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Collaborative Systems Thinking: Towards an Understanding of Team-level Systems Thinking

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Abstract

As the engineering workforce ages, skills with long development periods are lost with retiring individuals faster than are younger engineers developing the skills. Systems thinking is one such skill. Recent research, (Davidz 2006), has shown the importance of experiential learning in systems thinking skill development. However, an engineering career begun today has fewer program experiences than in past decades because of extended program lifecycles and a reduction in the number of new large-scale engineering programs. This pattern is clearly visible in the aerospace industry, which (Stephens 2003) cites as already experiencing a systems thinking shortage.

The ongoing research outlined in this paper explores systems thinking as an emergent property of teams. Collaborative systems thinking, a term coined by the authors to denote team-level systems thinking, may offer an opportunity to leverage and develop a skill in short supply by concentrating on the team in addition to the individual.

This paper introduces the proposed definition for collaborative systems thinking, as developed by the authors, and the outlines the structure and progress of ongoing case research into the role of organizational culture and standard process usage in the development of collaborative systems thinking.

Systems Thinking

Systems Thinking. Systems dynamics, systems science, and systems engineering all lay claim to definitions of systems thinking. Generic definitions of systems thinking vary, defining the skill from the use of one's abilities to apply sound reasoning in a given situation, to the application of different types of thinking. Figure 1 shows several common definitions of systems thinking from (Ackoff 2004), (Checkland 1999), (Gharajedaghi 1999), (Senge 2006) and (Sterman 2000). The cross-cutting vertical arrows show the recurring themes of component complexity, interrelationships, context, emergence, and whole is found within these commonly used definition of systems thinking.

Many of the definitions in Figure 1 come from systems dynamics and are typified by an emphasis on observing patterns of behavior and representing these patterns through cause-effect relations (Richmond 1993). To support exploration of these cause-effect relationships, systems thinking is supported by a body of knowledge and tools developed over the past 50 years to "make full patterns clearer and to help us see how to change them effectively" (Senge 2006).

A framework for systems with four basic ideas: emergence, hierarchy, communication and control. Human activity concerns all four elements. Natural and designed systems are dominated by emergence. (Checkland 1999)

A method of placing the systems in its context and observing its role within the whole. (Gharajedaghi 1999)

A skill to see the world as a complex system and understanding its interconnectedness. (Sterman 2000)

A skill of thinking in terms of holism rather than reductionism. (Ackoff 2004)

A method and framework for describing and understanding the interrelationships and forces that shape system behavior. (Senge 2006)

Component Complexity **Interrelationships** **Context** **Emergence** **Wholes**

Figure 1: Common definition of systems thinking and their recurring themes.

Systems Thinking Applied to Engineering.

Systems thinking within the engineering community is concerned with the system as a whole and elucidating patterns of behavior and interactions, but engineers go beyond observation to actively manipulate technology and manage systems with ill-understood cause and effect relationships. Because these systems do not exist until engineers build them, and are therefore not observable, systems thinking within engineering is based on the application of past experience to new situations. The engineering definitions of systems thinking therefore place a greater emphasis on interactions and interfaces because these contribute to emergence. For an excellent discussion of the benefits of systems thinking for engineering see (Davidz 2006).

Past Research. Systems thinking research specific to the engineering community has been spearheaded by (Frank 2000) and (Davidz 2006). In her dissertation, (Davidz 2006), presents a definition of systems thinking grounded in over 200 interviews with practicing engineers, as shown in Figure 2. The definition emphasizes the use of a variety of tools, methods, thinking styles, models and processes to consider the context, interrelationships, and dynamics of a system and its elements. In Figure 2, references to the common themes within systems thinking definitions are denoted by colors respective to those in Figure 1.

*Systems thinking is utilizing modal elements to consider the **componential**, **relational**, **contextual**, and **dynamic elements** of the **system** of interest.* (Davidz 2006)

Figure 2: Systems thinking as defined by (Davidz 2006).

Motivation for Team-Level Analysis

While work by (Davidz 2006) concentrates on the individual engineer, (Frank 2000) acknowledges a team effort is required to fully understand today's complex systems. A combination of demographic, technical and policy conditions contribute to the increased importance of teams within engineering.

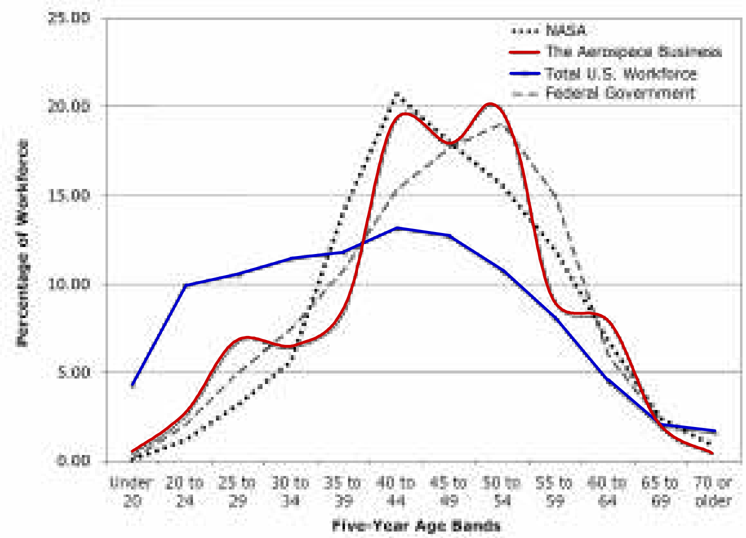

Figure 3: The aerospace engineering workforce is older than the U.S. workforce as a whole according to data in (Black et al. 2006).

Demographics Pressures. Engineering as a profession is aging faster than the U.S. workforce as a whole. More than 60% of engineers and scientists within the United States are over the age of 45 (Augustine et al. 2006). Within the aerospace industry an estimated 25% of the workforce will retire within the next five years (Black et al. 2006). Figure 3 shows the aerospace workforce in comparison to the U.S. workforce. The industry demographics are skewed towards older individuals whose career began in the late 1950's and early 60's. As these workers retire, invaluable tacit knowledge regarding the design of aerospace systems, in the form of systems thinking skills, is taken with them. Teams offer one means to expose younger engineers to the skills and knowledge of more experienced engineers. It is therefore worthwhile to understand what combinations of work experience, individual education and individual systems thinking capability enable team-level systems thinking.

Technical Pressures. Increasing technical complexity is another driver towards teams as the fundamental work unit in engineering. Both the breadth and depth of technical knowledge necessary to field a complex system has increased. Many individuals are required to provide the necessary expertise. Multidisciplinary teams, such as integrated product development teams, are evidence of this trend. Teams provide an opportunity to coordinate efforts from many disciplines early in development, contributing to better system performance. Technical design process specifies the ways in which disciplines interact during design. Well designed technical processes are a likely enabler of team-level systems thinking as these processes are critical in specifying how and among whom technical data is shared during the course of design.

Policy and Political Climate. Experience was identified by (Davidz 2006) as an important enabler of systems thinking development. Decisions to field fewer systems with longer development cycles, decisions often grounded in government policy, impact the number of programs an average engineer will experience over the course of her career. Within the aerospace industry, this trend is evident in a reduction in program starts. Figures 4 and 5 show the downward trends in the number of manned fighter aircraft programs and manned spacecraft programs over the course of a 40 year career (Murman et al. 2004; Neal et al. 1995). This pattern is repeated in commercial jetliners, manned space flight, and planetary probes. As a result, the collective number of programs worked by members of a team may be a better indication of team-level systems thinking than number of years worked in industry. In addition, the greater the variety of program experiences within a team, the broader the experience base the team has the draw upon, potentially an additional enabler of team-level systems thinking.

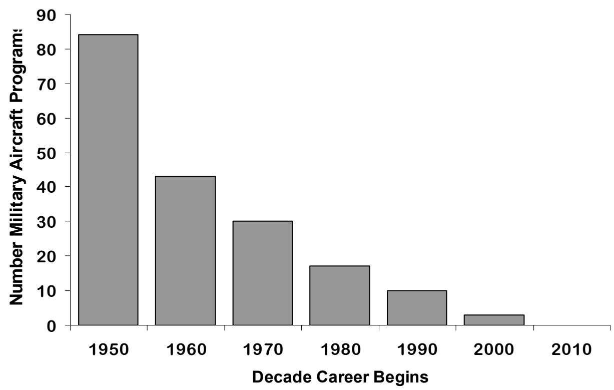

Figure 4: Number of manned fighter aircraft program starts during a 40 year career by decade of career start (Murman et al. 2002).

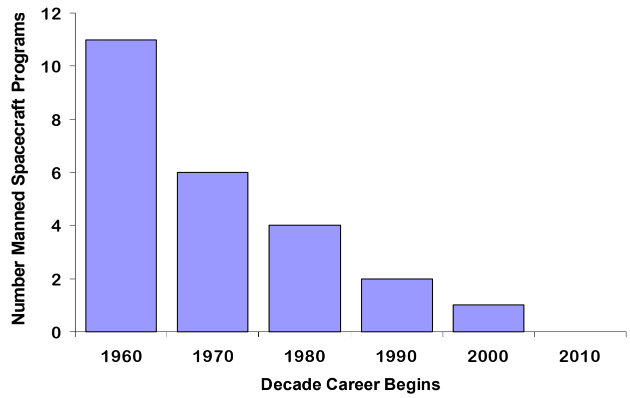

Figure 5: Number of manned spacecraft program starts during a 40 year career by decade of career start (Neal et al. 1995).

Collaborative Systems Thinking

Systems thinking, with its emphasis on social and technical interactions and influences, enables engineers to better mobilize, organize and coordinate resources (human, financial and physical) towards the completion of systems design (Beder 1999). Owing to the important role teams play within engineering complex systems and the shortage of systems thinking skills, researching the ways teams engage in systems thinking is a worthwhile pursuit towards leveraging limited systems thinking skills. The term collaborative systems thinking was coined by the authors to differentiate team-level systems thinking from individual-level systems thinking. Collaborative systems thinking considers the social component of engineering and the exchanges of knowledge and information within a team during the course of system design that result in team-level cognition.

Team Cognition in Design

One example of team-based thinking research is design thinking. Much research has focused on the way in which groups execute design, noting the role of communication, process, and behavior in enabling successful design. Among these enablers are a creative environment and the use of both divergent and convergent thinking styles (Dym et al. 2005; Stempfle and Badke-Schaub 2002). Divergent thinking operates in the concept domain, encapsulating the steps of generation and exploration. Convergent thinking operates in the knowledge domain and consists of comparison and selection.

The creative process requires both divergent and convergent thinking styles to explore the problem space and to act upon that exploration. The majority of engineers, however, express a preference for convergent thinking (Dym et al. 2005). This rush towards convergent thinking is a natural thinking mode engaging heuristics to reduce complex situations into manageable pieces and enable quick decisions despite uncertain information (Gigerenzer et al. 1999). This situation is common in engineering even though purely convergent thinking can lead to lower quality outcomes in complex situations.

Characteristics of effective design thinking include the ability to tolerate uncertainty, keep sight of the big picture, make decisions despite ambiguity, think and take action as a team, and to communicate using several media including verbal, sketching, math, and dynamic models (Dym et al. 2005). The references to big picture thinking and tolerating uncertainty draw clear parallels between design thinking and systems thinking. Because design thinking specifically references the ability to think as a team, it is a logical bridge between systems thinking and collaborative systems thinking. As such, the enablers, barriers and traits of design thinking are extremely pertinent to research into collaborative systems thinking.

Defining Collaborative Systems Thinking.

The proposed definition of collaborative systems thinking is based on accepted definitions of systems thinking, a dozen interviews with senior systems engineers and engineering executives, and numerous interactions with members of industry at conferences and poster sessions.

From these sources came the ideas that teams produce products, and therefore a component of collaborative systems thinking should be system execution. Additionally, teams offer a solution to the dichotomy of systems thinking traits (Davidz 2006) found in her research. The role of both detail-oriented traits and big-picture thinking traits emerged as important for systems thinking (Davidz 2006). Research by (Culp and Smith 2001) showed the performance advantage of teams with heterogeneous thinking preferences, thus showing one way in which a diversity of thinking styles strengthens a team and may contribute to collaborative systems thinking. Additionally, these successful design teams engage multiple media to communicate the ideas and information necessary to make design decisions (Dym et al. 2005).

From these inputs, the following definition of collaborative systems thinking was developed. Shown in Figure 6, the definition for collaborative systems thinking includes the five themes from Figures 1 and 2 in the context of a team setting utilizing several modes of thinking, established design practices and tools, and a rich set of communication methods.

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 towards executing systems design. (Lamb, 2008)

Figure 6: Collaborative systems thinking definition.

Ongoing Research Framework

Systems engineering is a discipline born out of practice. As such the theories governing systems engineering must be grounded in that practice. The goal of this research is to observe practice and to generate theory based on those observations. The objective of that theory is to provide organizations with actionable information for fostering collaborative systems thinking within their engineering teams.

Table 1: The important dimensions and categories used for theoretical sampling of case studies.

Sampling Dimension	Dimension Categories
Industry Sector	Aircraft; engines; avionics; spacecraft
Program Lifecycle	Conceptual design; detail design
System Level	Component; subsystem; system
System Customer	Government; commercial; private
Team Size	10-20; 20+
Organization Size (Relative)	Small; medium; large

This research follows the example set by (Davidz 2006) and the practices outlines by (Valerdi and Davidz 2007) for empirical research in systems engineering. An exploratory research framework utilizing grounded theory techniques was used to design a set of survey and interview tools for gathering case data. These lines of inquiry are guided by literature on team cognition, team-based design thinking, team theory, and organizational culture.

As with any research method, threats to validity must be addressed through research design and data analysis. In grounded theory research threats to construct, convergent, discriminant, external, and internal validity must be considered (Valerdi and Davidz 2007). The first three, construct, convergent and discriminant, were addressed by utilizing the well established constructs of organizational culture and technical process to explore the new construct of collaborative systems thinking. A discussion of these constructs can be found in (Lamb and Rhodes 2007). The remaining validity concerns, external and internal, are controlled by selecting an adequately sized and representative research sample and through utilizing multiple sources and triangulation to facilitate data analysis. Table 1 shows the parameters along which case studies are being selected to ensure a representative sample. All case studies are within the aerospace industry. Figure 7 shows an example of data triangulation. As case studies utilize surveys, interviews and data from primary documentation, each construct can be measured from multiple angles to aid in objective data analysis. In the case of communication media, knowledge about whether the team is co-located or distributed can be collected in advance; standards or procedures for sharing information will be part of the documented process; surveys will indicate how frequently team members communicate and using what tools; interviews will help assess the effectiveness of these communications; and researcher observation of the workspace will indicate if the physical workspace promotes communication

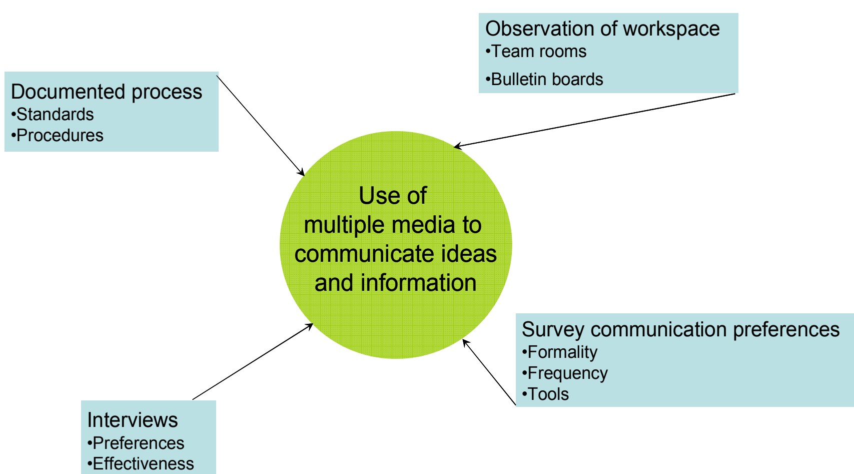

Figure 7: Data triangulation for measuring use of multiple communication media.

through common spaces and bulletin boards.

Table 2 shows a typical case study outline, highlighting how and when different types of data are collected. Six case studies are currently in different phases of commitment and execution. A total of between 15 and 20 case studies are ultimately desired to explore the sampling criteria. Each case study is designed to gather information from a variety of sources including team members, team supervisors and primary documentation. Artifacts such as organizational charts, process flow diagrams, and action item lists are used to gage team member awareness of their role within the system and organization as a whole. Interviews with team members and team observers will provide two perspectives on team culture and effectiveness.

Table 2: Example case study timeline.

Preparation	▪ Knowledge of team and design task ▪ Review organizational chart and process documentation (if available)
Day 1	▪ Introduction ▪ Team survey ▪ Observation of team dynamics
Day 2	▪ Team member interviews ▪ Observation of workspace
Day 3 (If necessary)	▪ Complete team member interviews ▪ Manager/Supervisor interview
Follow-up	▪ Share results

Conclusions and Next Steps

Past research on systems thinking has indicated experiential learning, individual characteristics, and a supportive environment serve as both enablers and barriers to individuals developing systems thinking skills. Motivated by these results and literature on engineering teams, team composition, organizational culture and standard technical processes are being used to explore collaborative systems thinking within engineering teams. The objectives of this research are to develop a definition of collaborative systems thinking, to identify traits of highly collaborative systems thinking teams, and identify heuristics for enabling collaborative systems thinking within engineering teams.

Pilot interviews and initial case sign-up indicate a strong interest from both industry and government in understanding systems thinking at the team level. Specifically, culture and technical process seem important in team cognition and fostering a creative environment with attributes that may enable collaborative systems thinking. The ongoing case study phase of research is scheduled for completion in summer 2008, with completion of data analysis and publication of results set for winter 2008.

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Biographies

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Professor Deborah Nightingale has over 35 years of broad-based experience with academia, the private sector and the government. Professor Nightingale joined the MIT faculty in 1997 and holds a dual appointment in the Dept. of Aeronautics and Astronautics and the Engineering Systems Division. At MIT she serves as the Co-Director of the Lean Advancement Initiative, a joint industry, government, and MIT consortium. Her research interests are focused on lean enterprise integration, enterprise architecting, and organizational transformation. She has led several executive lean transformation engagements in both industry and government. She is a member of the National Academy of Engineering and a Past-President and Fellow of the Institute of Industrial Engineers.

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