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Collaborative Systems Thinking: Uncovering the rules of team-level systems thinking

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Abstract* – As the aerospace workforce braces itself for the 'silver tsunami,' more emphasis is needed on how to develop systems skills in engineering workforce Research has shown this knowledge is tacit and based in experience. However, with nearly one-third of the industry's employees eligible for retirement, this systems-level knowledge is at risk of being lost. This paper focuses on the team as the unit of analysis and the elements of design process and team culture that foster collaborative systems thinking teams. Eight pilot interviews, ten full case studies and 14 abbreviated case studies were used to explore 'collaborative systems thinking,' or team-level systems thinking. From these data a definition of collaborative systems thinking is derived and generalizations about collaborative systems thinking teams are presented.

***Keywords* – systems thinking, collaborative systems thinking, engineering teams, workforce development.**

I. INTRODUCTION

The aerospace industry is built upon the systematic integration of several specialized functions. Through combining multiple different functions, aerospace engineers have succeeded in engineering exceedingly complex systems. In recent decades systems engineers have been the torchbearers of this systems-specific knowledge. Rapid advances in technology (e.g. Moore's law) have exponentially increased the computational capability of models and allowed once distinct interfaces to fuse in a quest for greater optimization and performance. This tighter integration of functions and subsystems has increased the need for systems-specific knowledge and thinking.

Much systems-level knowledge is tacit and therefore acquired through experience and interaction rather than formal study. Research on system design showed that at the component level 85% of design knowledge is documented. As components are integrated, 56% of the subsystem and 30% of the total systems knowledge is documented [1]. This implies that for a comparatively simple system, a car throttle body in the cited research, 70% of the system-level knowledge is undocumented. This tacit knowledge includes integration, trouble shooting, the rationale for past decisions, and a way of thinking at the systems level known as systems thinking. As the complexity of systems increase, systems thinking becomes more important as a means to solve and avoid design problems. However, as complexity increases, the base of knowledge and experience required to solve design problems also grows. This increased requirement for both breadth and depth of experience drives the move towards exploring systems thinking as a team-based property.

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A. Systems Thinking

Broadly defined, systems thinking is the consideration of the whole system and its context. Many definitions exist for systems thinking, but those related to engineering focus on the use of experience and tools to consider the technical and social components and interactions of a system [2]. The benefits of systems thinking include leveraging past experience to avoid future problems. Systems thinking skills include understanding dynamics system behavior, identifying feedback processes, finding and explaining patterns of system behavior, and devising methods to influence that behavior [3][4]. Systems skills aid in understanding the limitations of analytic models and help in identifying and influencing nonlinear processes [4]. Effective systems thinkers can leverage both quantitative and qualitative methods towards a solution. Engineering systems thinkers recognize both the technical and social components of a problem, allowing them to more effectively mobilize, organize and coordinate resources (human, financial, and physical) towards a systems solution [5].

Engineering systems thinking development is based on experience, individual characteristics (e.g. curiosity and tolerance for uncertainty), and a work environment that supports the development of systems skills [2]. Screening and developing engineering systems thinkers takes time and is a subjective process. There is already a recognized shortage of engineering systems thinking within the aerospace industry that is expected to worsen as the present aerospace workforce retires [6].

B. Motivation for Studying Teams

The pressures of increasing complexity and an aging workforce motivate the exploration of systems thinking as a team property. Aerospace engineers continue to retire at rates greater than replacement. Between 1989 and 2003, industry employment fell by 50% [7]. This employment reduction can be directly attributed to a contraction of the industry following the end of the Cold War. The side effects of that contraction are that fewer young engineers enter the aerospace industry each year and the industry's workforce has aged faster than the total U.S. workforce as shown in Figure 1. The result is an estimate that 25-50% of the aerospace workforce will be eligible for retirement within the next 5-10 years [8][9].

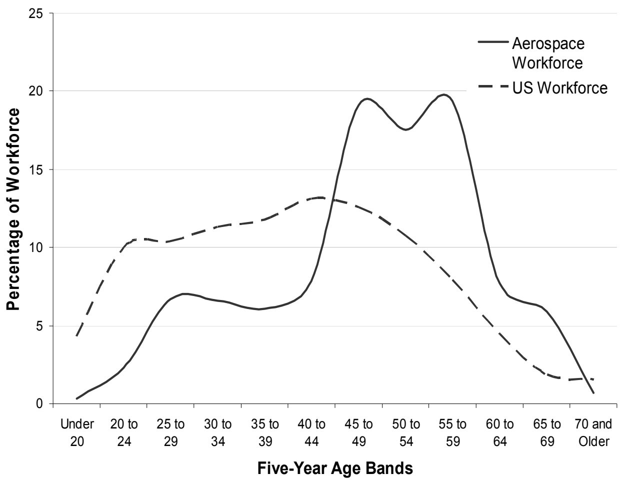

Figure 1. Comparison of aerospace industry and total U.S. workforce demographics. Adapted from [9]

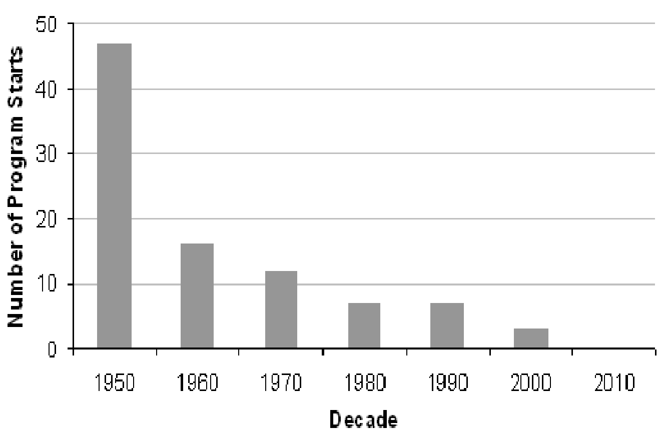

Figure 2. Manned fighter program starts by decade. Adapted from [10]

Further complicating the industry's demographics is a change in the size and number of programs. Increases in systems complexity and reductions in defense spending have resulted in fewer program starts and longer program lifecycles. For example, an engineer entering the workforce in 1950 would have the opportunity to work on any number of the nearly 50 manned fighter programs in that decade, as shown in Figure 2 [10]. By contrast, an engineer entering the workforce today would see only a few manned fighter programs over an entire career. Similar patterns of reduced program opportunity are repeated for manned spacecraft and commercial aircraft [11].

Fewer opportunities to work on different systems means today's engineers have more difficulty obtaining the systems experience necessary for complex system design. Focusing on systems thinking at the team level offers a potential solution that emphasizes systems thinking within teams and allows an individual within the team to leverage the entire team's systems knowledge.

Systems thinking teams create a supportive environment that values systems thinking and sharing design knowledge, thus satisfying two of the precursors for individual systems thinking development. Systems thinking teams would provide a natural mechanism for the transfer of tacit design knowledge from experienced engineers to younger and lesser experienced engineers. This will help to inculcate systems thinking in the next generation of engineers. In addition to the workforce development promises of systems thinking teams, by leveraging systems thinking at the team level, a broader range of experience and expertise can be brought to each design problem.

II. RESEARCH METHODS

The objectives of this research are to define collaborative systems thinking and to describe the generalized traits of collaborative systems thinking teams with the aerospace industry. Collaborative systems thinking is an ill-understood trait of teams enabling said teams to more effectively consider systems level issues and requirements. Empirical research methods are best suited to describe poorly understood phenomena. To focus the inquiry, standard technical processes, team structure, and organizational culture were chosen as the foci of investigation.

To gather data on collaborative systems thinking a series of case studies and interviews were conducted. The protocol used was modeled on grounded theory methods; combining quantitative and qualitative data to describe a real world phenomenon. Grounded theory research is characterized by concurrent and systematic data collection, analysis and theory development [12][13]. In the grounded theory method, data from multiple sources are used to identify important concepts and categories that are linked to form patterns. These patterns form a descriptive theory of the phenomenon under observation thus permitting future hypothesis based research for establishing causation [13]. Grounded theory methods provide a rigorous framework within which to collect and analyze data and avoid the pitfalls of revelation and intuition which threaten to relegate systems engineering to an art rather than a science [14].

The research structure used is this inquiry consists of four phases: literature review, pilot interview, case studies, and validation activities. This paper presents preliminary results from the case study phase. Because this research relies on the participation of professional engineering teams, steps have been taken to assure participant anonymity and to protect any proprietary data.[1]

C. Pilot Interviews

The pilot interviews consist of eight structured interviews. Questions asked in the pilot interviews focused on the differences between individual systems thinking and team systems thinking and on providing illustrative examples of such teams and the traits that enabled their systems thinking success.

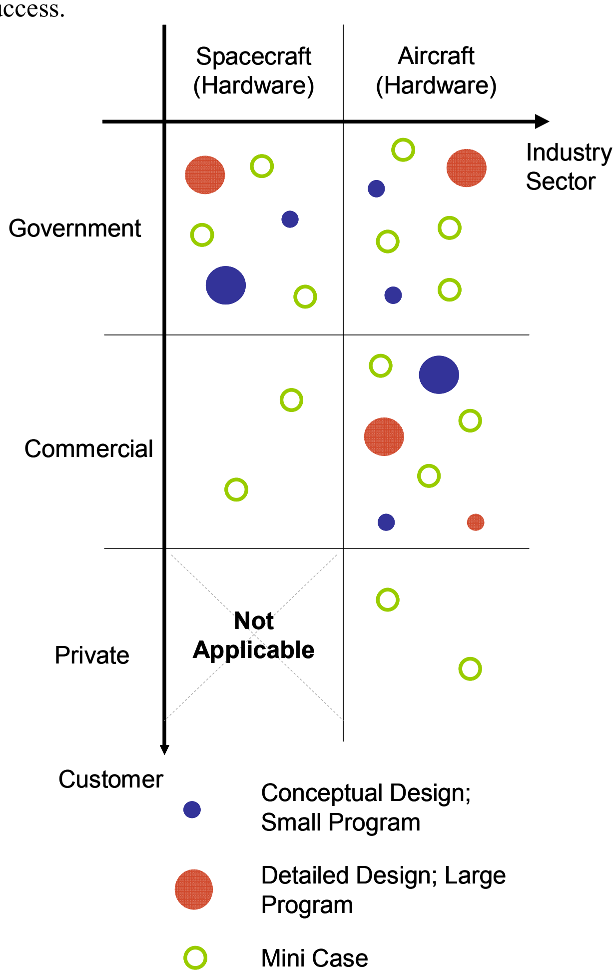

Figure 3: Case study selection criteria and completed case studies.

Identified differences between individual and team systems thinking include an increased emphasis on communication in support of the team cognition and the concept of delivering value through completed systems. The pilot interviews suggested that systems thinking teams were more likely to be product centered (in contrast to function or process centered) and would exhibit good team awareness. Interviewees differed on their opinions of team composition with some indicating that team systems thinking was a completely emergent behavior with no individual systems thinking capabilities required and others insisted that only teams of individual systems thinkers were capable of team-based systems thinking.

Results of the pilot interviews influenced the working definition of collaborative systems thinking.

D. Case Studies

Case studies were used to gather real-world data on teams and their ability to engage in systems thinking. Surveys, interviews, and publicly available data were used to learn about a team, its environment, diversity, communication, process usage and level of systems thinking. Established measures were used whenever possible and the final research instrument is the compilation of many different theories and past research. Because there is no established measure for systems thinking, or collaborative systems thinking, a triangulation method was used to approximate a team's level of collaborative systems thinking. This triangulation considered the self-reported collaborative systems thinking scores of several team members and a third party familiar with the team. While based on perception, the self reported scores for collaborative systems thinking were consistent within a team and varied from team to team, providing some validation of the measure.

Case studies were selected based on a matrix of parameters: industry segment (aircraft and spacecraft hardware), customer (government, commercial, or private), size of program (small or large), and phase of program (conceptual or detailed design). Ten full case studies were selected based on personal contacts and availability. An additional fourteen abbreviated case studies were completed to ensure generalizable results. The overlay of selection parameters and completed case studies is shown in Fig. 3.

Full case studies were conducted on site and included surveying between six and 20 members of a system-level design team. Follow up interviews were then conducted with 4-10 team members and at least one individual outside the team, but familiar with the team's task and performance. Abbreviated case studies were one-hour interviews with individuals from diverse aerospace programs covering team experiences and examples of positive and negative team systems thinking. The results of these case studies are presented in the following section.

III. RESULTS

The results described in this section are based on ten full case studies and 14 abbreviated case studies, as described in the previous section. Interpretation of the results is tied to existing theory and past research as appropriate.

[1] All data collection tools and protocol have been approved by the MIT Committee on the Use of Humans as Experimental Subjects (COUHES).

E. Defining Collaborative Systems Thinking

The pilot interviews and inputs from literature were used to construct a working definition of *collaborative systems thinking.* From the literature came five themes common to multiple definitions of systems thinking, as outlined in [15]. These themes are complexity, interrelationships (interfaces), context, emergence, and holism. From this it was determined that the definition of collaborative systems thinking should include these five universal themes defining systems thinking.

The pilot interviews reinforced these themes with common phrases such as 'holistic approach,' 'understand the problem, 'keeping a systems view', and 'teasing out interconnectedness.' The pilot interviews also introduced the concepts of producing a final product, managing interactions among multiple functions, using multiple and high-bandwidth forms of communication (e.g. face-to-face), the importance of a creative and supportive environment, the use of standard design process to manage design knowledge, being aware of other teams members, and the need for leadership recognition and support of systems thinking.

Inputs from literature were also considered when formulating a definition for collaborative systems thinking. Literature of team thinking and memory emphasized the role of team interactions, or transactions, in forming both a shared understanding of the system and pointers to specific knowledge and experience held by individual team members [16][17]. This reinforces the pilot interview themes of team awareness and the importance of interactions among multiple functions. The literature further refers to diversity of thinking styles (e.g. divergent, convergent, or metaphorical thinking) as important for the design process [18] and a need to communicate using multiple different communication media (e.g. sketches, prototypes or mathematical models) and levels of abstraction as important for conveying technical information [19].

From the literature, the following definition of engineering systems thinking was used as a template within which to integrate the themes from the pilot interviews and literature:

> Systems thinking is *'utilizing modal elements to consider the componential, relational, contextual and dynamic elements of the system of interest.*' [2]

The above definition was developed as part of a grounded exploration of systems thinking development and is based on interviews with nearly 200 practicing engineers. The definition was chosen as a starting point for the definition of collaborative systems thinking because it incorporates the five universal themes of systems thinking definitions into one engineering-specific definition. Further, the above definition for engineering systems thinking was developed in the context of the aerospace industry, matching the context of this research.

Using the above definition as a template, and integrating the themes from literature and the pilot interviews, the following definition of collaborative systems thinking was proposed:

> Collaborative systems thinking is *"an emergent behavior of teams resulting from the interactions of team members and utilizing a variety of thinking styles, design processes, tools, and communication media to consider the system, its components, interrelationships, context and dynamics toward executing systems design*."[15]

This definition captures the primary difference between individual and team systems thinking: the concept of team thinking, or the group processing of information the recall and interpretation as defined in [21]. The definition also emphasizes the five themes of systems thinking definitions in the context of executing, or delivering, a system design. This definition was used throughout the case studies and was well accepted.

F. Generalized Traits of Collaborative Systems Thinking Teams

While many generalized traits can be identified and illustrated through vignettes, this paper concentrates on four generalizations from the case studies: team structure, the role of experience, and aspects of team culture.

Team Structure: One consistent difference between teams with high and low rating of collaborative systems thinking was team structure. The structure observed consists of three levels of team membership: systems leadership, an intermediary group of developing systems professional with functional backgrounds, and functional experts. This structure, observed through organizational charts or discerned through conversation with team members, was observed in each of the six full case studies with high rankings for collaborative systems thinking. The pattern was also reinforced through the abbreviated case studies on the basis of asking those individuals to describe how their team experiences did or did not fit the three-tier membership structure.

The systems thinking leadership of a team is composed of one or more individuals, all strong individual systems thinkers, who balance both the technical and social interactions of the team. These individuals guide their team, adjusting their interaction style to best serve their purpose and audience. They excel at communicating at multiple levels of abstractions and multiple levels of system detail. These traits align with those of the 'highly regarded' systems engineers characterized in [21]. These traits, developed from a study of effective systems engineers at NASA, include the ability to influence others, strong communication skills, engaging in mentoring, critical thinking, risk management, and the ability to lead others to new insight using analogy and insightful questioning.

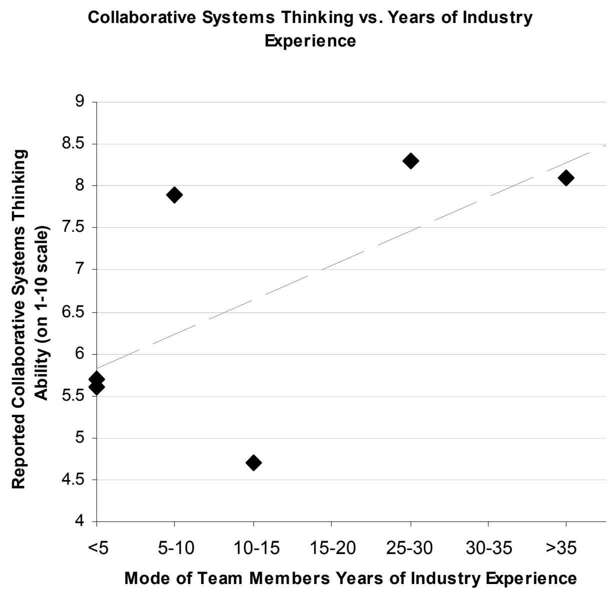

Figure 4: Collaborative systems thinking as a function of years of industry experience. The two parameters have a correlation coefficient of 0.63.

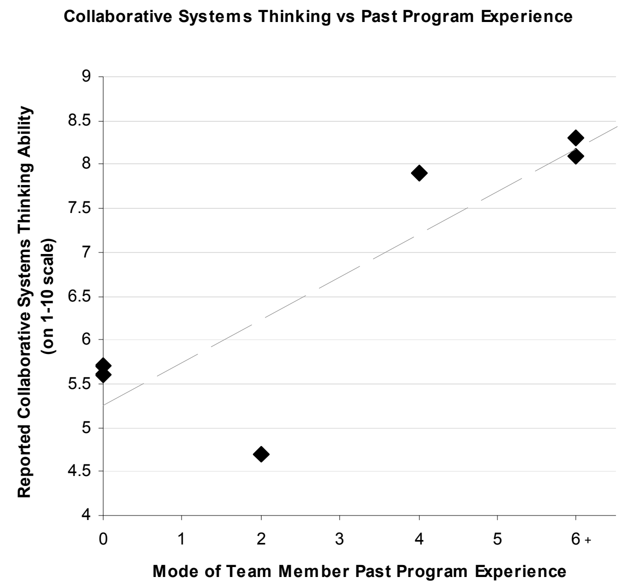

Figure 5: Collaborative systems thinking as a function of number of past program experiences. The two parameters have a correlation coefficient of 0.86.

The intermediary group of developing systems professionals consists of individuals with functional responsibilities (e.g. subsystems leads or representatives of different functions) who interact closely and have an appreciation for systems issues. These individuals act as an interface between the functional experts and the systems leadership. They excel at presenting detailed technical information at the right level of abstraction to permit system-level knowledge interchange and decision making. By nature of their role within the team, these individuals are well poised to develop strong systems skills.

The functional experts bring specialized technical knowledge to the team. These individuals are less involved in the day-to-day interactions and decision making of any single team, as they often contributes to several teams simultaneously. As such, the functional experts are less aware of systems issues and the greater systems picture.

A team lacking any one of these membership levels experiences a lack of leadership and/or a failure to get the information necessary to support decision making.

Experience: Past similar program experience is more highly correlated with collaborative systems thinking than years of industry experience. Figures 4 and 5 the mode, or most frequently cited, experience levels of team members and the correlation to collaborative systems thinking. Because levels of experience vary greatly within a team, the mode was chosen as more representative of a typical team members' experience than a team average of experience. To facilitate a comparison between the two parameters (year of experience and number of past programs) the responses were binned into seven response categories. These bins consist of 5-year increments for the years of experience and 1-program increments, saturating at 6 programs, for past programs.

The data show that mode of past similar program experience is a more powerful predictor of collaborative systems thinking than year of industry experience. Systems skills are based on an understanding or appreciation of the entire system, therefore the number of past similar systems worked is a logical indicator of systems thinking. This observation reinforces the value of internal research and design (IR&D) programs that expose new engineers to multiple smaller program cycles, as described in [22].

Team Culture: Teams with higher ratings of collaborative systems thinking had consistent cultural traits. Given that culture is an abstraction, these traits are quantify and are thus presented as qualitative descriptions resulting from the interview.

The most frequently cited cultural trait of collaborative systems thinking teams a sense of participation and inclusion. Members of these teams expressed satisfaction that their ideas were heard and considered. These teams utilized consensus decision making, thus ensuring everyone felt ownership over the team's direction. The survey administered to teams asked individuals to rank the relative frequency of individual decisions versus consensus decisions. This parameter has a strong correlation (C=0.70) with team reported collaborative systems thinking ability.

Other common cultural traits centered on a team's communication preferences. Collaborative systems thinking teams were more likely to describe their teams as having open and honest communication. These individuals expressed a preference for face-to-face communication. As one team members said, you "can't delete a walk-in." These teams were more likely to describe themselves as having a creative environment or being more family-like.

These cultural traits emphasize inclusion and communication and align with several themes found both in literature and the pilot interviews.

IV. CONCLUSIONS

The research presented above is part of ongoing work scheduled for completion in mid-2009. The objectives of this research are to define collaborative systems thinking and to identify the empirically generalized traits of collaborative systems thinking teams within the aerospace industry. This research has focused on traits related to team composition, process usage, and culture.

Demographics within the aerospace industry place the transfer and development of systems skills as top industry propriety over the next ten years. Cultivating systems thinking teams is one strategy the industry might use. Generalizations based on case studies of aerospace teams show that strong systems leadership is required; either in the form of a systems thinking program manager/leader or through cooperation between program managers and influential systems thinkers. Further generalizations show that while the median years of experience represented on a team is a good indicator of collaborative systems thinking the median number of past program experiences is more closely correlated to reported collaborative systems thinking ability. Collaborative systems thinking teams have open cultures that promote asking and answering questions. Some even describe these teams as having 'family-like' cultures that promote open and honest communication. Finally standard process, while generally seen as an enabler for collaborative systems thinking, has not emerged as in the case studies as a strong contributor to collaborative systems thinking. Rather, focusing on clear communication and having a transparent process (be it through documentation or discussion) are more important indicators of collaborative systems thinking.

The above results are based on empirical evidence gathered through interviews and case studies. A future validation activity is planned in which a subset of team traits will be used to predict a team's collaborative systems thinking and then compared against the team's self rating as a means to validate the above generalized traits. Future work on collaborative systems thinking should focus on longitudinal studies to track the performance of comparables teams to quantify the value of team systems thinking for improving team performance and fostering individual systems thinking. This would be a step towards developing training material, in the form of a team simulation or game, to measure and/or foster collaborative systems thinking development.

While the results are grounded in aerospace engineering teams, the results likely apply to other engineering industries and other countries, many of which are facing similar trends in demographics, number of program starts, and increasingly longer program lifecycles.

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