: the first conducted over 9-weeks with a team of six NASA researchers, four interns, and two design facilitators and the second conducted over a similar timeframe with a similarly sized team. In the first phase, the team conducted a stakeholder mapping process and identified individuals and organizations that play key roles in healthcare access. We then conducted roughly 35 interviews with over 50 stakeholders, including health care providers, patients, caretakers, insurance companies, transportation providers, policymakers, researchers, and advocates. Interviews were summarized and used to develop key insights and need statements. These were combined with healthcare and technology trends into 40 convergent problem statements which were eventually narrowed into six key problem areas: (1) non-emergency medical transportation, (2) emergency medical transportation, (3) organ transportation, (4) the virtual-physical care gap, (5) medical system interoperability, and (6) medical AAM regulations, certifications, and public trust. We pursued these problem areas through a second phase of work involving more interviews, site visits, and co-design sessions. Across both phases, the team interviewed, visited, or engaged in co-design with over 100 stakeholders. This effort resulted in a set of refined problem formulations and preliminary concepts through which aviation might play a transformative role in enabling access to healthcare in the United States

C. Wellness of the Aviation Supply Chain

Recognizing the supply chain challenges that most organizations now face since the disruptions caused by the COVID-19 pandemic, this effort sought to investigate the wellness of the aviation supply chain. Whereas other agencies and organizations are primarily concerned with policies and regulatory issues, commercial entities are motivated by their survival and profitability. NASA, on the other hand, is uniquely positioned to look across both civilian and defense aviation industries to identify gaps and opportunities within the aviation supply chain to ensure fair and equitable access to goods and services while driving innovation for advanced air mobility. We conducted three, half-day workshops to elicit stakeholder needs and map the sociotechnical challenges faced by organizations, actors, and consumers within the aviation supply chain. The three workshops collectively built a conceptual map of the aviation supply chain, treating it as an ecosystem of interconnected organizations and agents at six levels of scale. Wellness indicators for each level of scale were identified. Based on the participants and discussions across the three workshops, three key indicators of wellness within the aviation supply chain emerged: (1) efficient and on-time delivery of parts and materials, (2) regulatory oversight and certification, and (3) federally-funded research and development. The first key indicator underscores the wellness of the aviation supply chain and underlying ecosystem, the second key indicator ensures safe operation of all organizations and agents within the aviation supply chain, and the third key indicator helps sustain and drive innovation within the aviation supply chain, ensuring it is infused with new technologies to remain resilient to changes that might adversely impact the underlying ecosystem (e.g., global pandemics, material supplies, climate change, etc.).

IV. Cross-Cutting Characteristics of Complex Societal Problems Well-Suited for Aviation

In this section we use the example efforts described above to reflect on cross-cutting characteristics of complex societal problems that may be fruitful for aviation to address. Across the efforts, our teams took different approaches to identifying aviation-based opportunities within societal problems. Although the approaches and topics were unique, we found similar characteristics across societal problems that appear well-suited to leverage aviation. These similarities suggest that societal problems involving any of the following characteristics may present compelling opportunities for aviation.

A. Geographic Isolation

Problems with geographic distance present opportunities to use aviation advancements beyond point-to-point transportation. In the *Access to Healthcare* effort, we found that geographically isolated communities often faced challenges with transportation to preventive, routine, specialist, and acute care appointments. An obvious aviation solution could be to transport citizens needing care, but the team also identified aviation opportunities to close the distance in other ways like temporarily bringing providers to regional hubs of care, opening channels for expanded telemedicine capabilities, and creating new ways to provide medical supplies, medication, and diagnostics to patients. In another example, the *Resilient Rural Communities* project found that geographically isolated communities sometimes do not produce enough demand to maintain resources like grocery stores, restaurants, and entertainment options. In this case, geographic distance led to an opportunity to leverage aviation to share resources (e.g., food supplies, entertainment) between communities.

B. Time-Related Challenges

The potential for quick response and travel time can make aviation useful in time-related challenges. All three teams heard needs for expedited response and faster transportation. The *Access to Healthcare* effort found aviation opportunities for more rapid donor organ transport, especially given limited cold ischemic times (e.g., 12-18 hours for livers, 24-36 hours for kidneys). This team also found that timeliness is critical in emergency medical and fire services. For example, each minute saved in responding to a cardiac emergency call has been found to equate to a 1-2% decrease in mortality rate and over $1.5k in saved hospital costs on average per patient, leading to better patient recovery and a total estimated $7B reduction in US healthcare expenditures per year [25]. Stakeholder research also uncovered a need for timely response to calls for non-emergency challenges. Similarly, the *Aviation Supply Chain Wellness* effort found that disruptions in the complex aviation supply chain can impact the delivery of materials, parts, and other supplies which can have ripple effects across a global supply chain. Ensuring timeliness in air freight of critical parts and materials can help to prevent such global supply chain breakdowns.

C. Limited Crucial Resources

The problem of limited crucial resources can sometimes be an opportunity for aviation. Resources may be limited for multiple reasons, including distance or the time to cover a distance, as outlined in points A and B above. To illustrate, both the *Resilient Rural Communities* and *Access to Healthcare* teams found that rural healthcare facilities do not always have crucial supplies like blood and medications because these come in many varieties and have a short shelf life. Providers do not want valuable supplies to expire on the shelf. As a result, patients and/or supplies are transported between multiple facilities as needed. Human resources are another limited crucial resource. In the EMS system, there is limited access to medical expertise while transporting a patient; providers are connected to their patients in a one-to-one relationship during treatment in the field and transport to medical facilities. This model exists given current constraints, but we found that a "one to many" (one provider to many patients) relationship would be highly desirable and beneficial for both patients and providers. Aviation can play a part in increasing the reach of such complex systems' limited resources.

D. Real-Time Surveillance and Information Sharing Across Distances

Surveillance, remote sensing, and information sharing challenges can also offer compelling opportunities for the aviation sector. This is especially trye because aviation and aerospace have long been engaged in sensing, navigational, and communication technologies. In the *Access to Healthcare* effort, transferring patient health data between hospital systems and providers is a frequent concern and some hospitals are using UAVs to transfer medical documentation between providers. In another healthcare example, EMTs and paramedics are often dispatched to an emergency situation without trustworthy scene information. Scene data would be invaluable in assigning appropriate resources, preventing scenes from being under-resourced or over-resourced, and keeping limited emergency resources in service. Finally, there is a connectivity breakdown between EMS and hospitals during transit due to communication technology challenges and/or delayed/rudimentary communication of diagnostic imaging. These problems with lack of real-time surveillance, data collection, information sharing, and connectivity offer opportunities for aviation.

E. Management of Many-Part of Multimodal Systems

Problem areas that involve many-part or multimodal systems may also benefit from new aviation systems. For example, in the *Access to Healthcare* and *Resilient Rural Communities* efforts, stakeholders indicated that barriers to health and wellness may be reduced with greater use of virtual options. However, achieving this might involve a multimodal system that involves the delivery and/or pick-up of diagnostic tests and medications in coordination with telemedicine appointments. Similarly, the timely transport of donor organs is likely to involve some combination of commercial aircraft, UAVs, and/or ground transportation, and more effectively managing this multimodal transportation challenge could save many lives while also offering opportunities for the development of new aviation systems.

Taken together, this is a preliminary set of cross-cutting characteristics of complex societal problems that appear well-suited for aviation. We expect that as we and other aviation organizations pursue complex societal challenges, these characteristics will be refined, and new ones will be identified. Pursuing societal problems that have one or more of these characteristics may increase the likelihood that a design effort will yield a transformative aviation solution. With these characteristics identified, we now turn to reflecting on challenges that aviation organizations might face as they design for complex societal challenges.

V. Scoping Complex Societal Problems Using an Aviation Lens

Where to begin on a project? What to focus on, and at what level? Questions of scope are particularly challenging when working on complex societal challenges like revitalizing rural communities, enabling access to healthcare, and building resilient supply chains. Within such large topics, the 'slices' of the problem to address seem endless.

Scope can be defined in numerous ways: a directive from leadership, a project pitch from interested subject matter experts, or a broad problem area identified by a team and refined via rounds of research. Each approach has challenges. Narrow scope too quickly and a project may miss a more productive opportunity. Leave scope broad for too long and a team may flounder. We found that applying an aviation lens – honing scope by asking *where does aviation have a part to play?* – was a particularly important way to scope complex societal problems for NASA, and we experimented with doing so at three different stages in our process.

A. Delayed Use of an Aviation Lens

The *Resilient Rural Communities* effort intentionally delayed the application of an aviation lens throughout problem definition. To understand the system in all its complexity, we broadly scanned stakeholder needs regardless of whether we could see an aviation application down the line, which presented benefits and drawbacks.

Tactically, the *Resilient Rural Communities* team first identified and interviewed stakeholders with unique perspectives on their rural community's resilience, such as local government officials, emergency responders, and more. These interviews led the team to define 'community archetypes,' a method of grouping communities with similar needs. Having distinct community archetypes helped the team identify unique, high-impact opportunities for each archetype. After the team identified opportunity spaces, we then applied an aviation lens. We asked, *how might we leverage aviation to address these opportunities*? Approaching these opportunities with aviation led the team to formulate non-obvious aviation concepts.

There are benefits to this approach. By delaying the discussion of aviation solutions, the team listened for needs at the community level and, importantly, learned where their assumptions did not align with the stakeholders' perspectives. For example, our team assumed long-distance transport would be a barrier to community resilience. However, stakeholders did express long travel to a 'hub' as a challenge to their resilience. Instead, our team learned that communities struggle to staff critical community positions, such as doctors, nurses, and teachers, due to the geographic isolation from things such as entertainment. With this delayed-aviation lens, our team emerged with a validated understanding of the most critical needs in the system, and then was pushed creatively to formulate non-obvious aviation applications.

While this approach had benefits, it also presented important challenges. First, it was challenging for our NASA team to stay connected to the problem area. Although there is support for applying diverse expertise to an unrelated problem area, this approach offered few opportunities for our aviation subject matter experts to directly apply their expertise. During ambiguous stages of problem definition, it was hard to communicate about progress. Finally, delaying the aviation lens presents a risk of expending resources to explore a problem area that doesn't yield an aviation opportunity.

B. Periodic Use of an Aviation Lens

The *Access to Healthcare* effort applied an aviation lens throughout, using aviation as a decision-making tool at critical junctions. After an initial open-ended scan of the opportunity space and rounds of empathy-building with stakeholders, the *Access to Healthcare* team asked periodically: "Could this aspect of the problem intersect with an aviation solution?" Importantly, our team had a broad definition of aviation: an "aviation" solution could draw from flight management systems, flight communications and connectivity, sensor technology, flight acoustics, and more.

This periodic aviation lens helped teams make intentional choices about continuing down certain paths. We used a "Why NASA" lens to filter opportunities to hand off to industry versus opportunities uniquely suited to NASA. We tested "Why NASA" with three questions: Is this an opportunity a non-government entity/industry won't pursue (i.e. it may not be profitable, so industry will not pursue it)? Is this an opportunity non-government entity/industry can't pursue (i.e. not the right resources, expertise, facilities, or level of influence)? And is this this an opportunity for which non-government entity/industry needs guidance (i.e. establishment of regulations that ensure some level of equity, foundational datasets, or risk management)?

Using a periodic aviation lens increased team ownership over the work. Teams had assurance that they could choose to forego a particular direction if they did not see a potential for aviation. Teams also could decide to keep 'non-aviation' or 'non-NASA' opportunities in the mix to continue exploring whether an aviation intersection would emerge with more stakeholder research. Regardless, these lenses were beneficial as they periodically challenged the team to think critically when a path did not present an easy place for aviation or NASA to engage.

This approach also poses challenges. In early stages, using aviation as a decision-making tool required teams to measure the potential of aviation solutions for a still-being-defined problem statement or ambiguous opportunity area. This presented a challenge for some contributors and potentially created distrust within groups who shared concerns about trying to “guess” at a solution before the problem was defined. Additionally, some teams may have eliminated opportunity areas early because there was not an obvious application of aviation. While aviation solutions are the objective, uncovering areas for transformative advancement may require encountering an occasional dead-end to uncover a non-obvious – but rich – opportunity area.

C. Up Front Use of an Aviation Lens

An aviation lens was applied from the beginning when attempting to assess the *Wellness of the Aviation Supply Chain*. Using an aviation lens up front made it easy to identify potential workshop participants and define objectives for each workshop; however, challenges quickly emerged due to the scope and scale of the aviation supply chain. Do we only consider civilian and commercial aviation, or do we include military and defense use? While measuring passenger experience may indicate when planes are running on time, it may not assess the complex logistics that are going on behind the scenes to make sure planes are ready to fly at the right time. Most passengers, for example, are completely oblivious to the challenges of expediently delivering spares and replacement parts to the right place at a reasonable cost to ensure planes are flying on time. Different solutions have emerged at individual airlines, between airlines, among parts suppliers, at local airports, within regional networks, and even around the world (e.g., Singapore is a global hub for engine repair in that part of the world).

Rather than constrain the discussion by inadvertently scoping the aviation supply chain too narrowly, we created six levels of scale to provide a framework to discuss the aviation supply chain. As shown in Fig. 2, the Purpose is the highest level as it defines the “why” of the underlying ecosystem supporting the aviation supply chain. To achieve this purpose, Objectives are minimized or maximized by performing the Functions within the ecosystem. The functions consist of Activities that are undertaken by Organizations composed of independently acting Agents that are ultimately responsible for doing the work. The six-level framework was used to guide workshop participation and discussions.

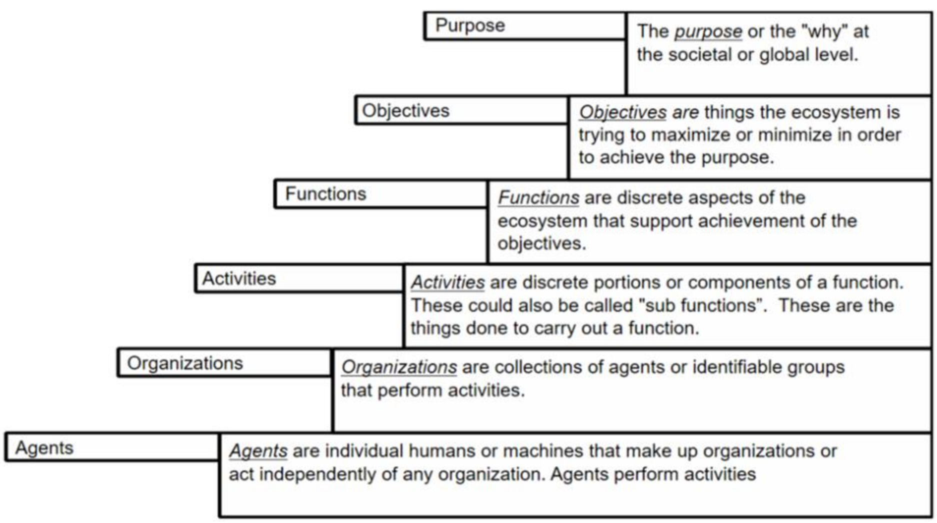

Fig. 2 Six-level framework used to elucidate the wellness of the aviation supply chain.

Overall, the six-level framework helped focus attention at each level of scale within the aviation supply chain. While the final instantiation of the framework was by no means a complete representation of the aviation supply chain, it provided sufficient detail to allow initial wellness indicators to be identified at each level. It also helped identify gaps and challenges within the aviation supply chain, for example, disconnects between different levels that were not mapped during any of the workshops. Subsequent workshops will be necessary to flesh gaps out further, focusing on specific Functions of Activities within the aviation supply chain, for instance. We are also reviewing the extent to which using an aviation lens up front and subsequently defining the six-level framework restricted discussions during the workshops and hindered participation by being either “too narrow” for participants to think broadly about wellness indicators or “too broad” for participants to focus on specific areas of concern that would impact the wellness of the aviation supply chain.

Taken together, we found that approaching societal problems presented an interesting tension: down-selecting to opportunity areas with clear aviation connections too early limited the types of opportunities revealed down the line. However, delaying the use of an aviation lens to guide a project's direction led teams to sink time and resources into areas that didn't always yield opportunities that fit the technical team's skills or that led to aviation solutions.

VI. Bringing Together Aviation Teams and Stakeholders to Address Complex Societal Challenges

Tactically, to run this type of work well at NASA, we needed to form NASA teams with strong internal bonds and connect those teams to external stakeholders. First, we found that establishing psychological safety on a team was not only critical for team bonding and culture, but critical to content and skill development. We learned successful structures to bring stakeholders into the fold and the skills needed on teams to respect that incoming stakeholder data. Finally, we learned that teams and stakeholders coalesced more successfully when traditional human-centered design tools were adapted to NASA's unique context.

A. Establishing Psychological Safety

We found that creating an atmosphere of psychological safety was vital to the teams' productivity. Working to understand complex societal challenges pushed team members into knowledge areas and processes outside of their expertise and comfort zone. Addressing those complex societal challenges required risk-taking (e.g., offering ideas, posing nascent questions, and presenting ideas still in 'draft'). In moments when the team may have felt unsure or insecure, psychological safety was critical to keep the generative conversation going.

Psychological safety on our teams was essential for a positive team experience, but also for the team's skill development. It was crucial foundation as the team developed difficult skills that enable them to engage dynamically with what they were learning about the problem space. As an example, to move the work forward, it is helpful for team members to be able to propose ideas, advocate for their analysis, and be willing to pivot – in other words, 'sparring' in service of strengthening the group's understanding. In industry, design professionals embrace the saying "strong opinions, lightly held". We found that teams nascent in their development of psychological safety had a difficult time holding strong opinions and sparring with each other's perspectives. Without a 'safe' environment, testing a partially formulated idea—especially for a topic area outside their expertise—was perceived as a risk for some team members. Psychological safety had to be made a priority to move both the team's results and skill development forward.

In the *Access to Healthcare* effort, we were able to form psychological safety on rapid (1.5-day to 1.5-week-long) sprints. To set a tone, these short-term teams acknowledged 'agreements'—the group's social contract —which set a standard of consideration and intentionality in the room. For example, one of our agreements was an agreement to have a generative mindset (we called it *being a builder*). By agreeing to take on a generative mindset, the *builders* promoted psychological safety because they focused on shoring up and strengthening each other's nascent ideas until they were strong enough to be judged, rather than evaluating each idea as it was introduced.

Beyond agreement-setting, we fostered psychological safety by inserting pauses into our agendas to get to know each other personally. Facilitators did not rush through moments of team bonding; in fact, they encouraged the creation and continuation of humor to form team culture. Teams, in their post-sprint feedback, would comment on how welcome they felt to be themselves.

B. Fostering Engagement Between Stakeholders and Aviation Teams

Beyond establishing psychological safety, we found that complex societal challenges could not be well formulated and addressed without fostering strong engagement between stakeholders and aviation teams. Each of the three case study teams engaged both aviation and non-aviation stakeholders in different ways and to different extents. The *Aviation Supply Chains* team engaged stakeholders through a series of three, open-invitation roundtable discussions and associated breakout activities. The *Resilient Rural Communities* team engaged stakeholders through conducting interviews with residents in rural communities across the United States. The *Access to Healthcare* team engaged stakeholders through conducting interviews with patients, health care providers, medical technologists, health care access researchers, and medical transport providers alongside three site visits and a dozen co-design sessions.

In our efforts to engage with stakeholders and aviation teams, we established that the richest discussions were with stakeholders who balanced empathy for other stakeholders in the system with their own expertise and experience. With these stakeholders involved, the team walked away with outsized understandings of multiple stakeholders in the system, because the stakeholders were able to describe the nuances of others' points of view as well as their own.

As our teams engaged stakeholders, effective discussion of project data required the development of another muscle: stakeholder perspective taking. Stakeholder perspective taking is the ability to look beyond one's own point of view, to be open to incorporating new data that explains how another stakeholder thinks about a complex situation or system. We used various intentional and organic methods to build stakeholder perspective taking skills on our teams. For example, we intentionally asked the team to include stakeholder data in system analysis activities.

C. Adapting and Applying Human-Centered Design for NASA Teams

There is a wealth of human-centered design (HCD) tools, methods, and processes employed in industry, taught in academia, and applied to projects of many kinds. HCD methods connect teams to other perspectives in a complex system. Our teams included HCD experts from both industry and academia who understood these tools' applications. We found HCD methods to be essential in creating a shared understanding of the problem space and engaging stakeholders; but, these methods had to be adapted to be uniquely suited to NASA. An off-the-shelf approach would not have been effective for our teams given NASA's unique characteristics: the NASA mandate, technical depth and breadth of its people, organizational complexity, funding structures, and the federal government context.

For example, as already stated, stakeholder input is a foundation of HCD. Understanding complex sociotechnical problems means gathering data from multiple members of a system. As a government agency, NASA must abide by specific rules and regulations on how teams can interact with stakeholders outside of NASA.

Further, in HCD, structured or templated activities are employed and reused often to lower the barrier to entry for this type of intersectional work; structure breaks an ambiguous process into concrete steps. With these activities, team members can plug in and engage where there may have only been big questions before. In our work with NASA, our team intentionally adapted workshop activities and templates to NASA's unique mission and outlook on the world. For example, it's common in HCD to conduct activities that define and prioritize ideas based on end-user value or impact. For NASA, these activities had to be adapted to match NASA's broader understanding of impact compared to a commercial player.

VII. Limitations and Future Work

At the time of writing, the outcomes of our approach (i.e., early-stage aviation concepts) remain yet to be seen. Project work continues on the three efforts presented in this paper, with intention to establish follow-on teams that will prototype aviation solutions to verify technical feasibility and identify and test critical uncertainties.

Conducting this work within a government context is not without limitations. For example, when engaging with stakeholders outside of the agency, teams must consider appropriate channels to connect that honor government constraints. However, NASA does have a vision to pursue aviation advancements 'for the benefit of all,' so it remains important to forge new pathways for stakeholder engagement. We acknowledge that NASA's unique context, resources, and history shape our approach to this work, and we believe many of the insights to be transferable to the aviation sector at large. For other organizations, it will be important to adapt methods to organizational culture and objectives and to the resources available.

We plan to refine and evolve our approach as we continue to pursue complex societal problems within CAS. Throughout these efforts, the authors have continuously evolved the methodologies to respond to team feedback, to address organizational constraints, and to support effective work. In addition to the dedicated project teams for each effort, the *Access to Healthcare* effort included additional, narrowly scoped sprint teams to test the limits of the approach and methodologies. To optimize for the factors previously mentioned, these additional teams tested methods for gathering stakeholder data, conducting analysis to generate insights, and co-designing concepts. The synthesized outcomes of these test sprints will guide upcoming efforts this year. Rapidly iterating and improving our methods is core to our objectives.

VIII. Conclusion

We conclude with a call to action for the aviation community to take a broad view in examining how complex societal challenges can be tied to aviation. The three example challenges described above illustrate our human-centered, systems-oriented, and futures-based design approach, multiple ways of scoping societal problems using an aviation lens, and key considerations for bringing together aviation teams and non-aviation stakeholders to co-formulate problems and co-create solutions. Additionally, we offer a preliminary set of six cross-cutting characteristics of societal problems that may be fruitful for aviation to address. These characteristics may serve as signals for aviation organizations that wish to expand their portfolios, realize compelling new use cases, and thereby develop transformative new innovations. They may also help non-aviation organizations to understand how they might benefit from the future of aviation.

Acknowledgments

This work was funded by the NASA Aeronautics Research Mission Directorate, Transformative Aeronautics Concepts Program, Convergent Aeronautics Solutions (CAS) Project. The authors wish to acknowledge the CAS Project Managers Keith Wichman, Gerard Welch, and Kurt Papathakis alongside all those who have contributed to CAS's early-stage design process and the projects described in this paper, including David Cannon, Steve Crimaldi, Kellie Kennedy, LeeAnn Maryeski, Anna McGowan, and Wes Ryan.

References

[1] Basner, M., Clark, C., Hansell, A., Hileman, J. I., Janssen, S., Shepherd, K., and Sparrow, V., "Aviation Noise Impacts: State of the Scienc," *Noise & Health*, Vol. 19, No. 87, 2017, pp. 41–50. doi.org/10.4103/nah.NAH_104_16

[2] Seidel, V. P., and Fixson, S. K., "Adopting Design Thinking in Novice Multidisciplinary Teams: The Application and Limits of Design Methods and Reflexive Practices." *Journal of Product Innovation Management*, Vol. 30, No. S1, 2013, pp. 19–33. doi.org/10.1111/jpim.12061

[3] Passchier-Vermeer, W., and Passchier, W. F., "Noise Exposure and Public Health," *Environmental Health Perspectives*, Vol. 108, No. S1, 2000, pp. 123–131.

[4] Collins, T. W., Nadybal, S., and Grineski, S. E., "Sonic Injustice: Disparate Residential Exposures to Transport Noise from Road and Aviation Sources in the Continental United States," *Journal of Transport Geography*, Vol. 82, 2020. doi.org/10.1016/j.jtrangeo.2019.102604

[5] Bengelink, R. "Key Challenges for the Aerospace Engineer of 2015," *AIAA Aerospace Sciences Meeting and Exhibit*, AIAA 2007-297, 2007. doi.org/10.2514/6.2007-297

[6] Boy, G. A., "Human-Centered Design of Complex Systems: An Experience-Based Approach," *Design Science*, Vol. 3, N. 8. 2017. doi.org/10.1017/dsj.2017.8

[7] Norman, D. A., and Stappers, P. J., "DesignX: Complex Sociotechnical Systems." *She Ji: The Journal of Design, Economics, and Innovation*, Vol. 1, No. 2, 2015, pp. 83–106. doi.org/10.1016/j.sheji.2016.01.002

[8] Baxter, M., *Product Design: A Practical Guide to Systematic Methods of New Product Developmen*,. Stanley Thornes, Cheltenham, England, 1999.

[9] McGowan, A.-M. R., Bakula, C., and Castner, R. S., "Lessons Learned from Applying Design Thinking in a NASA Rapid Design Study in Aeronautics," *AIAA SciTech Forum*, AIAA 2017-0976, Grapevine, TX, 2017. doi: 10.2514/6.2017-0976

[10] Ray, K., Cappuccilli, B., Hunter, J., Eichenauer, M., Sells, B. E., and Reid, T., "Ethical Human Centered Design: Practical Approaches for Aerospace Engineering Education," *AIAA Aviation Forum*, AIAA 2022-3711, Chicago, IL, 2022. doi.org/10.2514/6.2022-3711

[11] Müller, L., Budde, M., Weibel, N., Spencer, E. A., Beigl, M., and Norman, D., "Learning from Failure: Designing for Complex Sociotechnical Systems," *ACM International Joint Conference on Pervasive and Ubiquitous Computing*, New York, NY, 2017. doi.org/10.1145/3123024.3124460

[12] Moore, R. M., McGowan, A.-M. R., Jeyachandran, N., Bond, K. H., Williams, D., Cannon, D., and Rowan, C. T., "Designing the Design Process for Early Problem Discovery for a Complex Aeronautics Systems Challenge." *Interntional Conference on Engineering Design*, Gothenburg, Sweden, 2021. doi.org/10.1017/pds.2021.116

[13] Buchanan, R. "Wicked Problems in Design Thinking." *Design Issues*, Vol. 8, No. 2, 1992, p. 5-21. doi.org/10.2307/1511637

[14] Irvine, T. B., "Emerging Technologies, Societal Trends and the Aerospace Industry," *AIAA SciTec Forum*, AIAA 2022-0398, San Diego, CA, 2022. doi.org/10.2514/6.2022-0398

[15] Seager, T., Selinger, E., and Wiek, A., "Sustainable Engineering Science for Resolving Wicked Problems," *Journal of Agricultural and Environmental Ethics*, Vol. 25, No. 4, 2012, pp. 467–484. doi.org/10.1007/s10806-011-9342-2.

[16] Lönngren, J., and Svanström, M., "Systems Thinking for Dealing with Wicked Sustainability Problems: Beyond Functionalist Approaches," *International Conference on Engineering Education for Sustainable Development*, Vancouver, CA, 2015.

[17] Grozer, T., *Learning Causality in a Complex World: Understandings of Consequence*. Rowman & Littlefield Education, 2012.

[18] Burge, S. E., "Systems Engineering: Using Systems Thinking to Design Better Aerospace Systems," *Encyclopedia of Aerospace Engineering*, 2010.

doi.org/10.1002/9780470686652.eae536
[19] Buede, D. M., and Miller, W. D., *The Engineering Design of Systems: Models and Method*. Wiley, Hoboken, New Jersey, 2016.
[20] German, B., and Daskilewicz, M., "An MDO-Inspired Systems Engineering Perspective for the "Wicked" Problem of Aircraft Conceptual Design," *AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, AIAA 2009-7115, Hilton Head, South Carolina, 2009.
doi.org/10.2514/6.2009-7115
[21] DeTurris, D., and Asmady, A., "Systems Thinking for Complexity in Aerospace," *Complex Systems Engineering: Theory and Practice*, edited by Flumerfelt, S., Schwartz, K.G., Mavris, D., and Briceno, S., 2018, pp. 1–24.
[22] Dugan, K. E., Mosyjowski, E. A., Daly, S. R., and Lattuca, L. R., "Systems Thinking Assessments in Engineering: A Systematic Literature Review," *Systems Research and Behavioral Science*, Vol. 39, No. 4, 2022, pp. 840–866. doi.org/10.1002/sres.2808
[23] Sanders, E. B.-N., and Stappers, P. J., "Co-Creation and the New Landscapes of Design." *CoDesign*, Vol. 4, No. 1, 2008, pp. 5–18.
doi.org/10.1080/15710880701875068.
[24] Udoewa, V., "An Introduction to Radical Participatory Design: Decolonising Participatory Design Processes." *Design Science*, Vol. 8, 2022,
doi.org/10.1017/dsj.2022.24.
[25] RapidSOS, "Outcomes: Quantifying the Impact of Emergency Response Times," URL:https://rapidsos.com/our-latest/quantifying-impact-of-emergency-times-whitepaper-download/ [retrieved April 2023]