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Managing Complexity through Collaborative Intelligence

Mary EI Maa
Cal Poly State University
San Luis Obispo, CA 93407
memaa@calpoly.edu

Alexander IN Derkatsch
Cal Poly State University
San Luis Obispo, CA 93407
aderkats@calpoly.edu

Dianne J DeTurris
Cal Poly State University
San Luis Obispo, CA 93407
ddeturri@calpoly.edu

Abstract. Systems engineering needs new ways to visualize where and how the increasing complexity found in large-scale aerospace programs affects development processes. Following sensemaking principles provides a vector for comprehending confusing or roadblock events by enhancing communication and decision making to improve the organizational management of complexity. The sensemaking process can be applied through collaborative intelligence, an example being collaborative engineering principles that can guide team dynamics as a method of visualizing complexity. The use of applied sensemaking can document personal interaction in beneficial ways. Communication styles are largely captured in a collaborative intelligence technique called thinking talents. Utilizing the collective thinking talents of the people who work within a team enables communication to be more effective for both the individual and the organization. Thinking talents are a simple organizational development tool that has been incorporated in a suggested implementation strategy with sensemaking. Using thinking talent data enables a collaborative engineering environment that is proactive in focusing collective attention on uncovering potential failure earlier in the development process as a way to manage complexity.

Managing Complexity in Aerospace Systems

Dealing with complexity in aerospace system development requires new ways to expect the unexpected. Time after time, large programs get delayed by errors that show up at the end of the integration process rather than early in the design phase where corrections are easier to implement (Becz et al. 2010). Existing systems engineering processes need to be reexamined to account for the unique complexity of aerospace. The answer is not in making new processes, but in taking on a new view of the core functioning of systems engineering as a whole (Griffin 2010).

Former NASA Administrator Michael Griffin (2010, p.3) notes one particular way to rethink systems engineering by observing that failures tend to occur at the interfaces between components, and often between components that were thought to be unrelated. Evaluating a given aerospace subsystem in its relation to other subsystems within the same architecture yields only as many insights and revelations as the company is willing and able to allow (Baalbergen 2016). Steps must be taken to create a more holistic approach that includes elements of collaboration as underlying

dynamics, even when free flow of information is restricted due to classifications or physical separation between departments. Since systems development is intrinsically a team effort that requires members of distinct disciplines to work together, then the human interactions that lead to the final result must be included in any comprehensive theory of systems engineering (Griffin 2010). The idea of collaborative engineering via sensemaking (Jantunen, p. 810) results in a strategy for systems development that encourages embracing the uncertainty in human interaction and thinking, courageously and humbly (Sheard et al. 2015).

In Sheard et. al (2015, pp. 4-6), there are fifteen principles to which a complexity perspective should adhere, one of which is collaboration exactly. Adding to the list of principles, or perhaps underlying them all, is the resolutions-focused holistic process of finding and commanding a group's capacity to understand and communicate with one another, provoking the wide range of thinking needed in complexity management. The Cynefin framework long analyzed and successfully practiced its sensemaking framework as the challenging of reductionist assumptions (Kurtz & Snowden 2004), enriching an organization's strategy and capacity to manage uncertainty. A common element between the Cynefin framework and the fifteen principles exculpated in Sheard et. al is the interaction of diverse groups working together by thinking about their products. Groups must be taught to focus on using their combined perspectives to effectively communicate the abstract and unknown. Traditionally, aerospace has found much use in the systems engineer to field this job by connecting vast specialties amongst large projects, however the shortcomings are becoming more pronounced with today's drastic increase in demand for complex systems.

The traditional systems engineering diagram shown in Figure 1 (Becz et al. 2010) indicates that 70 percent of faults are introduced during the decomposition phases, however, the majority of these faults are not found until the integration phases where they become increasingly more expensive to fix. The expense of additional labor and supplies needed to backtrack and then rework the design strains development goals. Finding faults earlier in the design translates to on-time schedules and budgets within bounds for the overall program. Open-mindedness to the human factor involved in these failures, through means of a "risk list" or different stages of checklists, increase coherence of the team around the mission objectives, bolstering success (Emmons et al. 2018).

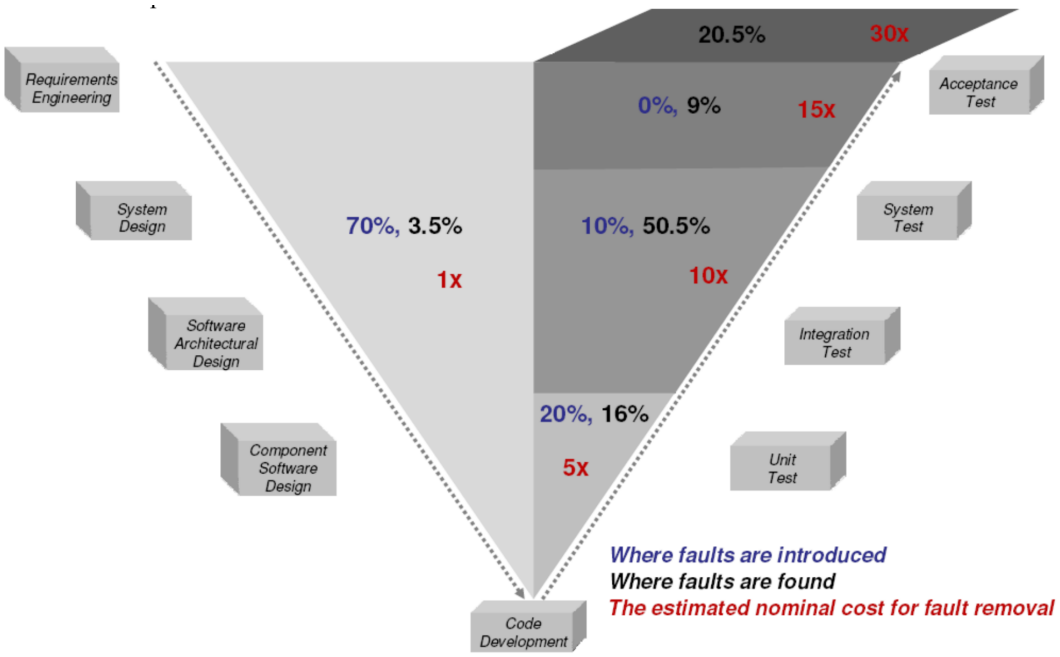

Figure 1. Where Faults are Introduced and Found in Aerospace Systems (Becz 2010)

A potential solution for the aerospace community to uncover faults earlier in the development process is exploring what makes communication and collaboration effective. Increasing collaboration alone is not enough. An examination of the wider engineering context showed success had almost always to do with higher levels of both quantity and quality of communication (Willaert, deGraaf & Minderhoud 1998, pp. 94-95). To address classic quality-quantity coupled systems, a technical and professional skill is required. An examination of failures across dozens of spacecraft projects showed that errors most commonly involved misunderstandings (Newman 2001, p. 526) due to poor communication quality which is a professional, rather than technical, skill. Experienced systems engineers reduce the impact and permeability of misunderstandings and communication failures, however sometimes an impractical number of them are needed because the specific lessons learned by one group must be generalized to be readily accessible to the next group (Newman 2001).

The systems engineer provides a translation service between specifics of subsystems and components, by relating to the larger vision contained within the requirements. With the responsibility being on the systems engineer, there is a lack of focus on individual's being asked to comprehend the larger system in their own design groups. Generalization can be most difficult across system interfaces where the ability to translate the problem into the perspective of the other subsystems becomes a formidable task. By refocusing attention to the individual's capacity to understand and communicate the complexities of the wider system, some elements of systems engineering are carried out by those most directly affected by it, the engineers and technicians themselves.

The importance of communication and collaboration is known beyond engineering. In emergency rescue teams and teams in a medical context, where effective communication means life and death, it is vital for teams to adopt standards of relating to one another. In the expertise of Crew Resource Management (CRM), Flin, O'Connor & Mearns (2002) have found that problems emerge overwhelmingly due to failure of cognitive and social skills, rather than technical sophistication of designs. CRM techniques are collaborative endeavors, whether those that teach and benefit from CRM know it or not. Within the study conducted by Griffith, Roberts & Wakeham (2015), they found a lack of reliable processes to quantify the factors of CRM that lead to increased effectiveness of their fire fighting teams. Thus, even though an increase of effectiveness could be measured, it was unclear why the effectiveness increased. When trying to visualize complexity, a process is needed for collecting and analyzing the data in a manner that makes sense. The concept of sensemaking is a process that introduces perspectives by which patterns in the noise can be discovered. Sensemaking can explain why the effectiveness increases.

Sensemaking, Collaborative Intelligence, and Collaborative Engineering

One way to understand the impact of human interactions in aerospace complexity is through sensemaking, which can be described as a "situation that is comprehended explicitly in words and that serves as a springboard into action" (Ancona 2007, p. 4). Understanding perspectives in human interaction can help discover meaningful patterns that, without sensemaking, appear random. Sensemaking requires an articulation of the unknown to illuminate the need to change direction. Unknowns in aerospace complexity can be sophisticated technical aspects of the design in subsystems or interfaces, as well as unknowns in the organizational capacity of the team.

Sensemaking begins with the process of forming plausible understandings, testing them via action, and then either refining those understandings or abandoning them in favor of new ones that better

explain a shifting reality. Achieving collaborative engineering begins with the sensemaking process. This is the kind of process that enables us to turn the ongoing operation of the engineering team into a profound influence on the finished product of that team (Griffin 2010).

Moreover, sensemaking is facilitated by a common goal. For example, there is the story of a military unit conducting a training exercise that gets lost in the mountains in a snowstorm. After one person provides a map, they all reference it and decide together how to get out. They determine the map is not entirely accurate, but they have enough information to move forward with their plan. Eventually, they all successfully complete the exercise. It turns out that the map was of the wrong mountains, but bringing everyone together into a team provided a way for everyone to agree on how to achieve a common goal (Ancona 2007, p. 6).

In an engineering setting, the ongoing stories across simultaneous projects can be synthesized at the same time reflection takes place, introducing what sensemaking would call, the "ante-narrative", which is the pre-narrative speculation in a story (Boje 2002). Narratives are not present early in the development phase, because narratives function as luxuries in that they grant us beginnings, middles, ends and plots to tie together the stories into a meaningful whole. Sensemaking is a process of achieving narrative from the pre-narrative to ultimately create an environment that can readily manage complexity. It is also a dialectic endeavor because what is known at the time may be fragmented, partial and temporary, obscured by hegemony, or incoherent. Sensemaking is a present-minded, rather than retroactive, process (Boje 2002).

At the same time, sensemaking facilitates effective leadership in that it includes emotional intelligence, self-awareness, and the ability to deal with cognitive complexity (Ancona 2007, p. 6). At an organizational level, leaders "engage in sensemaking to understand why their teams are not functioning, why their customers are leaving, or why their operations are falling short on safety and reliability" (Ancona 2007, p. 5). Table 1 lists the general guidelines for sensemaking (Ancona 2007). The steps don't have to be followed in order, but include seeing the situation from multiple perspectives, looking at it in a broader context, actively questioning and testing your assumptions, and iterating on a solution. By first applying the sensemaking process at an individual level, a common understanding can be developed which facilitates the creation of a collaborative environment. The pre-narrative becomes codified as a narrative through sensemaking. Think of the aerospace team that seems to outpace all the other teams, despite working under the same constraints, because they either intentionally or unintentionally followed a sensemaking process. So how do we increase intentionality in team structuring?

Table 1: Five Steps for Effective Sensemaking

1	**Explore the wider system**	Gather data from a variety of sources
2	**Question your assumptions**	Actively pursue differing opinions
3	**Test your assumptions**	Use low risk experiments to gather data
4	**Adopt multiple perspectives**	Keep an open mind
5	**Iterate**	Refine ideas or abandon them as data indicates

The five step sensemaking process leads to individuals developing perspective on the situation. Collaboration among colleagues in this process allows organizations to achieve a common understanding to survive and innovate in a rapidly changing environment. When individuals share a common understanding of the premises and processes of their organization, it is easier to collaborate (Jaatinen & Lavikka 2008).

In her book, *Collaborative Intelligence*, Markova defines Collaborative Intelligence as a strategy or practice which makes it possible for individuals to learn about their unique way of thinking and how their way of thinking relates to others. When individuals with distinct thinking talents problem solve together, it broadens the solution space and reduces habitual right/wrong bias. Collaborative Intelligence allows individuals to maximize the combined value of their intellectual diversity, allowing them to be open to new possibilities when facing complex challenges (Markova & McArthur 2015, p. 15).

A mechanism for incorporating individual contribution into the collaborative environment is provided by Markova's 'thinking talents', which are defined as, "identifying the specific ways of thinking that energize you and others." (Markova & McArthur 2015, p. 109). She also describes the process in which a person identifies their thinking talents as "finding the 'me' in 'we'" (Markova & McArthur 2015, p. 105). When people believe that they are positively contributing to their organization, they are more motivated to work collaboratively.

The thinking talent quadrants, introduced in Table 2, can be utilized to fulfill the five steps for effective sensemaking that are listed in Table 1. The quadrants fulfill the five steps of sensemaking in a collective sense. The process begins with individuals determining their thinking talents and sharing them with others in their workplace. This is the first step of the sensemaking process, gathering data from a variety of sources.

Thinking talents can also provide the basis for questioning assumptions. Once teams can determine how to balance their members' thinking talent strengths, they can use this information to actively pursue different opinions. In teams that have been formed using thinking talents, individuals can learn how the application of their thinking talents can be used to solve problems. Problem solving using thinking talents then fulfills the sensemaking step of testing assumptions. The team of people with balanced thinking talents ensures that each person's differing assumptions about how things work will be included.

Collaborative intelligence is group intelligence rather than an individual intelligence like intellectual intelligence or emotional intelligence. Contrast a team with balanced thinking talents with a team where everyone concentrates on their own contribution without really looking into all the possible interactions in the system. A plausible scenario is a satellite with one operational state where the solar panels are positioned so they interfere with the stationkeeping thruster exhaust. But no one sees it until it happens after deployment. Everyone had done their job correctly, except for missing an unintended interaction between components thought to be separate. Managing interactions between people is as important as managing interactions between components. Finding new ways to see things from others' perspectives is more than team building, it's about enhancing the design process.

Essentially, taking advantage of thinking talents is a process that encourages the adoption of multiple perspectives. Keeping an open mind is an important aspect of using thinking talents, as the building blocks for collaboration are an iterative process. As ideas are discussed and developed among team members, the goal is to refine or abandon those ideas as data indicates. The data would be based on the ability to achieve either a positive or negative response to an idea from the team as a whole, while individuals present their different perspectives based on their thinking talents. This method of visualizing complexity elucidates a strategy for problem solving, rather than simply encouraging collaboration without a valid framework. The aerospace industry could benefit from working collaboratively by integrating teams not just through roles, but also through incorporating multiple perspectives and backgrounds.

The thinking talent quadrants shown in Table 2 reveal four different cognitive styles. Two of the styles, analytic and procedural, represent left-mode dominant processes. The other two styles, relational and innovative, represent right-mode dominant processes. Cognitive styles indicate the specific ways people process information. In a collaborative setting, people who have different preferred cognitive styles will provide alternative perspectives to solving the same problem. It is like playing a team sport, where everyone's separate abilities must work together for the team to perform successfully. In combination with thinking talents, this strategy assists in identifying a person's unique communication talents and increases their collaborative potential. When collaborative potential is maximized, teams develop the best solutions faster and with fewer setbacks.

Table 2: The Four Thinking Talent Quadrants

1	**Analytic**	concerned with data, facts, numbers, being logical and rational
2	**Innovative**	concerned with the future, newness, possibilities, big picture, strategy
3	**Procedural**	concerned with process, operations, logistics, tactics
4	**Relational**	concerned with feelings, morale, teamwork, development of people

Following the directions provided in Appendix 1, the 'Thinking Talents Table', can be used to determine an individual's natural thinking talents. In order to distinguish thinking talents from personality traits, the ratings are based on three specific characteristics outlined in the book, *Collaborative Intelligence* (Markova & McArthur 2015).

1. The first characteristic is that thinking talents represent a person's innate ways of thinking, meaning that, "you've always been really good at doing them, even if you have never had any specific training, and you tend to use them when faced with challenges."
2. The second characteristic is that using your thinking talents gives you natural joy and energy and does not cause you to burn out.
3. The third characteristic is that "you excel in using these talents and enjoy developing capacities with them".

An individual's dominant thinking talents fulfill all three characteristics and represent natural and comfortable ways of thinking. After an individual determines their dominant thinking talents, the Drivers of Thinking Map provided in Figure 2 (Markova & McArthur 2015) reveals their cognitive style. This will be indicated based on which of the four quadrants contains their most dominant thinking talents. Some folks may have more talents coming from one cognitive style, whereas

others may be more balanced. Where people are in the map determines how their differing perspectives can help them contribute and collaborate with others.

Figure 2. Drivers of Thinking Map (Markova 2015)

Markova, D & McArthur, A 2015, *The Drivers of Thinking Map from Collaborative Intelligence*, Spiegel & Grau, New York, digital leaflet.

In order to achieve the most successful collaboration, it is equally important to determine your thinking blind spots as well as thinking talents. If you have any quadrants that are devoid of thinking talents, these are considered your blind spots. Blind spots reveal areas where support from others is helpful, and you should be encouraged to, "form thinking partnerships with those whose strengths complement your blind spots" (Markova & McArthur 2015, p. 144). The benefit comes

from working with others who have dominant thinking talents which balance your blind spots. Contribution in this way will encompass the most helpful perspectives for the given situation.

For example, Peter has a commanding leadership style that doesn't bring out the best in his people. He doesn't ask questions, so neither do they. Unfortunately this is bad for Peter's business. Peter learns that procedural inquiry is a more effective mode in a meeting to get information from people who don't think the same way he does. This is new to Peter and does not come as naturally as his other talents. Yet, when he seeks multiple perspectives rather than making definitive statements, with a focus on listening and intent on understanding, the organization's outcomes improve (Markova & McArthur 2015, pp.190-194). Peter had those perspectives in his blind spots the whole time, it just took locating the team members in the cognitive style quadrants that were different from his and including them. He found people to fill his blindspots. The easy way to apply this in our own world, for example, is to think about the introvert that actually has a lot to say but waits to be asked to say it.

Determining how to collaborate with others, integrating teams where individuals can apply their thinking talents, and filling in one another's thinking blind spots, shows how the sensemaking process can be effectively applied in an engineering setting. When teams are able to determine what thinking talents every member contributes to the group, a common understanding can be gained. This creates an environment where collaborative engineering can be developed within an organization. Organizations that focus on creating these shared understandings can then apply these to problem solving concerning strategy, organization and resources (Jaatinen & Lavikka 2008).

Collaboration can be the pinnacle of success when it is based on effective communication. The goal for communication is for it to help achieve a common understanding. Doing so with cognitive tools like thinking talents ensures sensemaking is being applied to the visualization of complexity by acknowledging the variation in perspective. When individuals begin to understand one another using thinking talents, they see things from different perspectives.

Collaboration applied to engineering specifically, through collaborative engineering, has a practical focus in supporting collective work. Collaborative engineering is best defined as, "the engineering design process within an intentionally developed community as a complex network, created to promote and maximize the individual and shared learning of its members, through ongoing interaction, interplay, dialogue, and collaboration…" (Putnik et al. 2021, p. 2). Further, thinking talents promote both individual needs and common understanding through the sensemaking process. "Seen through the lens of sensemaking, collaborative engineering addresses the individual's needs as well as supporting a common understanding while solving the overall problem" (Jantunen & Koivisto 2016, p. 810).

Collaborative engineering can also be effective in unifying a single team that executes a single goal focusing on both functional and industrial design (Mas et al. 2014). Within collaborative engineering practices, there isn't a tool that is used uniformly in aerospace that supports the creation of collaboration processes. It seems that, "As collaborative endeavors become more popular from the engineering domain to the commercial and academic domains, the need for tools to assist in communication and knowledge management will continue to be a major focal point in collaborative environment research." (Gu & He 2019, p. 179). We can manage our knowledge better by understanding what makes communication more effective, rather than just developing software to increase collaboration.

Current industry solutions for collaboration include a mix of software tools and technology that are often focused on supporting the technical, rather than professional, aspects of engineering design (Bergman & Baker 2000). This does not necessarily create a collaborative engineering environment, because not everyone is using the same software, or using the same software in the same way. Then there is a disconnect. The software increases communication channels but doesn't necessarily improve its effectiveness. People can have many tools, but not use them effectively. This is how thinking talents help, they get us using thinking tools in a way that is effective for each of us. These concepts suggest a need for an implementation strategy as a tool that combines sensemaking and collaboration through thinking talents.

In Bergman and Baker's review of potentially useful software tools for increasing collaboration, their main findings indicate that software tools would in fact increase the quantity of collaboration, but not how collaboration is implemented or what aspects of collaboration are important. Baalbergen et al. (2016) provides a similar advocacy for collaboration quantity increasing software tools, as does Gu & He (2019), Mas et. al (2014), Liu & Raorane (2007), Johnson (2003), and Monell & Poland (1999). However, it is not the software that leads to better quality of collaboration. Software cannot explain why collaboration is better, only that it occurs more frequently. Thinking talents are cognitive tools that explain the aspects behind why collaboration works, and provide avenues to explore how to enrich the quality of collaboration. A key point of quality collaboration is seeing others perspectives.

Collaborative engineering takes advantage of these different perspectives. Team members look at the same design details and see something different, but they can actually all be correct. Team building using the thinking quadrants creates a balanced team that is filling in for one another's thinking blindspots rather than just academic or experiential blindspots. This means the thinking talents themselves put the right people in the room, and then when the system is described from different perspectives, a more comprehensive understanding emerges. In addition to solving the problem right, they can also solve the right problem.

What does collaborative engineering look like in aerospace? One way perspective appears is as a feedback mechanism for finding potential problems. After investigations into the Challenger and Columbia Space Shuttle accidents showed that organizational causes were just as relevant as the technical causes, NASA wanted to get more input on safety. Collaboration improved when they started an Engineering Technical Authority to bring more people into the decision making process (Clearfield & Tilcsik, 2018). The Engineering Technical Authority included consultants outside the project and a way for engineers to voice concerns through a mechanism that was not confined to regular communication channels. The project's independent reporting route adds a checks and balance system to ensure mission success (Andary, So & Breindel, 2008). This effect can be amplified by teaching thinking talents, and then incorporating sensemaking and common understanding gets us a more widely implementable strategy.

Figure 3 summarizes how sensemaking is a foundation for collaborative engineering, which is a mechanism for managing complexity. The sensemaking comes from goal definition, then the collaborative intelligence technique collects different points of view. Collaborative intelligence acknowledges that an organization has motivations at two levels. The thinking talents come from meeting an individual's needs in terms of what is the best way for them to communicate effectively, which actually helps the whole team to collaborate. We can use a frame of collaborative engineering from effective communication and common understanding as a tool for managing complexity.

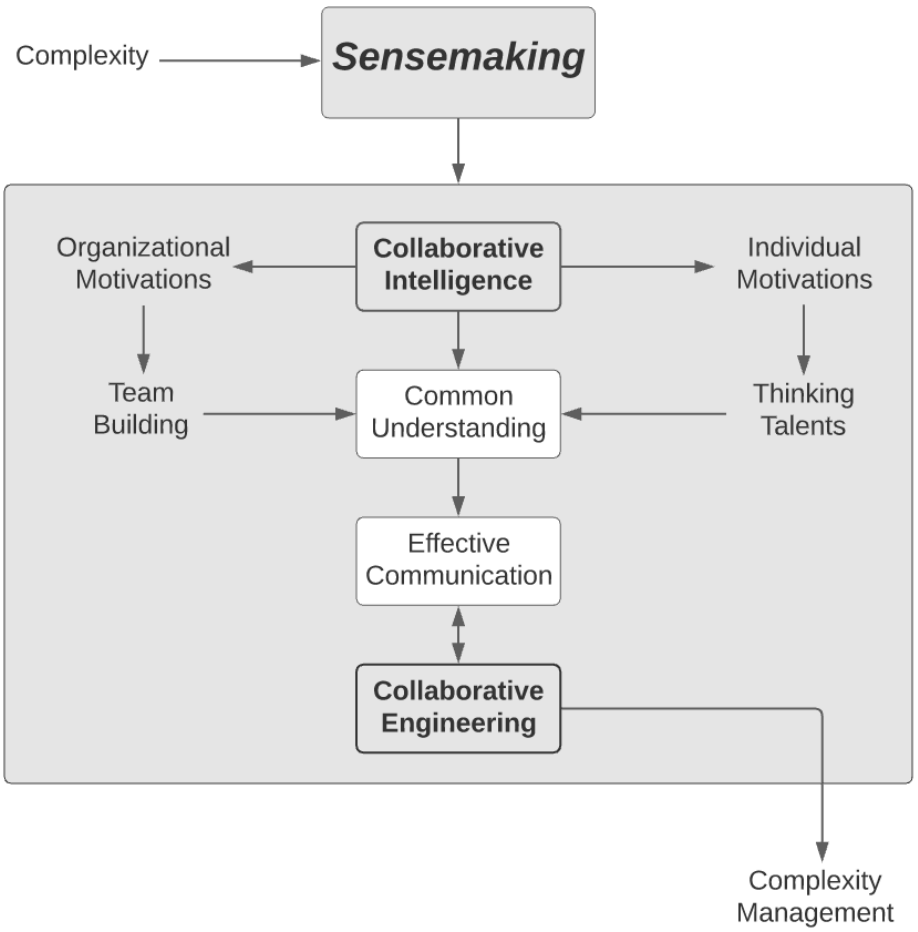

Figure 3. Combining Individual and Organizational Motivations Through Sensemaking

Sensemaking is regularly employed when someone is operating in an unfamiliar context, like a new business, a new country or a new technology. The sensemaking steps are applicable in any industry and have been shown to work in military, industrial and educational settings (Ancona 2007). Using the individual thinking talents of the people in the organization is a way to see the situation from multiple perspectives and in a broader context, a key sensemaking step.

Markova shows how thinking talents improve communication and lead to a common understanding, which is a foundational aspect of collaborative engineering. Using sensemaking tools in engineering practice makes actively questioning and testing your assumptions, and iterating on a solution, a normal and foundational part of the process. These steps include a conversation about ways to find faults earlier in the development process where mitigation requires fewer resources. Sensemaking on its own doesn't make unintended events disappear, it just gives engineers one more option for discovering them before expensive rework demands it.

Being explicit about thinking talents will definitely reduce the miscommunication that normally happens with a group of people that don't know each other very well. As an illustration of how this could work, "Imagine a forty-five-minute phone call with a group of people you have never met from around the world; it begins with everyone announcing their thinking talents, their blind spots, and how you can most effectively communicate with them. This would give you, in effect, an operating manual for one another's minds, and as the meeting progressed you could easily avoid

counterproductive assumptions that you would normally attribute to personality"(Markova & McArthur 2015 p. 20). Going into a meeting with knowledge of how to get the best out of the people at the meeting improves how each person views their contribution in relation to the rest of the group. You can effectively "Consider meetings a precious opportunity to make use of mental resources and to challenge yourself and your team to try new processes, until you find the ones that really work to maximize your collaborative intelligence." (Markova & McArthur 2015 p. 306)

To summarize these concepts, consider that sensemaking is a useful tool for managing complexity. The five sensemaking steps apply in any setting to bring more perspective to the issue. The steps can be more effectively implemented by employing the collective thinking talents of the team because of the added communication potential. Combining these tools produces the Implementation Strategy, as summarized in Figure 4, which is a strategy that offers extra insight into the way teams can best collaborate. Understanding the thinking talents of people in a team can facilitate taking advantage of different ways of approaching problem solving. Having a team of people that represent all four thinking talent quadrants has been shown to lead to the group offering potentially breakthrough solutions.

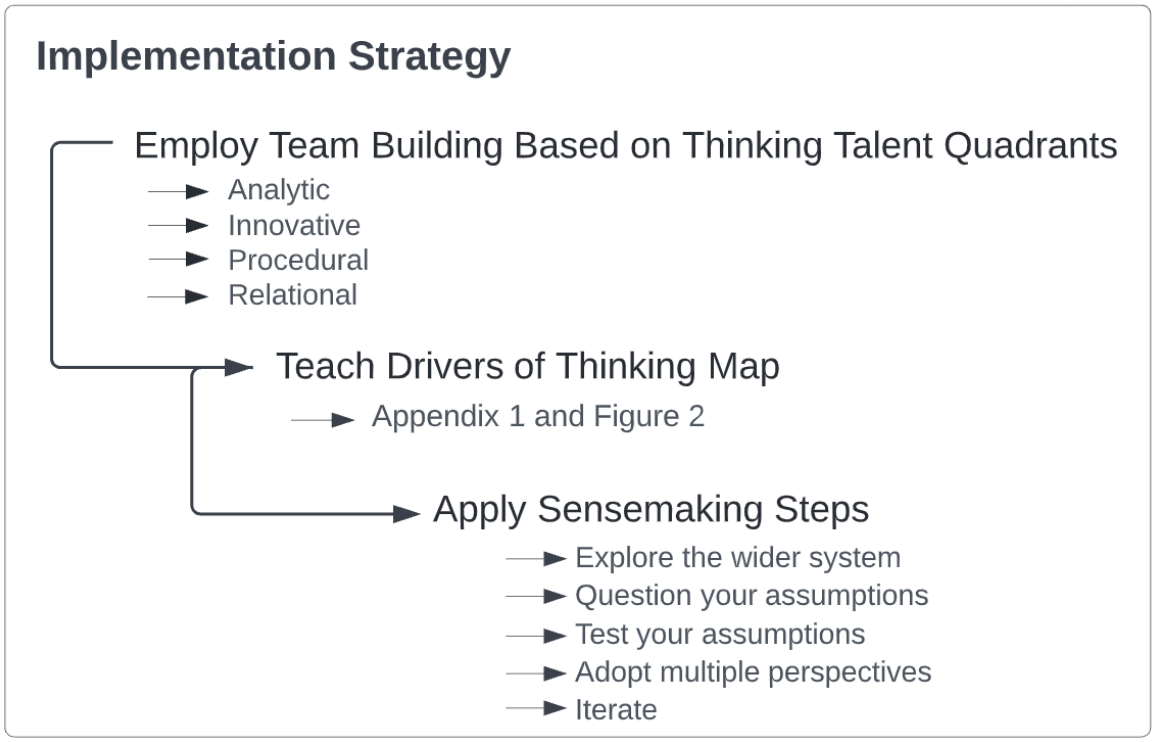

Figure 4. Implementation Strategy for Employing Thinking Talents within Sensemaking

Conclusion

Aerospace systems demand increasingly more parts, more functionality, and more sophisticated and integrated system of systems operations. Complexity must be addressed to manage unwanted and unintended behavior that regularly shows up later in the development process. A design that solves the right problem, rather than just solving the problem the right way, can be achieved through sensemaking. The strategy is to combine the goal-definition of sensemaking, the common understanding within a team achieved through use of thinking talents, and the effective communication of collaborative engineering.

Without sensemaking, complexity can appear randomly generated, difficult to address, and complicated to work around. The sensemaking process gives individuals and teams at all levels a way to manage the unknowns more effectively. A tool like collaborative intelligence can foster an environment that uncovers faults to reduce the likelihood of undesired emergent behavior. By applying collaborative intelligence, a common understanding forms the basis of an organizational narrative.

Achieving a common understanding requires ascertaining the motivations of the organization as well as those of the individual. A key component in understanding organizational motivations are the exploration of thinking talents and the solutions discovered by building teams around them. Organizational motivations go beyond meeting the needs of various stakeholders and into the personal fulfillment for individual contributors. This is the power of collaborative intelligence.

Individuals that understand how they approach their work can better relate to others within the analytic, innovative, procedural, or relational thinking talent quadrants. Organizations can use the quadrants to build teams within and across functional units. These teams will be better equipped to engage in thinking that finds faults earlier in the design process, at a greater rate, and remedy them faster. Balancing thinking talents among team members introduces a new opportunity for people to relate to one another. This method shifts the focus from an "either/or" approach in problem solving to treating collaborative experiences as an opportunity for knowledge sharing. Thinking talents provide the building blocks for a collaborative environment that is based on how individuals think together regardless of perceived personality traits, management level, or experience level. It allows for people to apply their individual thinking talents collectively in order to achieve a common goal.

A team with balanced thinking talents, where blind spots are minimized, promotes collaborative engineering. Implementing a strategy of collaborative engineering, as an outcome of sensemaking, improves communication specifically focused on addressing emergent behavior in complex systems. Avoidance of collaborative engineering throughout the systems engineering life cycle costs companies time and money.

References

Ancona, D 2012, 'Sensemaking: Framing and Acting in the Unknown', in SA Snook, N Nohria & R Khurana 2011, *The Handbook for Teaching Leadership: knowing, doing and being',* SAGE Publications Ltd, California, pp. 3-19.

Andary, JF, So, MM & Breindel, B 2008, "Systems Engineering Technical Authority: A Path to Mission Success", *INCOSE 18th Annual International Symposium,* June 2008.

Bergman, R & Baker, JD 2000, 'Enabling Collaborative Engineering and Science at JPL', *Advances in Engineering Software*, Elsevier Science Ltd, vol. 31, no. 8-9, pp. 661-668.

Baalbergen, EH, Lammen, WF, de Wit, AJ, Maas, R, Moghadasi, SM, Kos, J & Chiacchio, F 2016, *Collaborative Engineering technologies enabling multi-partner thermal analysis in early design stages of aircraft*, Royal Netherlands Aerospace Centre, NLR-TP-2016-087.

Becz, S, Pinto, A, Zeidner, L, Khire, R, Reeve, H & Banaszuk, A 2010, 'Design System for Managing Complexity in Aerospace Systems', *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, AIAA, Fort Worth, pp. 1-7.

Boje, D 2002, *Narrative Methods for Organizational and Communication Research*, SAGE Publications Ltd., London.

Clearfield, C & Tilcsik, A 2018, *Meltdown*, Penguin Press, New York.

Emmons, D, Mazzuchi, T, Sarkani, S & Larsen, C 2018, 'Mitigating Cognitive Biases in Risk Identification: Practitioner Checklist for the Aerospace Sector', *Defense Acquisition Research Journal*, vol. 25, no. 1, pp. 52-93.

Flin, R, O'Connor, P & Mearns, K 2002, 'Crew Resource Management: Improving Team Work in High Reliability Industries', *Team Performance Management: An International Journal*, vol. 8, no. 3/4, pp.68-78.

Griffin, MD 2010, 'How do We Fix Systems Engineering', *61st International Astronautical Congress*, Prague.

Griffith, J, Roberts, D & Wakeham, R 2015, 'A Meta-Analysis of Crew Resource Management/Incident Command Systems Implementation Studies in the Fire and Emergency Services', *The Journal of Aviation/Aerospace Education and Research*, vol. 25, no. 1, pp.1-25.

Gu, Y & He, S 2019, 'Collaborative Engineering as an Efficient Tool for Coordination among Stakeholders in Aerospace Industry', *International Journal of Sciences: Basic and Applied Research*, vol. 43, no. 2, pp. 173-180.

Jaatinen, M & Lavikka, R 2008, 'Common Understanding as a Basis for Coordination', *Corporate Communications: An International Journal*, vol. 13, no. 2, pp.147-167.

Jantunen S, & Koivisto, T 2016, 'Supporting Organizational Sensemaking with Collaboration Engineering', *49th Hawaii International Conference on System Sciences (HICSS)*, IEEE, Koloa, pp. 807-816.

Johnson, T 2003, 'A Guide to Successful Collaboration in the Aerospace Industry', *Aircraft Engineering and Aerospace Technology*, Emerald Group Publishing Limited, vol. 75, no. 2.

Kurtz, CF & Snowden, DJ 2003, 'The New Dynamics of Strategy: Sense-making in a Complex and complicated World', *IBM Systems Journal*, IEEE, vol. 42, no. 3.

Liu, X & Raorane, S 2007, 'A web-based Intelligent Collaborative System for Engineering Design', in Li, WD, McMahon, C, Ong, SK & Nee, AYC 2007, *Collaborative Product Design and Manufacturing Methodologies and Applications*, Springer, London, pp. 37-58.

Markova, D & McArthur, A 2015, *Collaborative Intelligence: Thinking with People Who Think Differently*, Spiegel & Grau, New York.

Mas, F, Menéndez, JL, Oliva, M, Servan, J, Arista, R & Valle, C 2014, 'Design within Complex Environments: Collaborative Engineering in the Aerospace Industry', in Escalona, JM, Aragón, G, Linger, H, Lang, M, Barry, C & Schneider, C 2014, *Information System Development: Improving Enterprise Communication*, Springer, Heidelberg, pp. 197-205.

Monell, DW & Poland, WM 1999, 'Aerospace Systems Design in NASA's Collaborative Engineering Environment', *50th International Astronautical Congress Acta Astronautica*, Netherlands, vol. 47, no. 2-9, pp.255-264.

Newman, JS 2001, 'Failure-Space: A Systems Engineering Look at 50 Space System Failures', *Acta Astronautica*, vol. 48, no. 5, pp 517-527.

Putnik, G, Putnik, Z, Shah, V, Varela, L, Ferreira, L, Castro, H, Catia, A & Pinheiro, P 2021, 'Collaborative Engineering: A Review of Organizational Forms for Implementation and Operation', *IOP Conference Series: Materials Science and Engineering*, vol. 1174, no. 1, pp.1-11.

Sheard, S & Cook, S & Honour, E & Hybertson, D & Krupa, J & McEver, J & McKinney, D & Honduras, P & Ryan, A &Scheurer, R & Singer, J & Sparber, J & White, B 2015, 'A Complexity Primer for Systems Engineers', Complex Systems Working Group, INCOSE.

Weick, K 2007, *Managing the unexpected: Managing the Unexpected Resilient Performance in an Age of Uncertainty*, 2nd edn, Jossey-Bass, California.

Willaert, SSA, deGraaf, R & Minderhoud, S, 1998, 'Collaborative Engineering: A Case Study of Concurrent Engineering in a Wider Context', Journal of Engineering and Technology Management Jet-M, vol. 15, no. 1, pp. 87-109.

Appendix 1

Instructions: Go through the list of thinking talents and choose a category that best describes you based on the characteristics that light you up and burn you out. After choosing all your categories for each thinking talent, go through the table and choose your top five thinking talents in the ALWAYS category, these are your natural thinking talents. From the Drivers of Thinking Map in Figure 2, the quadrants devoid of your thinking talents are your blind spots.

Thinking Talents Table, Adapted from *Collaborative Intelligence,* Drivers of Thinking Map

Markova, D & McArthur, A 2015, *Collaborative Intelligence: Thinking with People Who Think Differently*, Spiegel & Grau, New York, digital leaflet, https://lfp.learningforward.org/handouts/Dallas2018/7824/A19_HO21_Thinking_Talent_Characteristics.pdf

Thinking Talents	**Lights You Up**	**Burns You Out**	**Categories**	**Quadrant**
Adapting *"How can I adapt to what's happening now?"*	• Helping when there are many balls to juggle or plans go awry • When there is rapid change happening	• When others are inflexible • Long-term plans or routine	ALWAYS SOMETIMES NEVER	*Innovative*
Believing *"Does this mesh with my beliefs?"*	• When there is a strong sense of purpose • When you can make decisions based on your values	• People who don't know where they stand • Having to compromise your values	ALWAYS SOMETIMES NEVER	*Relational*
Collecting *"What am I interested in here?*	• Acquiring, compiling, and filing away things • Collecting data, facts, or information	• Thinking linearly • Conflict	ALWAYS SOMETIMES NEVER	*Analytic*
Connection *"How is this part of something larger?"*	• Making connections between things or ideas • Linking people to one another	• Thinking linearly • Conflict	ALWAYS SOMETIMES NEVER	*Relational*

Creating Intimacy *"How can I be closer and more genuine with the people I already know?"*	• Teaming with others long-term • Consistent one-on-one connection with others	• Meeting and greeting new people in casual settings • Hectic schedules that don't allow for deeper connection	ALWAYS SOMETIMES NEVER	*Relational*
Enrolling *"How can I relate to this new person?"*	• Meeting new people • Looking for chances to sell or enlisting others	• Maintaining close relationships over time • Isolation and routine in relationships	ALWAYS SOMETIMES NEVER	*Relational*
Equalizing *"Is everyone being treated fairly?"*	• Creating and applying rules and regulations to maximize fairness • Making expectations explicit and consistent	• Unfair or special treatment • Changing guidelines	ALWAYS SOMETIMES NEVER	*Procedural*
Feeling for Others *"What are people feeling now?"*	• Demonstrating emotional care for someone • Anticipating others' needs and feelings	• Being around negative feelings or pessimistic people • Too much communication (email, text) when you cannot sense the other person's emotions	ALWAYS SOMETIMES NEVER	*Relational*
Fixing It *"What's the solution to this problem?"*	• Identifying or anticipating what might go wrong and fixing or averting it – people, situations, or things • Rescuing or saving people, things, or situations	• When you can see what's wrong and can't fix it • When others don't want you to help – for instance, when they want to learn to do it themselves	ALWAYS SOMETIMES NEVER	*Analytic*
Focusing *"What's the point here?"*	• Uninterrupted freedom to concentrate on a goal with timelines • Keeping others on point	• Being interrupted or having to multitask • When purpose, task, deadlines are not clearly defined or understood	ALWAYS SOMETIMES NEVER	*Procedural*
Get to Action *"What can I do right now?"*	• Spurring others out of talk into action	• Indecision or meetings without clear goals	ALWAYS SOMETIMES NEVER	*Procedural*

	• Making something happen as soon as possible; short timelines	• Contemplation and analysis rather than action		
Goal setting *"What can I accomplish today?"*	• Defining and tracking daily concrete goals to work toward • Big targets and challenging goals and assignments	• Absence of specific ways to measure progress • Time off or work that is not challenging	ALWAYS SOMETIMES NEVER	*All*
Having Confidence *"What, me worry?"*	• Autonomy of action and decision • Calming challenging situations with employees or customers	• Being in a position where you have to ask for help • Being told what to say, do, or think	ALWAYS SOMETIMES NEVER	*Procedural*
Humor *"What is amusing about this?"*	• Lightening otherwise-tense moments and putting others at ease • Using humor in written communication or speeches	• Using humor as a defense strategy to protect yourself from others or your own emotions • Highly analytic situations or those where humor is seen as a challenge to authority	ALWAYS SOMETIMES NEVER	*All*
Including *"How can I stretch the circle wider?"*	• Finding ways to make others feel a part of the group • Welcoming new people	• Firing people, sharing bad news or difficult information • Excluding someone from a situation where they would be useful	ALWAYS SOMETIMES NEVER	*Relational*
Innovation *"How can this be done differently?"*	• Creating new processes or products • Figuring out all the new ways to accomplish something or keep them interesting	• Routine and standardized ways of doing things • Looking back at how something was done before	ALWAYS SOMETIMES NEVER	*Innovative*
Love of Learning *"What can I learn next?"*	• Continual learning • Sharing what you are learning	• Leapfrogging from learning thing to thing without any depth • Having to do routine things when no learning is involved	ALWAYS SOMETIMES NEVER	*Innovative*

Loving Ideas *"What's a thrilling idea or theory to explain this?"*	• Having a new idea, concept, or theory • Being involved at the beginning of something	• Having no place to contribute your ideas • Coming in at the middle or end of a project, when you have to suppress your ideas or give input on how it could be done	ALWAYS SOMETIMES NEVER	*Innovative*
Making Orders *"How can I align all these different variables?"*	• Lining things up in a logical way • When many things are going on at the same time and you get to create a sequence	• When your capacity to align different variables isn't needed or valued. For example, there is already a system developed and you cannot offer input • When you cannot make order out of chaos or confusion	ALWAYS SOMETIMES NEVER	*Analytic*
Mentoring *"What can help others grow?"*	• Helping others grow their potential • Guiding people through new situations	• Trying to help a struggling employee when it's appropriate to give up • When there is no opportunity to grow someone. For example, if the focus is only on the bottom line and not on development of people	ALWAYS SOMETIMES NEVER	*Relational*
Optimism *"What's right about this?"*	• Finding ways to recognize what's right about a challenging situation • Painting an exciting picture of possibilities	• Being around skepticism • Having to recognize pitfalls, problems, or give negative feedback	ALWAYS SOMETIMES NEVER	*Relational*
Particularize *"How is each of us unique?"*	• Recognizing and sharing what is unique about someone • Tailoring something to meet the specific needs of someone else	• When a one-size-fits-all or standardized approach is required • Generalizations about people	ALWAYS SOMETIMES NEVER	*Relational*
Peacemaking *"Where is the common ground?"*	• Resolving conflicts or arguments • Finding common ground or consensus	• Unresolved conflict • Standing up for your own needs	ALWAYS SOMETIMES NEVER	*Relational*

Precision *"How can I order this chaos?"*	• Setting up predictable routines, timelines, and deadlines • Maintaining progress and productivity	• Situations that require flexibility, instinct; unpredictable changes • Unable to question how exactly to do things	ALWAYS SOMETIMES NEVER	*Procedural*
Reliability *"How can I do this right?"*	• Living up to commitments • Delivering on time - every time	• Others' excuses and rationalizations for lack of performance or not living up to commitments • Being responsible for others and things not in your control	ALWAYS SOMETIMES NEVER	*Procedural*
Seeking Excellence *"How can this be excellent?"*	• Doing the best you can with the least • Continual improvement to make things better	• Inefficient processes or meanings • Having to accept something mediocre or go with the status quo	ALWAYS SOMETIMES NEVER	*Analytic*
Standing Out *"How can I be recognized?"*	• Doing something for which you know you'll be recognized • Performing in a way that allows you to stand out as having made a difference	• When your contribution is not acknowledged • Being invisible in a team or group	ALWAYS SOMETIMES NEVER	*Innovative*
Storytelling *"How can I bring these ideas to life with a story?"*	• Bringing ideas to life through story • Inspiring others to engage through narratives	• Having to think with only facts and figures • Thinking only in "why" and "how"	ALWAYS SOMETIMES NEVER	*Relational*
Strategy *"What are alternative scenarios, and what is the best route?"*	• Finding alternative possibilities and options • Anticipating future challenges and their solutions	• Shortsightedness • Single-mindedness as in "My way or the highway."	ALWAYS SOMETIMES NEVER	*Innovative*
Taking Charge *"How can I get others aligned with me?"*	• Directing others into action • Unifying engagement	• Working alone • Having no opportunity to lead	ALWAYS SOMETIMES NEVER	*Procedural*

Thinking Ahead *"Wouldn't it be great if?"*	• Seeing the possible future outcomes of an action or event • Helping others overcome fears of the future	• People whose thinking is stuck in the past • Others' dismal view of future possibilities	ALWAYS SOMETIMES NEVER	*Innovative*
Thinking Alone *"What can I think about now?"*	• Time to think through situations and contemplate pros and cons • Solitude to explore what you believe at your own rhythm	• Being put on the spot to respond immediately, without advance notice • No personal space or time to mull over a decision	ALWAYS SOMETIMES NEVER	*All*
Thinking Back *"How is the past a blueprint for the present?"*	• Setting a historical context for a present problem • recalling how things were done in the past	• When others don't learn from history • When others jump into what is new without considering what has already been done	ALWAYS SOMETIMES NEVER	*Procedural*
Thinking Logically *"Why is this true?" "Prove it to me."*	• Thinking about explaining why something is the way it is • Exposing holes in partial thinking	• Intuitive action • Hidden or partial logic	ALWAYS SOMETIMES NEVER	*Analytic*
Wanting to Win *"Am I better at this than everyone else is?"*	• Competing against someone else • Having specific targets to measure who wins	• "Everyone wins" philosophy • Having no way to prove you can be the best	ALWAYS SOMETIMES NEVER	*All*

Biography

Mary EI Maa. Mary Maa is an avid scholar working to develop new ways to manage complexity and provide helpful tools for complexity management. Publications include a paper entitled, “Managing Aerospace Complexity through Modeling Communication Using Collaborative Intelligence” which was presented at the AIAA SciTech Forum 2022. Mary Maa is a recent graduate of California Polytechnic State University, SLO with a bachelor’s degree in Aerospace Engineering and is currently pursuing her graduate studies at the University of Southern California.

Alexander IN Derkatsch. Alexander Derkatsch is a dedicated systems thinker looking to innovate and practice in contemporary complexity management. Alexander Derkatsch graduated from California Polytechnic State University, SLO, with a bachelor’s degree in Aerospace Engineering. His other publication includes a paper on systems complexity with the AIAA for the 2022 SciTech Forum, entitled, “Managing Aerospace Complexity through Modeling Communication Using Collaborative Intelligence”.

Dianne J DeTurris, PhD. Dr. Dianne DeTurris has degrees in Aerospace Engineering from Georgia Tech, Penn State and Virginia Tech. Her PhD research is experimental hypersonic airbreathing propulsion. Since joining Cal Poly State University, San Luis Obispo in 1998, she has taught aerothermodynamics, propulsion and complex systems courses. Dr. DeTurris has been interim Co-Chair of the Aerospace Engineering Department and faculty advisor for Cal Poly Space Systems, which conducts high power rocket research. She held a position as Cal Poly’s Director of Global Technical Education Initiatives for three years. She is currently researching systems competency for addressing complexity in aerospace systems.