Design Thinking, Lean Startup, and High-Technology Marketing for Human-Centered Systems Engineering

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Abstract
The use of design thinking, lean startup, and high-technology marketing in systems engineering are presented as a case study. All were used and evaluated for their potential to improve systems engineering processes and design, address the challenges of culture change, increase the adoption rate of new technology, and engage with potential users and sponsors more effectively. Multiple examples of training and use on a model-based systems engineering initiative at a large government agency showcase how these approaches were tailored and used successfully for significant benefits such as enhanced collaboration and better problem definition and design solutions. Challenges remain for use by quiet thinkers and with virtual teams. These new ways of thinking are well aligned with creating and using new technologies and are suitable for situations involving innovation, uncertainty, and change within organizations. This case study intends to familiarize systems engineers with the application of these human-centered approaches, to interest systems engineers in incorporating these approaches into their work processes, and to inspire the systems engineering research community to investigate further.

KEYWORDS
Design thinking, human-centered, systems engineering processes

I INTRODUCTION

In 2016, NASA formed its Model Based-Systems Engineering (MBSE) Infusion And Modernization Initiative (MIAMI) with the goal of moving away from a document-centric approach for systems engineering to using new digital technologies and approaches to manage complex systems, enhance knowledge transfer, and improve communications.[1,2] The focus of the MIAMI leaders, who included the authors, during the first two years was understanding technical implementation. A consistent message from NASA engineers was their desire to understand how MBSE would make their jobs easier. As the MIAMI leaders learned more about MBSE, cultural adoption presented a larger challenge than the technical implementation. Alternative approaches of design thinking, lean startup, and high-technology marketing, which this paper terms "human-centered systems engineering," were investigated to see how they could help NASA engineers understand where and how MBSE might be useful to them, and, assist leaders in determining which strategies might be best for infusing MBSE into projects.

Though other human-centered approaches exist, design thinking, lean startup, and high-technology marketing were chosen because resources describing them and how to use them were readily available. In addition, they share three common themes. All three encourage listening to the customer, the "human" in human-centered systems engineering, to guide decision making. Human-centered approaches encourage communication in alternative ways, not as a side effect, but as a primary strategy for eliciting innovation. All three encourage small tests and iterations towards a larger goal, as opposed to one large attempt prior to testing the solution. All have less formality with their iterations than Agile[2,3] systems engineering, so they might be easier to implement in conjunction with other methods. Lastly, all three have a bias towards action. They provide encouragement to move quickly by failing at a small scale in safe environments and use the lessons learned to adapt and scale to a larger scope. Since MIAMI aimed to infuse MBSE into project engineering environments, there was perceived value in moving beyond MBSE research.

After trying and successfully using tools from several human-centered systems engineering approaches, the successes and challenges are being shared as a case study. This paper showcases approaches that were applied to MBSE infusion work. MBSE is the context for this paper, not the focus. This paper demonstrates that human-centered approaches can

be used successfully when applied to systems engineering. We intend for systems engineers to develop an interest in incorporating human-centered approaches into their work and the research community to be inspired and investigate these approaches further.

The remaining sections describe the context, methodology, results, and conclusions from the use of design thinking, lean startup, and high-technology marketing. The paper is a case study with five examples of how the approaches and tools were modified, adapted, and used for systems engineering within a large government agency. The paper concludes with our overall results, thoughts on use with systems engineering processes, and possible applications for the future.

2 BACKGROUND AND CONTEXT

This section describes aspects of the design thinking, lean startup, and high-technology marketing approaches that were used in this case study.

2.1 Design Thinking Characteristics and Known Challenges

The definition and practice of design thinking, which has its origins in human-centered design[4], have evolved over time with the development of the field through research and experience. Several recent publications briefly trace the history of design thinking since its origins in the last half of the 20th century.[5-7] A recent definition states that design thinking "is the search for a magical balance between business and art, structure and chaos, intuition and logic, concept and execution, playfulness and formality, and control and empowerment."[8] Common aspects of design thinking are a focus on the user experience, models to examine complex problems, prototypes and testing, a tolerance for failure, and deliberate choices about what to do and what not to do. Storytelling, empathy interviews, journey maps, rapid ideation with sticky notes, voting, cardboard prototypes, and testing early and often with real users all provide a different look and feel for engineers and designers. Design thinking uses many tools for its basic processes of understand and observe, define a point of view, ideate, prototype, and test in order to build around user needs.[9] Divergent thinking and convergent thinking are used for problem definition and solution definition and can be visualized as a double diamond.[9-10]

Design thinking and related strategies may turn designers, such as systems engineers, into design thinkers. Design thinkers are curious, observant, and able to create and harbor empathy. They do not seek merely to optimize; they challenge themselves and organizations to innovate, and they consider the big picture.[11] These characteristics and qualities provide insight into possible overlaps with the characteristics of systems engineers.

Design thinking has differences from traditional product design that may present obstacles.[6,7] Organizations are asked to accept more ambiguity, as the initial return on investment from design thinking cannot be estimated in usual ways. Leaders are asked to embrace risk and create a culture of innovation that builds and tests prototypes before having complete understanding of a problem. Expectations that design thinking can solve all problems are unrealistic,[6] and the design thinking timeline needs to recognize the pace of culture change in the organization.

2.2 Lean startup

The lean startup movement began in the early 2000s after many startups failed and several key differences between startups and traditional business ventures were recognized.[12] One was that startups and entrepreneurs are dealing with many unknowns and best guesses and plans need to be confirmed or changed after testing of hypotheses with customers, rather than having a traditional five-year business plan. A second added agile product development. This combination is then used to develop a minimum viable product that is used for learning. A third was the business model canvas, a template based on nine business model building blocks[13] that is used to map and keep track of the hypotheses. A main principle is that validated learning is the essential unit of progress.[14] The approach "favors experimentation overelaborate planning, customer feedback over intuition, and iterative design over traditional 'big design up front' development."[15]

2.3 High-technology marketing

The approaches, language, and tools for high-technology marketing are useful for analyzing and planning the adoption of new technology within organizations.[16] The technology adoption curve has five segments; each segment characterizes the extent to which people embrace new technology and who they reference when making decisions.[16] Other groupings of customer segments may be users, buyers, decision makers, and influencers. Success or failure often depends on understanding the value proposition that gets the targeted customer to say "yes."[13] Recommendations for how to cross

the chasm between early adopters and early majority use a targeted deployment that proves out new technology in a small subsection of the early majority using the expected product.[16] Once a targeted deployment is successful in the small, early majority subsection, others in the same segment are likely to trust the opinions of their peers about the value of the new technology.

The whole product model identifies four different levels of completeness: generic, expected, augmented, and potential product.[16] New technologies enter at the generic level, i.e., the product itself, and then expand to the expected product, which is the minimum configuration that a customer expects. Additional growth occurs as the product is augmented with additional features; the potential product represents further room for growth. Each level of the whole product builds upon the parts that come before it.

The strategy of high-technology marketing as applied within an organization aligns well with the approaches for responding to opportunities presented by disruptive technologies.[17] Traditional management practices, which are effective for sustaining technologies, are inadequate for disruptive technologies. Instead, organizations are advised to examine their resources, processes, and values with respect to decision-making, resource allocation, and abilities to create new capabilities internally. Within an organization, this may manifest as an innovation arm identifying a mainstream division or project as a candidate for targeted deployment.

3 METHODOLOGY

We proposed that the application of human-centered approaches and tools would significantly augment the systems engineering processes of the ISO/IEC/IEEE 15288:2015 standard[18] and the NASA systems engineering engine.[19] The processes of Acquisition, Supply, Life Cycle Model Management, Infrastructure Management, Project Portfolio Management, Human Resource Management, Business or Mission Analysis, Project Planning, Project Assessment and Control, Decision Management, Stakeholder Needs and Requirements Definition, System Requirements Definition, Architecture Definition, Design Definition, and Validation were of particular interest.

We used direct experience to assess the applicability, ease of use, and benefits of human-centered approaches and tools. In addition, we thought that human-centered approaches provided a stronger connection between problem solving in complex systems and systems engineering, and would result in better problem definition and better solutions. The human-centered approaches appeared at times to be significantly different from the ways NASA engineers work, where institutional processes that are in place for safety and to avoid failure may reduce flexibility and limit creativity and agility.[20]

The authors led or participated in multiple training sessions and use events over two years. The approach was to apply human-centered approaches during our project work as much as possible rather than set up tests with subjects, controls, and measurements. Results were assessed from the systems engineering work products and from participant feedback on the usefulness, ease, and challenges of using human-centered approaches for systems engineering. This paper provides highlights of the results from different projects that cover a breadth of applications.

4 CASE STUDY

The case study presents five examples in sequential order. The human-centered approaches and the topic of each example are as follows:

- Example 1—design thinking: plans for project startup
- Example 2—design thinking and lean startup: project evaluations and annual plans
- Example 3—design thinking, lean startup, and high-technology marketing: grow a sustainable community of practice
- Example 4—design thinking: sustain and advance a discipline
- Example 5—lean startup and high-technology marketing: strategies to infuse new technology

The contents of each example are the event type, when it occurred, objectives, number and roles of participants, goals with respect to the example, description of the activities, and results.

4.1 Example 1—Project Startup

The authors introduced design thinking to seventeen participants during a five-day face-to-face training and planning meeting. The overall objectives of the meeting were for the participants to draft work plans for the next twelve to eighteen months and to identify next steps to start up their projects. The participants were members of MIAMI and were on new project teams for a sounding rocket and experiment, a new working group, or on other spaceflight projects. The

participants were early, middle and late career engineers from ten different locations within the United States, although many of them knew each other from previous project work. None of the participants had significant previous experience with design thinking before this meeting. The goals with respect to this case study were to provide the participants with multiple design thinking tools, as it was not known beforehand which tools would appeal to each person, and to observe which, if any, of the design thinking tools assisted with achieving the overall objectives of the meeting. Additional goals were to encourage creative thinking and innovation, add to everyone's toolbox, and promote technical leadership. The training implementation was in a cyclical fashion. Participants learned a concept from each design thinking process stage, practiced the concept with a sample problem, implemented the concept in their project work, and then repeated the cycle.

4.1.1 Design thinking

The principal activities were six modules: introduction to design thinking, project summary, stakeholder engagement, framing the problem, brainstorming and prototyping, and feedback. The participants were at tables of six people for the training and practice exercises, and then moved to be with their project teams for their project work. The participants went through a full design thinking cycle.

The first module covered the benefits of design thinking, the five step process, and design thinking features, especially those of focus on human values, bias toward action, and embrace experimentation. The module concluded with a warm-up activity of "yes, and", and an invitation for the participants to place their thoughts on a feedback grid.

In the second module, the participants summarized their projects with their current understanding in both words and pictures. A template had blocks for sketches and captions to visualize the problem or opportunity in a storyboard, a persona outline for stakeholders and elements of the environment, and blocks to sketch stakeholder emotions. Each participant completed an individual project summary and compared with their teammates to check for common understanding or differences of thoughts. The participants shared with their peers on other projects for additional perspectives.

The third module covered the design thinking process of understand and observe. The participants were presented with benefits on the value of stakeholder engagement, saw a demonstration of an empathy interview, and received how-to tips. The participants planned approaches and questions for a practice interview, and interviewed other participants in the room. The emphasis of the interviews was to understand the stakeholder's point of view, to seek memorable stories, to record quotes, and to dig deeper into the problem.

In the fourth module, the participants practiced using three reframing tools (empathy interview analysis template, Powers of 10, and Why-How Laddering) to define a point of view. The participants analyzed their project stakeholder interviews using all three of the tools and wrote a point of view statement, "We wonder if this means…" for a focal point during the brainstorming.

The fifth module combined ideate, prototype, and test. The participants practiced generating a large quantity and broad expanse of alternatives using "How Might We" and addition or removal of constraints, and learned the differences between generating and evaluating ideas. After ideation, the participants grouped their ideas and voted. Each participant had six votes – two for each criterion. The tables looked at the voting results and selected an idea to test. The participants then regrouped into their project teams and repeated brainstorm, group, and vote for their projects. After a break, the participants learned about the value of rapid prototyping and the different types of prototypes. The participants practiced building early, low-fidelity prototypes using craft materials, prototyped their selected project ideas, planned how to test their prototypes, and practiced with other participants. Lastly, they tested with their project stakeholders in person or by telecon.

The final module collected feedback from the participants and occurred both during and at the end of the training. Participants populated a feedback capture grid divided into quadrants labeled "I like (+)," I wish (Δ)," "I wonder (?)," and "Aha! (💡)" with their thoughts recorded on sticky notes. At the end of the training, the whole group moved sticky notes into themes and categorized each theme, as shown in Figure 1. The colors of the sticky notes are unimportant; the figure illustrates how each participant contributed thoughts and how the thoughts were grouped. The figure is an example of a completed feedback capture grid from actual use.

Place Figure 1 here

4.1.2 Results

The comments about the design thinking tools liked by the participants are in Table 1. One or more positive comments were received on each of the design thinking tools or approaches that were presented. Individuals responded to and expressed preferences for the different tools, and different people preferred different tools. The comments state that participants learned more than they anticipated and the tools were more powerful than they anticipated.

Place Table 1 here

The participants had positive feedback comments on the design thinking approach and team exercises and those are listed in Table 2. The participants liked the team collaboration, energy, enthusiasm, participation and insights.

Place Table 2 here

Comments with negative feedback or concerns are listed in Table 3. The comments revealed that not all participants liked the design thinking exercises, and some found it difficult to work in a different way, especially with imposed time constraints of a face-to-face meeting.

Place Table 3 here

The systems engineering processes that were used during this example and the human-centered approach paired with it are in Table 4. The feedback from the participants showed that design thinking tools and approaches contributed significantly to a successful meeting. The teams understood their stakeholders in new ways, had new ideas for their work plans, and could use new approaches for the next steps to start up their projects.

Place Table 4 here

After these initial training and use sessions, the participants used design thinking and related principles in their work. At least one team continued to use the rough prototypes they developed during their initial training as a reference during conversations with their stakeholders.

4.2 Example 2—Customer Analysis

This example was a combined annual review and academic training for 26 participants, seven months after the face-to-face training and planning meeting in Example 1—Project Startup. The overall objectives of the meeting were for the participants to have their work evaluated and identify their goals and objectives for the next twelve months. The participants were members of MIAMI and were on project teams for a sounding rocket and other spaceflight projects, a working group, or a strategy group. Ten of the participants had attended the Example 1—Project Startup. The goals with respect to this case study were to provide training in design thinking and lean startup and observe in what ways the participants benefited from the training.

4.2.1 Design thinking and lean startup

Training in design thinking and lean startup were provided through an academic institution. The instructors attended the annual review feedback session and were able to coach the participants during the training part of the meeting.

On Day 1, the instructors presented an introduction to design thinking, common misconceptions about design thinking, and the importance of reframing the project scope into a problem space and a solution space. The instructors divided the participants into groups of three for a quick practice design thinking cycle. Then the participants formed into their project teams as the instructors led the participants through parts of the design thinking cycle on their projects. The project teams selected from empathy interview, shadow experience, journey map, or extremes to gain more insight. The project teams then brainstormed ideas from new insights or tested ideas.

Day 2 expanded participants' knowledge of lean startup. The instructors presented information on the business model canvas aspects of customers and value propositions for identifying stakeholders and which of those are primary, defining what problems are being addressed, and considering if those are the right problems to be addressed. The participants learned how customer segments provide insight into who in an organization makes decisions and their influencers, and, how value propositions provide insight on what each customer segment bases its decisions. The participants practiced in a role play as an executive committee making an investment decision.

The participants formed into their project teams, identified and categorized stakeholders into customer segments, gave each a persona, and listed value propositions. Figure 2 shows an example of a completed customer segment and value proposition matrix that identified the engineering workforce as User; engineering managers as Decision Makers; mission support, programs, and projects as Payers; and eight groups as Influencers. The figure illustrates that all perspectives from participants of multiple organizational levels, as indicated by the different colors of the sticky notes, were valued and considered.

Place Figure 2 here

The project teams brainstormed ideas for addressing the value propositions and chose an idea to test. In addition, they identified assumptions that would endanger their projects if they were wrong. They used their assumptions and ideas to evaluate their next steps and make adjustments. The project teams partnered with other teams for peer-to-peer feedback. Each project team presented to peers, which helped to clarify their work, and received feedback from knowledgeable, independent peers. The day ended with a verbal debrief session.

4.2.2 Results

Each of the teams was able to use the design thinking and lean startup tools for the sample exercises and for their real projects. The participants provided comments of appreciation for the design thinking and lean startup approaches and tools. They expressed their opinions on the helpfulness of having instructors attend the annual review feedback session prior to the training and their thoughtful assistance for their particular projects.

The systems engineering processes that were used during this example and the human-centered approach paired with it are in Table 5. The verbal feedback during the meeting, as well as the energy and level of discussion, indicated that the participants generally liked using the tools. The participants were better able to understand the progress of their projects and identify approaches for problem areas. The participants stated that the customer segment and value proposition matrix provided a format that was easy to use and understand and helped them determine the goals and objectives for their next steps. The business model canvas was an additional tool for decision-making. The peer-to-peer feedback during the event itself provided a quick check before the teams invested more time in finalizing their project plans for the next twelve months.

Place Table 5 here

4.3 Example 3—Community of Practice

In contrast to the larger groups in Examples 1 and 2, eight members of a Community of Practice (CoP) met for a three-day working meeting. The objectives of the meeting were to gather and share experiences, to experiment with new ways to address challenges, to define the work to move forward, and to think larger picture for growing a sustainable community. Some participants had not attended the previous events, so the meeting included training on the approaches and tools. A facilitator was on-hand to lead the training and to assist the group. The goals with respect to this case study were to provide training in design thinking, lean startup, and high-technology marketing and observe in what ways the participants benefited from the training.

4.3.1 Design thinking, lean startup, and high-technology marketing

Training and exercises covered an overview of the design thinking process, warm-ups to encourage exploratory thinking, and an introduction to the Powers of 10, journey map, interview unpacking, reframing questions, brainstorming, and idea selection. The group addressed one of their top challenges, that of getting projects started with MBSE. The group divided

in half for empathy interviews of two participants; one had experience for a large, multi-center project and one had experience for a small project. The groups captured the processes on a journey map, identified pain points by sketching smiling or frowning faces next to a step, and compared the two different experiences. The group rejoined and used design thinking tools for problem definition and point of view, brainstorming, idea evaluation, and idea selection to generate a list of deliverables to support the adoption process and sustain proficiency.

A second round of training briefly covered the technology adoption curve, targeted deployment, and whole product model. The group then addressed a capability roadmap. The group first identified the target customer segment so as to focus their scope. The roles of line manager, project manager, and lead systems engineer were listed, characterized, and given value proposition statements. The group decided that lead systems engineers were the target customer segment for the CoP, based on having the largest impact if their value proposition was met by the CoP. The group generated ideas on the key capabilities and minimum configuration of the CoP and other resources. The group voted on the ideas for how well they would serve the value proposition and prioritized them for future work. The top priority ideas for the CoP were added to the task list and systematically covered over the following year.

4.3.2 Results

The participants left the meeting with a good understanding of the pain points for getting started in MBSE and a list of items that were needed to support the process from the CoP and from interested projects. The tools provided a quick way to identify key stakeholders and high priority ideas. At the end of the meeting, the CoP Lead reported the following four major takeaways:

1. Having dedicated time to brainstorm through these topics was invaluable
2. Sharing experiences with team members helped to gain common understanding of what challenges we are facing
3. Design Thinking and Lean Startup ideas are vital to solving the culture problem with MBSE adoption as well as close the capability gap
4. The work is not done; we need to translate what we've learned into action and lean on the CoP community to bring these ideas to life

After the event, the participants were asked to provide feedback via a survey on benefits, successes, opportunities, and challenges. The following represents a selection of the responses received from six of the eight participants to the underlined questions:

Did you see benefits from using the tools?

- Sharing experiences with team members helped to gain common understanding of what challenges we are facing.
- Design thinking and lean startup ideas are vital to solving the culture problem with MBSE adoption as well as close the capability gap.
- Rapid prototype is an important lesson.
- Understanding the differences between all the customers to get to who is the main influencer, and whom I need to please. It isn't always management as we are taught.

Success in using the tools?

- The team made a great attempt to learn new information and tools, and use it immediately.
- Warmups are good for transition to communicating as a team quickly.
- When you brainstorm based on value propositions, you can find ideas at all levels of details. And these are all useful at different stages of planning.
- We followed the progression through the design thinking well enough that we generated high-value ideas on which to focus near term. I think we identified a good strategic value proposition to target and I think there is a good plan for moving toward it.

What did you enjoy about using the tools?

- The tools got the team to talk. I felt the collaboration and how we went about it was a rewarding experience that helped all of us come to a similar consensus on the way we should be moving forward while not being able to insinuate opinion(s) that would drive the conclusion. Dictating (or not) the answer gives a different outcome.

- The way we approached getting to a resolution adopted everyone's thoughts, experiences, and ideas so that we came to a consensus based on everyone's input. At first this was a bit out of the box from what I am used to when having similar collaboration meetings, but by the end I definitely saw the value in this approach.
- The journey map lets you see commonalities between the different methods to find overlap or what might help out all the different journeys evaluated.
- Really thinking through situations across time, different perspectives, different values. When it comes to assuming a domain boundary I'm as guilty as the next engineer, and it was helpful to forcibly peel back my natural inclination to assume constraints.

Opportunities

- Maybe some blanks to fill in to work across a wall, like point of view (POV) section with "We wonder if this means…" written several times.
- I would like to know what a rapid prototype would help out with based on our customer segment. The exercise with the teacup is okay when you know what you are prototyping, but if you have no idea, it is hard to wrap your head around it.
- I wonder what are good 100% value proposition statements.
- I wonder how to deal with segments that are multiple roles, and how you choose which customer segment to focus on.

Challenges

- It would've been helpful to have a design thinking facilitator in the room to "herd the cats."
- We tended to drop into understanding the engineering solutions or dropping into details rather that forcing ourselves to stay with the big picture.
- Time to apply each to problem at hand after we try the example.

The responses show that the participants generally found value in applying human-centered approaches. They reported higher and easier collaboration and more creative solutions. The journey map assisted in understanding stakeholder expectations, differences among all of the different customers of the CoP, and setting the system boundary. The point of view, brainstorming, and idea selection helped the team generate high-value ideas that were beyond the apparent engineering solutions and covered different levels of time and perspectives. The team reached a consensus on the path forward while considering all the individual thoughts and ideas. The customer segment and value proposition tools helped the team to decide where to focus their efforts and resources. The participants did express frustration with the chaos and format of some of the design thinking activities and provided suggestions for increased understanding and ability to use.

The systems engineering processes that were used during this example and the human-centered approach paired with it are in Table 6. The participants were able to use the human-centered approaches to share information quickly, to generate ideas from multiple levels and perspectives, and to reach a consensus for their next phase of work. The participants identified ways to partner with and provide services and expertise to others. The participants planned for their next phase of work by prioritizing those items deemed most essential for processes, infrastructure, community building, and advancing the skills of the workforce.

Place Table 6 here

4.4 Example 4—Sustain and Advance a Discipline

This example was a series of virtual and face-to-face meetings among two of the MIAMI leaders and a temporary co-lead. The objective was to understand leadership and community roles to sustain and advance the systems engineering discipline. The goals with respect to this case study were to use human-centered approaches to gather information and observe if the information content was sufficient to provide recommendations for organizational roles and responsibilities.

4.4.1 Empathy Interviews

The leaders applied the concept of empathy interviews and interviewed six engineering workforce members and stakeholders who belonged to similar communities to understand how their communities continue to adapt and provide value to their respective workforce segments. They chose the empathy interview tool as a way to obtain useful information in fast, easy way. Six interviews were performed over a period of one month. The interviews included the following design thinking- and lean startup-inspired questions and prompts:

- Describe your role in this area.
- What worked well? Tell us a story about when it worked well.
- What didn't work well? Tell us a story about when things didn't work well.
- What would you keep doing?
- What would you do differently?

After the interviews, the leaders used human-centered principles to analyze the information individually. Each recorded a persona, "golden nuggets" and insights, striking quotes, most surprising information, and big takeaways for every interview subject.

Later, the leaders met to consolidate findings and make decisions on the next steps. An example interview summary analysis from one interviewee, who leads a community similar to the MBSE community, is given in Table 7. This person faced challenges in organizing the effort to grow and advance the technical expertise of an engineering discipline. Among the big takeaways are reaching out to the workforce and meeting their needs, and to identify a real problem that needs to be solved to gain increased advocacy and resources.

Place Table 7 here

4.4.2 Results

Although this example occurred over a calendar time period of six months in total, the actual work hours were significantly less and added up to a total of approximately one hundred hours. The interviews provided valuable information, which may not have been otherwise obtained, due to the type and format of the interview. The analysis of persona, striking quotes, most surprising findings, and big takeaways provided clear clusters of themes and trends, and identification of those aspects most important for the advancement and sustainment of the discipline. The results from the interviews reinforced the need to focus on the working engineer level. Many interviewees emphasized the need to engage with the user segment, and to continue to do so even while management changes occur. This information served as encouragement to continue to provide an organizational and technical support structure and to proceed with their deployment.

The systems engineering processes that were used during this example and the human-centered approach paired with it are in Table 8. The interviews and their analyses, along with customer segment and customer persona, provided significant understanding of stakeholders, which allowed new insights and approaches for defining the requirements of leaders and their roles and responsibilities. The interview analyses provided new ideas that were incorporated into plans for the next year, which included partnerships to assist with growing the community and its expertise and ways to provide the community expertise back to projects. The interview analyses also provided insights on how to approach those who control and influence the infrastructure, training, and project opportunities.

Place Table 8 here

4.5 Example 5—Promote Infusion of New Technology

This example involved the same leaders as Example 4—Sustain and Advance a Discipline and occurred over a time period of eight months. The objective was to understand how to promote infusion and adoption of new technology by an organization. The goal with respect to this case study was to select tools that were thought to provide the best opportunity for understanding and planning the adoption of MBSE and observe if they provided different insights and approaches.

The leaders applied customer segment and market segments from the technology adoption curve, a modified market development strategy checklist, and the whole product model.

4.5.1 Technology Adoption Curve

The leadership team examined the five segments of the technology adoption curve[16] and considered the characteristics of the people within each segment and how those characteristics related to their work. The MIAMI community had been previously acting as and working with innovators and early adopters. The innovators were those who did much of the exploratory work in the discipline.[21,22] The early adopters were many of the early users of MBSE on shadow or small projects, and include the MBSE Pathfinder team members.[23] The early majority were decision-makers or influencers on the projects who were known to be increasing or interested in increasing their use of MBSE.

The leaders decided to target the early majority segment to promote MBSE adoption on a larger scale. The question then became, what role on a project was the one that fit best into the early majority segment? The leaders were familiar with the roles of project manager, chief engineer, lead systems engineer, and system modeler through their own project experiences. The roles and responsibilities were listed and their characteristics were assessed, such as who would are the decision-makers on the use of MBSE on a project and who would best be able to create positive word-of-mouth among their peers about their experiences with MBSE on a project. The lead systems engineer was selected as the most important market segment within the early majority.

4.5.2 Marketing Development Strategy Checklist and Targeted Deployment

The leaders examined multiple projects to plan for a targeted deployment. Projects in human exploration, space science, small satellites, communications, and launch vehicles were selected as potential targets and were mapped onto the technology adoption curve.

The set of potential projects in the early majority were evaluated with a marketing development strategy checklist after the checklist was modified to be appropriate for a government agency as shown in Table 9.[16] The first four and last five criteria were “deal breakers” and “nice to have”, respectively.

Place Table 9 here

The field was narrowed by scoring each project from 1 to 5 for each of the “deal breaker” criteria, for a total maximum score of 20. The scores from each evaluator were summed to arrive at a total score for the project and showed a clear break between five projects that could gain support for MBSE and five projects that likely could not.

The top five projects were further evaluated using the “nice to have” criteria. After speaking with the lead systems engineers of each project to discuss a potential partnership in more detail, one project was chosen. An agreement was reached that outlined how MIAMI would help the project be successful in its implementation of MBSE in return for feedback on creating a whole product for MBSE and positive word of mouth among lead systems engineers.

4.5.3 Whole Product Model

The leaders used the simplified whole product model[16] to identify the standards and procedures, additional software, additional hardware, system integration, installation and debugging, change management, and training and support for the expected product, which was the minimal set of items a project user would need to successfully implement MBSE. The simplified whole product model and gap analysis for MIAMI’s MBSE expected product are shown in Figure 3, using the same format as in Reference 16. A gap analysis identified those items for which gaps existed, and those items are enclosed in rectangular boxes. A complete enterprise solution was considered to be part of an augmented product and was beyond the scope of the work.

Place Figure 3 here

4.5.4 Results

The technology adoption curve, modified market development strategy, and whole product model were approachable tools that assisted the leaders with different insights and different approaches, such as a targeted deployment. They provided terminology that captured what the leaders had been expressing among themselves and assisted their communications. The technology adoption curve was a way to categorize many different projects as to their maturity and suitability for consideration as a targeted deployment project. The modified market development strategy checklist criteria was a quantitative, objective method for comparing seemingly similar projects. The simplified whole product model categories helped the leaders clarify a complex problem and generate insights, and the graphical depiction helped the team communicate with each other and with other groups. The leaders tested the items on hand and explored the development of missing items with the targeted deployment project. The targeted deployment partnership between MIAMI and the project ran for a year and was very successful in helping both MIAMI and the project.[24] In the end, the targeted deployment project contributed to the evaluation of the efficacy of the whole product.

The systems engineering processes that were used during this example and the human-centered approach paired with it are in Table 10. The technology adoption curve provided deeper and different insights into stakeholders, motivations, and needs. The modified market development strategy checklist offered new criteria for making decisions, and allowed the leaders to consider potential targeted deployment projects from acquisition and supply perspectives. The targeted deployment approach fed directly into the technical planning for the next phase of MIAMI, and provided a different and better way to evaluate projects under consideration prior to commitments of resources to advance new technology. The whole product model provided an easy way to capture the life cycle processes, infrastructure and tools, and the support and expertise needed for the workforce to be successful. The emphasis on the expected configuration, rather than the augmented or potential product, captured the step-by-step growth of the new technology and allowed identification of the gaps in the current configuration that let the leaders focus their efforts. All of these led to a better definition of the problem, opportunities, and potential solutions.

Place Table 10 here

Many of the key characteristics of the MIAMI effort itself aligned well with the recommendations in *The Innovator's Dilemma*[17] for how organizations might respond to disruptive technologies. The MIAMI effort was set up outside the scope and responsibility of an established program or project by the NASA Technical Fellow for Systems Engineering. The MIAMI leaders were given responsibility and resources to advance the capability. The approach was to test, learn, revise, and grow. Interested users came from small, medium, and large projects to work on the MIAMI pathfinder projects. The acceptance of failure and reduced expectations for the MIAMI projects made the risk of failure less consequential and provided an environment within which people could freely explore. Then-current offerings of software, along with some customization, were employed on over a dozen use cases, which provided evidence of the usefulness of the new technology and served to grow the interest of established programs and projects.[25]

5 DISCUSSION

5.1 Overall Impressions

Over the course of two years, the authors saw mostly positive results and the participants provided overwhelmingly positive feedback for human-centered approaches. Participants enjoyed most of the training and project experiences. The approaches, although not required for MBSE, enhanced collaboration. They helped people generate better design solutions and identify and focus on important stakeholders, who are not always obvious among the larger stakeholder group. The application of human-centered approaches gave people new ways to generate insights and interact with their customers with increased success.

The case study examples were similar in that all of the participants were part of the MIAMI effort for the development and advancement of new technology and approaches. Even though people were from geographically dispersed organizations, many had previously worked with each other over the course of several years. The experiences in using human-centered approaches may have been affected by previous interactions among the participants and their openness as innovators or early adopters. The participants had enough trust to try the training and use the approaches and tools even though it was different from previous engineering or leadership training. They did feel that they needed assistance using some of the tools and keeping their groups focused on the correct abstraction levels while using them. More practice with the tools, fill-in-the-blank type examples, and facilitators early on may help with this.

Human-centered approaches do not fit well with all personality types. Design thinking, for instance, has a "bias towards action" principle that can be uncomfortable for quiet thinkers and those inclined to spend time contemplating their ideas into well-detailed and structured plans. The time constraints that design thinking may impose made most of the participants uncomfortable, including those who are action-oriented. For example, the teacup activity referenced in the participant feedback in Example 3 showed participants that they could achieve similar results when spending shorter or longer periods of time on the same activity. A participant pointed out that this may only be valid when participants have a clear understanding of what they are designing. Even with these difficulties, many participants still attempted to use human-centered approaches in their work. In-person meetings allow frequent use, although it was more difficult to use in virtual settings due to the physical nature of many of the tools. For instance, many involve physical movement or utilizing materials—a challenge when many participants work remotely from each other. As organizations and industries continue to move toward globalization, human-centered approaches will need to adapt to accommodate this reality, either through changes in the approaches, changes in the tools, or changes in the technology used to execute the approaches and tools.

The potential for easily transitioning design thinking to the virtual environment is evident. The rapid conversion of the co-located workplace to virtual work in order to minimize the spread of the COVID-19 virus in early 2020 was a forcing function that provided new opportunities to explore virtual human-centered approaches. Our organization provided collaboration tools to screen share simultaneously with audio conversations for real-time meetings, and chat and file posting options for asynchronous communications. The collaboration tools enabled large team interactions and breakout the large group into smaller groups. Specialized software specifically for design thinking and related areas was explored for problem definition, brainstorming, idea analysis, and voting, all in a virtual workspace and whiteboard canvas.

5.2 Use With Systems Engineering Technical Processes

The ISO/IEC/IEEE 15288:2015 standard defines common terms and provides a standard set of systems life-cycle processes.[18] Systems engineers and other users of the standard select the application methods, such as the life-cycle model, development methods, and tools, to perform the processes. The use of human-centered approaches may be used to advantage to perform systems life-cycle processes. In addition, as the authors used and taught design thinking, lean startup, and high-technology marketing, the approaches and terms from these areas were easily translated into those that systems engineers use and understand. Design thinking and lean startup were easy to use for stakeholder engagement and design prototypes, and high-technology marketing was easy to use and execute for detailed design and implementation of a strategic approach. Though all these approaches may likely apply to all phases of a project life cycle, this case study used them during validation primarily for obtaining customer feedback from rapid prototypes. Tables 4,

5, 6, 8, and 10 summarize the use of human-centered approaches and tools for systems engineering processes; the details for each are in the case study examples.

5.3 Addressing Challenges for MBSE Adoption

Based on the results in the case study examples, human-centered approaches may be well-suited to help address some of the challenges related to increased MBSE adoption. The top factors were studied and summarized in Reference 26. These factors, which may not have or need technical solutions, present significant barriers. Relevant case study examples and the brief summary of results that could address the top factors are listed in Table 11.

Place Table 11 here

6 CONCLUSIONS AND APPLICATIONS TO THE FUTURE

The principles, terminology, and tools of design thinking, lean startup, and high-technology marketing were explored as potential ways to improve systems engineering processes and design, to address the challenges of culture change, to increase the adoption rate of new technology, and to engage with potential users and sponsors more effectively. After brief training and practice, engineers began use on real projects.

This case study presents information from five examples that show the benefits of using human-centered approaches for systems engineering. The combination of approaches and tools led to user-focused solutions that allowed the practitioners to apply their limited resources to areas most likely to drive success. The most valuable benefit from the application of human-centered approaches was increased communication and empathy between the designers (the MIAMI leaders and participants) and the users (the greater NASA MBSE community). While this benefit may seem obvious, its value cannot be overstated. This was most evident in examples 1, 2, and 3 when teams used their design thinking tools to facilitate discussions with their customers and in example 4 when the leaders interviewed similar communities to understand what lessons they had drawn from their users. Understanding and communicating with the right customers contributed significantly to MIAMI's success. These human-centered approaches provided the drive to understand who the customers are and how to best serve them. In example 5, the leaders used the technology adoption curve to choose a targeted deployment project that would best serve and represent the ultimate customers, Lead Systems Engineers. The technology adoption curve encouraged a look at people who have the most informal influence and a narrowing of the targeted deployment down to those who could experience the benefits. This approach may be useful for infusing other innovations related to systems engineering processes, as well. There are areas where other approaches may work better, and challenges remain, such as those relating to virtual teams.

The use, observations, and results in this case study demonstrate that human-centered approaches can be tailored for use at organizations other than businesses, such as at a large government agency. Terminology and approaches from design thinking, lean startup, and high-technology marketing were adapted, as were principles meant for businesses in innovation spaces. Situations in which a new human-centered designer uses these tools will vary. It is likely that these tools can be tailored for each application, and they should be tailored in order to assist the user to take full advantage of their capabilities and benefits.

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FIGURE 1 Completed feedback grid

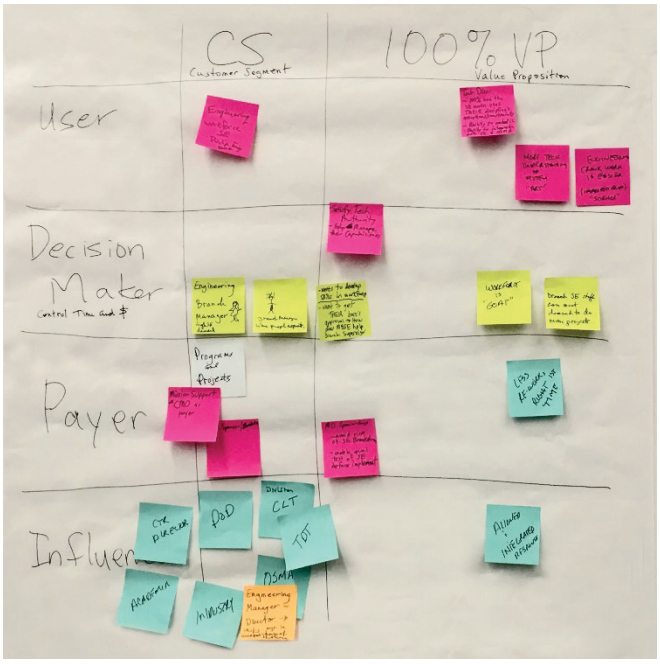

FIGURE 2 Completed lean startup stakeholder identification and needs satisfaction matrix

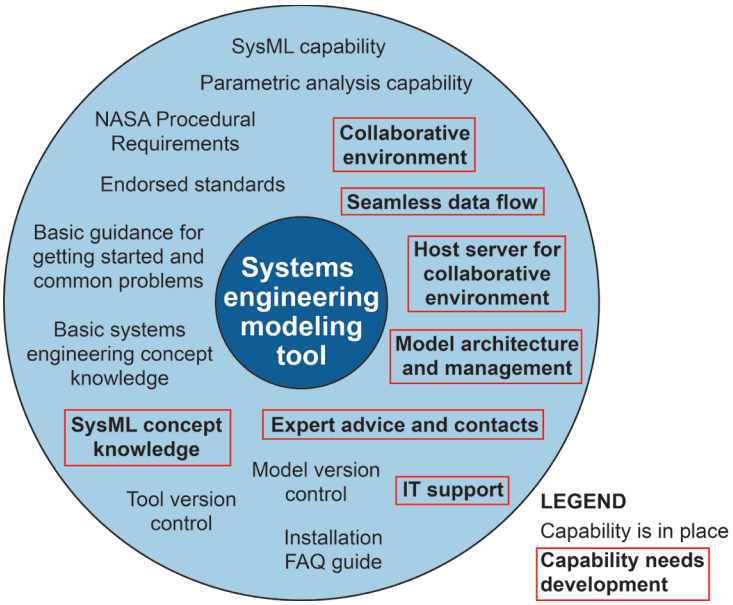

FIGURE 3 Simplified whole product organization MBSE gap analysis

TABLE 1. Positive feedback comments on design thinking tools

Theme	Sticky Note Content
Interviews	(+) Productive Day, learned a lot doing group interviews and being interviewed (+) Interview training and practice (+) The idea of asking for stories during an interview, and following it to find the deeper issues. (+) I gained a lot more from the interviewing method than anticipated. I'll definitely use this in the future. (💡) Asking for stories versus asking direct questions (💡) I see a lot of use in interview experiences in stakeholder discussions (💡) Stakeholders have feelings!
Reframing, Powers of 10, Why-How Laddering, and Point of View	(+) I like the Power of 10 exercise, because it helps identify different dimensions to the problem. (+) I like P^{10} bird eye view of the problem. (+) I like the way the power of 10 approach can decompose a problem. (+) Found the Why/How laddering interesting (+) I like the ladder – why/How. Helped expand items better. (+) That reframing was more powerful than I anticipated. (+) Point of view exercise (💡) How/why useful for self-exploration (💡) POV statement development – good process and POV carried them to work plan
Brainstorming	(+) Creating ideas -> Grouping -> Voting concept
Prototypes	(+) Prototype development with the team helped me see other POV's (+) Visualize opportunity to others can "see" (💡) Prototypes are useful for visualization even without stakeholders present.

TABLE 2. Positive feedback comments on design thinking approach and team exercises

Theme	Sticky Note Content
General design thinking	(+) Some aspects, not all, of the "design thinking" exercise (💡) Go through the entire training with "yes, and" mentality. (💡) I can use various parts of the design thinking in my day-to-day work.
MIAMI collaboration	(+) I like the team collaboration (+) All of the interteam cross pollination. (+) All of the interesting insights across projects (+) Exercises help new team members understand our team's current objectives and focus.
Enthusiasm	(+) The Team Energy (+) Great team participation and energy (+) Fun, creative time (+) The teams seem very able and motivated - gonna be fun (+) Team enthusiasm
Emotions	(+) Project summary -> emotions
Design thinking	(💡) POV statement development – good process and POV carried them to work plan (💡) Heard lots of commonality in concerns to be used to refine work plan objectives
Common goals	(💡) We can work together toward common MBSE goals (💡) All of the teams share common issues, needs, and objectives
Idea capture	(💡) Post-its are very helpful (excellent) in design process learning (💡) Working in small groups are very helpful. Good idea!

TABLE 3. Negative feedback or concerns on design thinking tools and approach

Theme	Sticky Note Content
General	(+) Some aspects, not all, of the "design thinking" exercise
Doing work a different way	(Δ) It was easier to keep from reverting to old practice (Δ) We could move closer to a bias towards action
Time	(Δ) the exercises could have been done in one session (Δ) We had more time/practice with ideation (Δ) Do it again in ~ 3 months.
Future use	(?) Not clear on why and how tool but understand concept

	(?) I wonder if the teams will use this after this week (?) I wonder how this training would be if we exercise “No, but.”

TABLE 4. Project Startup processes and approaches

Systems Engineering Process	Human-Centered Approach
Project Planning	Test results, feedback grid
Decision Management	Feedback grid
Stakeholder Needs and Requirements Definition	Empathy interview
System Requirements Definition	Empathy interview analysis, Powers of 10, Why-How Laddering, Point of View
Architecture Definition	Brainstorming
Design Definition	Brainstorming, rapid prototyping
Validation	Test via interview

TABLE 5. Customer Analysis processes and approaches

Systems Engineering Process	Human-Centered Approach
Project Planning	Test results
Project Assessment and Control	Feedback from user, peer-to-peer feedback
Decision Management	Business model canvas
Stakeholder Needs and Requirements Definition	Empathy interview, shadow experience, journey map, extremes, customer segments, customer persona, value proposition
Design Definition	Interview analysis, brainstorming, rapid prototype
Validation	Test with user

TABLE 6. Community of Practice processes and approaches

Systems Engineering Process	Human-Centered Approach
Acquisition	Idea evaluation, idea selection via voting
Supply	Idea evaluation, idea selection via voting
Life Cycle Model Management	Brainstorming
Infrastructure Management	Brainstorming
Human Resource Management	Brainstorming
Project Planning	Idea selection via voting
Stakeholder Needs and Requirements Definition	Empathy interview, journey map, customer segment, customer profile, value proposition
System Requirements Definition	Point of view
Design Definition	Brainstorming, key assumptions, identification of rapid experiments

TABLE 7. Example stakeholder interview summary and analysis[a]

Topic	Finding
Persona	• Late majority (standardize on tool set, set goal, and track number of users). • Decision maker, doer, and acts upon things. • Has a working group as part of agency-level responsibilities.
Striking quotes	• Over the past 10 years, assigned technical area went from being the tall tent pole on the project to being a lesser concern. Defects are down, productivity is up. • “Smart buyers” from educated workforce. Civil service workers know what contractor products should be and look like. • “Outside people to ask what are you doing (about problem) is helpful,” such as the Government Accountability Office.
Most surprising	• They had initial multimillion dollar investment for an improvement initiative for a couple of years in the 2000s. Last 2 years, it went down. This does not include the funding for other assigned work. • Working group operations—meet once or twice a year as a group, discussed policy changes and don’t do wordsmithing there, then iterate. • Working group used to meet weekly on telecon; now quarterly, may be more if needed.
Big takeaways	• The working group will continue doing what needs to be done.

Topic	Finding
	• They are big on reaching out to their workforce. Teach training at the local organization. They use a survey to find out what workforce wants. • To get funding, need to identify a problem that needs to get fixed. Multiple failures involving technical and management. Have to get mission organizations to believe a real problem exists. Get buy-in, then discuss jointly.

[a]As part of the analysis process, researchers highlighted in gray the findings they considered most important.

TABLE 8. Sustain and Advance a Discipline processes and approaches

Systems Engineering Process	Human-Centered Approach
Acquisition	Interview analysis
Supply	Interview analysis
Infrastructure Management	Interview analysis
Human Resource Management	Interview analysis
Project Planning	Interview analysis
Stakeholder Needs and Requirements Definition	Empathy interview, customer segment, customer persona
System Requirements Definition	Interview analysis

TABLE 9. Modified marketing development strategy checklist

Criteria	Working definition
Target Customer	Is there a lead systems engineer on the project? Is that person interested in MBSE?
Compelling Reason to Buy	Ability of the project to meet their success criteria using our capability?
Whole Product	Significant, well-scoped problem?
Competition	Project not significantly bought in to another method to solve their problem?
Partners and Allies	MIAMI has relationships with other groups to solve the project's problem?
Distribution	MIAMI and the project have point(s) of contact for interactions?
Pricing	Project has the resources to afford the capability and continue work after the end of targeted deployment?
Positioning	Does MIAMI have credibility with the lead systems engineer?
Next Target Customer	Obvious follow-on or related next project?

TABLE 10. Promote Infusion of New Technology processes and approaches

Systems Engineering Process	Human-Centered Approach
Acquisition	Marketing development strategy checklist
Supply	Marketing development strategy checklist
Life Cycle Model Management	Whole product model
Infrastructure Management	Whole product model
Project Portfolio Management	Targeted deployment
Human Resource Management	Whole product model
Business or Mission Analysis	Technology adoption curve, marketing development strategy checklist, whole product model
Project Planning	Targeted deployment
Decision Management	Marketing development strategy checklist
Stakeholder Needs and Requirements Definition	Technology adoption curve, customer segment, market segment
System Requirements Definition	Technology adoption curve, customer segment, market segment

TABLE 11. Approaches to address MBSE adoption challenges

Example and Approach	Result
Cultural and general factor	
3—Technology adoption curve, customer and market segment, value proposition	Influential stakeholders along with their openness to new technology and their decision-making factors
4—Empathy interview and analyses	Insights on how to obtain lasting change
5—Targeted deployment	Identified a project that would benefit from MBSE and help convince others to use MBSE
Perceived value factor	
1—Empathy interview; prototype and test with customers	Insights into what is valued by the stakeholders; provided direct feedback on what customers valued in the proposed solution
2—Customer segment, value proposition	Roles of different stakeholders and their decision-making factors and concerns
3—Target customer segment, value proposition	Target customers and what they valued; roadmap with the minimum configuration that provided key capabilities.
4—Empathy interview	Ideas on how to demonstrate the value of new technology to influencers and decision-makers
5—Target customer segment	Approaches to gain advocates by understanding stakeholder roles, interests, and concerns
Availability of skills factor	
3—Journey map, target customer segment	Visual depiction of what was needed for and from modelers of different skills levels
4—Empathy interview	Effective working groups and sharing of knowledge, approaches for collaboration and to grow the discipline use of new technology
Management support factor	
2—Customer segment, value proposition	Roles of managers and others along with their decision-making factors and concerns, which were used for planning future work
4—Empathy interview	Roles and responsibilities of leaders at all levels, and insights into what managers consider valuable from new technology
5—Market development checklist	Criterion to assess influence of targeted development project on gaining advocates
Learning curve factor	
3—Journey map	Visual depiction of the process and pain points for getting projects started with MBSE
3—Customer segment, value proposition, whole product model	Key customer of MBSE, value proposition, and key capabilities and minimum configuration for a capability roadmap
4—Empathy interview	Ideas for how to grow a learning community, obtain training, and increase opportunities for use

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