Collaborative Systems Thinking: An exploration of the mechanisms enabling team systems thinking

by

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S.B. Aeronautics and Astronautics, Massachusetts Institute of Technology 2003

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Abstract

Aerospace systems are among the most complex anthropogenic systems and require large quantities of systems knowledge to design successfully. Within the aerospace industry, an aging workforce places those with the most systems experience near retirement at a time when fewer new programs exist to provide systems experience to the incoming generation of aerospace engineers and leaders. The resulting population will be a set of individuals who by themselves may lack sufficient systems knowledge. It is therefore important to look at teams of aerospace engineers as a new unit of systems knowledge and thinking. By understanding more about how teams engage in collaborative systems thinking (CST), organizations can better determine which types of training and intervention will lead to greater exchanges of systems-level knowledge within teams.

Following a broad literature search, the constructs of *team traits*, *technical process*, and *culture* were identified as important for exploring CST. Using the literature and a set of 8 pilot interviews as guidance, 26 case studies (10 full and 16 abbreviated) were conducted to gather empirical data on CST enablers and barriers. These case studies incorporated data from 94 surveys and 65 interviews. From these data, a regression model was developed to identify the five strongest predictors of CST and facilitate validation. Eight additional abbreviated case studies were used to test the model and demonstrate the results are generalizable beyond the initial sample set.

To summarize the results, CST teams are differentiable from non-CST teams. Among the most prevalent differentiators is a team's self-reported balance between individual and consensus decision making. Teams that engage in consensus decision making reported stronger engagement in collaborative systems thinking. Another differentiator is the median number of past program experiences on a team. Teams whose members reported more past similar program experiences also reported more engagement in collaborative systems thinking. Data show the number of past similar programs worked is a better predictor than years of industry experience. The apparent enabling effects of qualitative team traits are also discussed. The conclusions of this document propose ways in which these findings may be used to improve training and team intervention within industry, academia, and government.

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Executive Summary

The aerospace industry is maturing in more than one way. The industry's workforce is greying: rapidly approaching retirement age. Many of the contributing disciplines have reached a level of advancement that permits accurate modeling and prediction of complex phenomena. These two conditions collide at a time when the industry is increasingly being asked to execute complex system design with fewer people, fewer monetary resources, all without compromising on performance. The result is an increased need for systems expertise and fewer opportunities to organically develop systems skills at a time when the industry is loosing much of its systems expertise to retirement.

To address this conundrum, empirically-based research into the development of systems thinking has emerged as a tool to develop a grounded expertise for interventions within academia, industry, and the government aimed at understanding and improving the systems engineer development pipeline. Past research has focused on the individual as the unit of systems thinking and the unit at which to intervene. While fundamental questions still remain as to 'how' systems thinking develops, there is now empirical evidence supporting the importance of experiential learning, certain personal characteristics, and a supportive context as enabling individuals to develop systems thinking skills. The same research found evidence implying there is no shortcut to developing systems skills.

Since the industry finds itself with an insufficient number of people in the pipeline to fulfill its near-term need for systems thinking, this research turns to the team as a unit for leveraging systems thinking. The term 'collaborative systems thinking' is introduced to differentiate systems thinking within teams from that by individuals.

The questions guiding this exploratory research are 1) What is collaborative systems thinking and how does it differ from individual engineering systems thinking? 2) What are the empirically generalized traits of systems thinking teams within the context of the aerospace industry? and 3) What observed mechanisms best predict collaborative systems thinking?

The research consists of in four phases: the literature review, the pilot interviews, the case studies (including in-depth case studies and additional abbreviated case studies), and the validation case studies. The in-depth case studies consist of multiple surveys and interview per team. The abbreviated case studies and validation case studies relied on interviews with one member per team. Combined, these represent a progression of exploration that starts with a wide net being cast over many different bodies of literature and ends with a set of focused recommendations for industry, academia, and the government.

The pilot interviews focused the exploration on a few important areas: names team composition, organizational culture, and standard technical processes. The pilot interviews also provide the basis for a definition of collaborative systems thinking as 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 systems attributes, interrelationships, context and dynamics towards executing systems design.*

The case studies revealed a set of generalized traits that appear highly correlated to team collaborative systems thinking. The majority of these traits touch on 'soft' issues within teams and include utilizing consensus decision making, having more supportive and creative work environment, and the presence of both social and technical leadership. Technical indicators included an apparent link between conceptual design practices and collaborative systems thinking and suggest that teams whose members have greater past program experience and moderate concurrent program participation also engage in more collaborative systems thinking.

From the case studies, a rudimentary model was constructed. Five factors that combined account for 85% of the observed variability in collaborative systems think-

ing ratings were married into a multivariate regression model for validation purposes. Data were collected for eight validation case studies as a test of the broader applicability of the initial case study results. The five predictive factors accounted for 72% of the observed variability in validation case study collaborative systems thinking ratings, bolstering the broader applicability of the results.

From the model and additional supporting qualitative results from the interviews conducted, three sets of recommendations are put forth for industry, academia, and government.

The three recommendations for industry include the use of IR&D funds for small development programs to provide employees with pertinent systems experience; encouraging informal mentoring relationships that incorporate real program experience; and placing an emphasis on both technical and social capabilities when training and selecting program leaderships.

The four recommendations for academia center on providing systems experience to students, structuring team activities to introduce students to effective team work practices, coursework in technical writing and speaking, and an introduction to drafting, model making, and other media used for exchanging systems-level knowledge.

Finally, there are four recommendations for government. These are to support policies that provide incentives for corporate IR&D funding to provide systems experience to the aerospace workforce, to support research funding within academia that will ensure sufficient numbers of students are in the systems skill development pipeline, to utilize black-world programs or similar to allow for some programs to greater risks and familiarize the workforce with greater uncertainty, and to promote entrepreneurship within the industry through continued support and expansion of small business grants and partnerships with smaller aerospace companies.

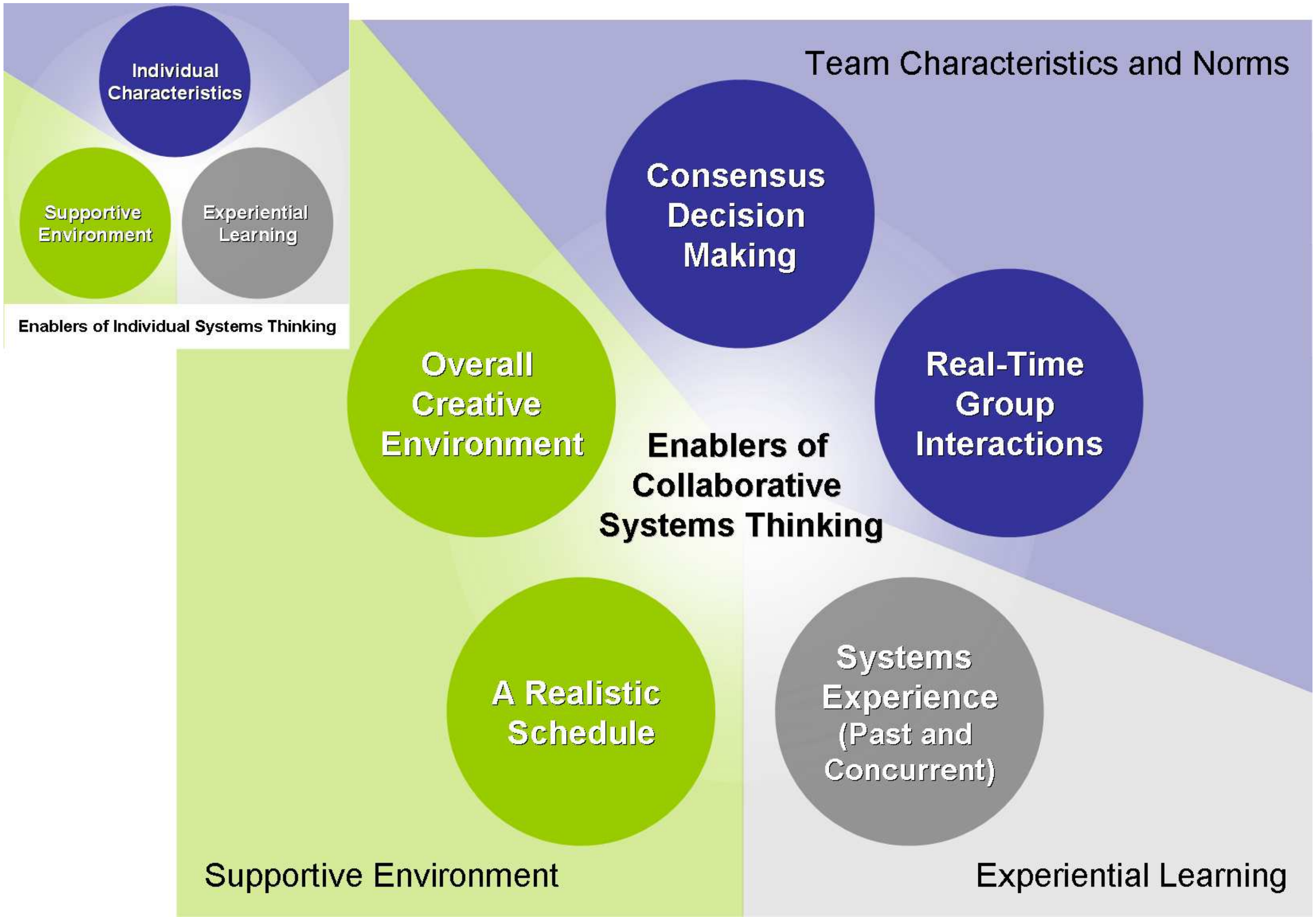

Figure 0-1: Summary Graphic Showing Enabling Traits of Collaborative Systems Thinking and Links to Enablers of Individual Systems Thinking

Dedication

A scientist discovers that which exists.

An engineer creates that which never was.

-Theodore von Karman

This thesis is dedicated to engineers $\sim$ the world's *dreamers* and *doers* $\sim$ and to my husband, whose support and encouragement have enabled me to follow my dreams.

Acknowledgements

This dissertation has been both an intellectual and personal journey. This journey was facilitated by the guidance and support of my committee: Prof. Deborah J. Nightingale (chair), Dr. Donna H. Rhodes, and Prof. Annalisa L. Weigel. These three advisors and role models allowed me the opportunity to explore and define my own path while providing advice that will carry me well into my career. For introducing me to those who would become my committee, I owe a deep debt of gratitude to Prof. Earll M. Murman. Of course, this research would not have materialized without the financial support of the the Lean Advancement Initiative (LAI), the National Defense Science and Engineering Graduate (NDSEG) Fellowship, and the American Institute of Aeronautics and Astronautics (AIAA) Graduate Award and the intellectual and logistical support from the staff and students of LAI and the Systems Engineering Advancement Research Initiative (SEAri).

To all the engineers and companies who indulged my inquiries–it was a privilege to speak with you and to learn from your broad experiences–both about engineering and about life. Even though I cannot list your names you know who you are; I hope you gain as much insight and new knowledge from this thesis as did I receive from our interactions. This research also benefited from the fabulous interactions afforded me by my position as the Student Liaison to the AIAA Board of Directors. It was a rare and valuable opportunity to speak with the leaders of the aerospace industry.

Finally, my deepest thanks go to those family and friends who supported me along what has not always been an easy path.

- To my mother, Dianne Binger, for being my first teacher. She pushed me to explore my world and ask lots of questions. Now, I look forward to cheering her on as she writes *her* thesis.
- To my father, Bruce Twomey, for nurturing an early interest in planes and rockets. We lost nearly every model rocket we ever built–most to the roof of Arrowhead High School–but those experiences launched my career.
- To my step-father, Norman Binger, for his unwavering faith and support. He drove my car cross country; spent vacation time renovating my kitchen; treated me like one of his own. In many large and small ways, he helped make the past four years more enjoyable.
- To my mother-in-law, Deborah Allinson, for providing weekend respites from research. She has shown me the world–quite literally–and taught me more than she may realize about how to interact with that world.
- To my father-in-law, Thomas Lamb, who first impressed upon me the need for a graduate education, but did not live to see me graduate. He was my cheerleader and resolve those days I wanted to quit.

Most importantly, my thanks and love go to my husband, Andrew Lamb. Andrew has always been here for me with a hug to celebrate victories and a shoulder to lean on through trials. He has sacrificed many opportunities to allow me this opportunity. I now look forward to helping him realize his dreams.

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Chapter 1

Introduction

There's nothing odd about looking at 40 year old hardware in museums...but only in American Aerospace...can we go to a museum and look at certain artifacts and wish that we could still do as well, and that fact should sober everyone here.

–Michael Griffin, speaking at the NASA 50th Anniversary Gala,
26 September 2008

The aerospace industry designs and builds some of the most complex systems ever imagined. Aerospace systems have shrunk the globe to a few hours travel, put men on the moon, and enabled the global flow of information. In short, aerospace technologies are a major contributor to the world as we know it and enable growth and new efficiencies in other industries. In 2008, $640 billion in US gross domestic product (GDP), or 5.4%, was enabled by civil aviation activity [11]. In addition, the space industry contributes great value to the GDP via vast constellations of global positioning and communications satellites. Global positioning satellites (GPS) enable more accurate surveying, more efficient agriculture, and more accurate construction. Communication satellites enable real-time information sharing across the globe and provide both television and radio signals, improving communication in areas otherwise too remote for ground-based infrastructure. Aerospace also contributes to intangible benefits such as security and scientific exploration.

The aerospace industry has become a critical component of our society and like many other industries is being asked to produce more advanced systems with fewer resources, manpower included. Aerospace engineers are retiring faster than the industry is hiring new talent, resulting in a 'silver tsunami' [2]. With 25% of aerospace workers eligible for retirement within five years [12, 20, 137], the industry stands to lose much of the knowledge and design skill required not only to develop new aerospace systems but to maintain current systems. The failure to maintain an aerospace skills base within the United States will have a negative, and possibly very large, impact on the economy. It is therefore important to understand how systems skills develop and to explore new ways in which to leverage systems skills and to thus avoid having even more artifacts in museums for which we no longer possess the requisite systems knowledge.

This dissertation concentrates on the skill of systems thinking. Broadly defined as 'big picture' thinking, systems thinking is a necessary skill for complex systems design [137]. Systems thinking provides a link between the pure analytic side of engineering and the creative design side [59]. Systems thinking is a critical skill for communicating between design and analysis, ensuring the final product delivers the desired functionality, identifying and managing interfaces (social and technical), and brokering effective design tradeoffs. However, systems thinking skill development is poorly understood. An empirical study of aerospace engineers showed the importance of work and personal experience, individual traits, and a work environment that values systems thinking as enablers for individual systems thinking development [35], but little is known about the impact of training interventions or the overall time required to identify and develop a strong systems thinker. More data are required to understand the phenomena of systems thinking and to identify the best options for enabling its development in the next generation of aerospace engineers.

This research focuses on the team level as a new way to conceptualize systems thinking with potential promise for improving system development and providing a new means to promote systems thinking skill development within the workforce. As aerospace product development cycles often span decades, the shift to the team level for systems thinking is natural. Programs may span multiple careers and individuals will come and go from teams. Teams, however, have a more stable existence within programs. The team focus is also motivated by increasing system complexity and a shift toward defining work at the team level based on evidence that teams are better able than individuals to make decisions in complex situations [124]. A new term, collaborative systems thinking, is introduced to refer to team-based systems thinking and to differentiate this team-based phenomena from individual systems thinking.

1.1 Motivation

Engineering problems are under-defined, there are many solutions, good, bad and indifferent. The art is to arrive at a good solution. This is a creative activity, involving imagination, intuition and deliberate choice.

–Ove Arup

1.1.1 The Importance of Systems Thinking: Bridging the "Two Cultures" of Engineering

Within the past 20 years, the aerospace industry has seen a shift in the way projects are managed and organized. Changes include the bringing together of different engineering disciplines earlier in the development cycle to avoid problems later in systems integration and operation. Bringing the disciplines together earlier in design has placed an emphasis on teams within engineering, especially multi-disciplinary teams. Yet, despite strides towards cross-functional design, there is still evidence of a gap between designers and analysts. This gap impedes communication and understanding and is therefore a barrier to improving both the ways in which systems are engineered, as well as the systems themselves.

Former NASA administrator Michael Griffin likened the communication gap within engineering to the cultural divide between the sciences and humanities [59]. One side, engineering science, is rooted in analysis, numerical methods, and the pursuit of objectivity. Engineering science relies on a convergent thought process: using the scientific process or similar to find a single correct answer. The other side, engineering design, is rooted in experience, creativity, intuition, and in using science and technology in novel ways to find multiple solutions to a problem. Engineering designers are encouraged to use divergent and creative thought processes to find as many potential solutions as possible [149]. Best designs are then selected on the basis of satisfying sets of requirements, not by natural laws. Engineering is the skillful combination of science and design. However, current industry emphasis is on the science side of engineering and underemphasizes the role of creativity and imagination. Balance may be achieved through the application of systems engineering and systems thinking [59]. Systems thinkers are able to engage in both convergent and divergent thinking, thus bridging the gap between engineering science and design [45, 149] and facilitating a more thorough exploration of the design space and therefore more innovative design solutions.

Within academia, attempts to close the engineering science-design gap and cultivate systems thinking skills have been addressed through industry-academia partnerships and initiatives such as **C**onceive, **D**esign, **I**mplement and **O**perate (CDIO) [24], which have sought to bring an awareness of the entire engineering lifecycle back to engineering education. However these initiatives alone are insufficient [65], and more research is necessary to understand systems thinking, not just at the individual level, but also at the team and organizational level [35]. Within industry training, job rotation, and continued employee education are used to promote systems thinking skill development [35] and to address the industry need for more systems thinking within the aerospace community [59, 65, 24, 70, 87, 98, 105, 118].

As a necessary skill for senior systems engineers, systems thinking is a recognized mode of thinking that facilitates identification and understanding of the technical and social interdependencies and feedback dynamics within a system [35]. Systems thinking is credited with producing better process, more effectively coping with complexity, aiding in identifying interfaces, and the efficient allocation of resources to manage these interfaces and interactions [35]. Systems thinking is a skill that must be learned, developed, and maintained. It is grounded in experience and tacit knowledge. As system complexity increases, a greater fraction of the necessary design knowledge is tacit, and systems thinking becomes more important. For simple components, 85% of the design knowledge is explicit and documented. The remaining 15% is categorized as experiential, or tacit [41]. The knowledge distribution shifts dramatically even for relatively simple systems. Fully 70% of the design knowledge for an automobile throttle body is tacit, as shown in Figure 1-1 [41].

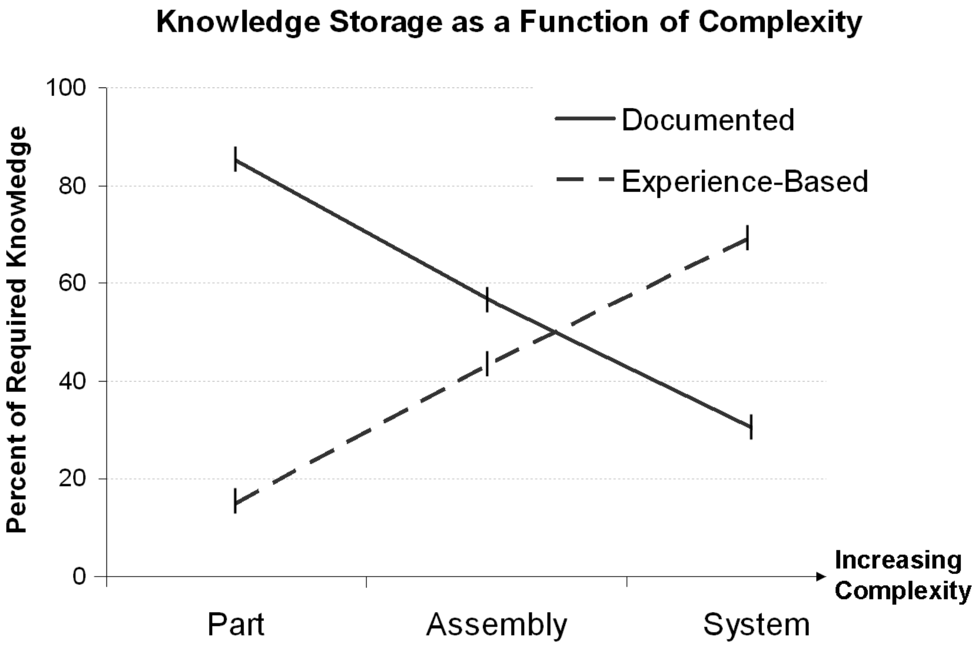


Figure 1-1: Distribution of design knowledge between documentation and experience for an automobile throttle body. Figure adapted from [41].

Systems thinking within teams is a more complex problem because the tacit knowledge required for systems development lies with individuals, each of whom brings her unique set of design experiences and skills to a team, but must be effectively leveraged by the entire team. To address the engineering science-design gap within teams, it is necessary to understand how teams think about problems, allocate resources (mental, financial, and material), and facilitate design. Within engineering teams, it is proposed that synergies and tensions between team norms and process usage form a set of enablers and barriers to an emergent mode of team thinking based on holistic systems perspectives. This construct shall be called *collaborative systems thinking* and is an emergent property of teams, whereby a group of individuals are able through their interactions to appreciate and value inter-disciplinary interactions and interfaces, thus facilitating systems design. Because teams execute design, efficiencies are gained when a team is able to realize and make necessary design decision as opposed to having these decisions facilitated by a small number of systems thinkers who must then overcome the team's inertia to affect change.

1.1.2 Anticipating a Future Shortage of Systems Thinking

Good judgment is usually the result of experience. And experience is frequently the result of bad judgment. But to learn from the experience of others requires those who have the experience to share the knowledge with those who follow.

–Barry LePatner as quoted in **To Engineer is Human**

Like most engineering fields, the aerospace industry in graying: more than 60% of scientists and engineers in the United States are over the age of 45 [12]; the average age of an engineer at NASA is 49 [83]; and within the aerospace industry, 25% of the workforce will be eligible for retirement in the next five years [20]. As these workers retire invaluable tacit knowledge regarding the design of aerospace systems, in the form of systems thinking skills, is lost. Figure 1-2 shows how much older the aerospace workforce is relative to the overall US workforce.

Because experience is a necessary contributor to systems thinking development, it is a great loss to lose so many of the industry's experienced workers within a short timeframe. The loss of experienced workers, however, is made even worse as few opportunities to gain necessary design and implementation experience are presented to today's young engineers.

Data show a reduction in the number of military aircraft program starts from 50 program starts in the 1950's to only three program starts in the 1990's as shown in Figure 1-3(a). This pattern is repeated in commercial jetliners, manned space flight, and planetary probes. For example, commercial jetliner program deliveries peaked

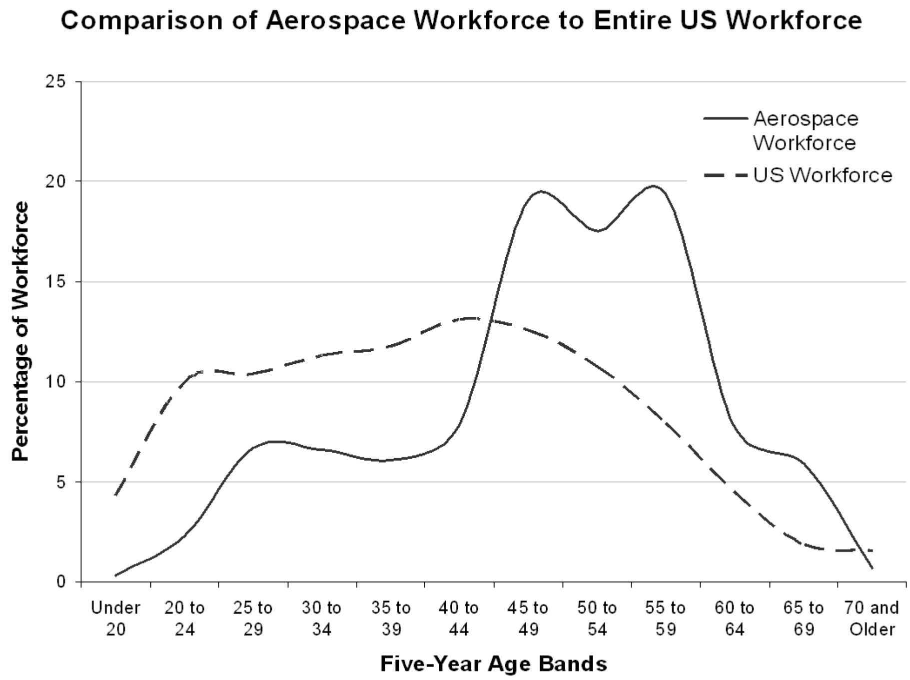
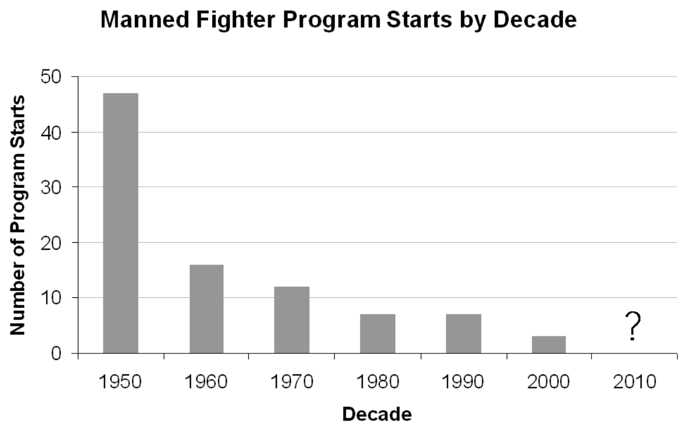


Figure 1-2: The aerospace workforce is older than the overall US workforce. Figure adapted from [20].

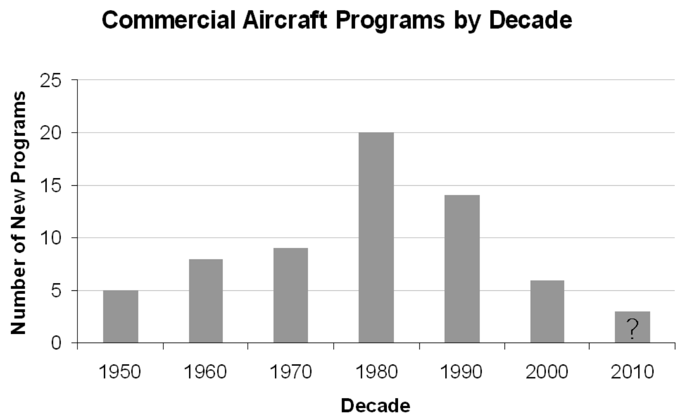
in the 1980's with 20 new and derivative airframe designs delivered, compared to the six airframe designs and derivatives that are expected in the first decade of the 21st century, as shown in Figure 1-3(b) [4, 5]. Figure 1-3(c) shows the pattern repeated in human space flight, with a dramatic reduction in the number of human space flight programs since the 1960's [107].

The trends illustrated above imply that an engineer graduating today can expect her career to span just one military aircraft program, one human spaceflight program and only a handful of commercial aircraft programs. While these trends testify to the durability of past designs, it also is a symptom of longer development times, post-cold war budgets and higher fuel costs. The result is engineers are provided with fewer opportunities to develop the experiential knowledge that composes upwards of 70% of the required knowledge for system-level design [41].

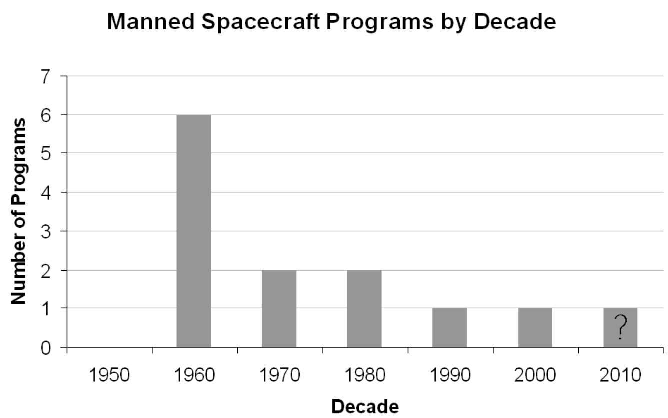
The question then becomes how to encourage the transfer of knowledge eluded to in the LePatner quote above: How do engineers compensate for reduced program



(a) Military aircraft starts have slowed from a high of nearly 50 program starts in the 1950's [103].



(b) Commercial airframe development peaked in the 1980's and has subsequently dropped by 70% [4, 5].



(c) There are only a small number of human spacecraft development programs today as compared to 40 years ago [107].

Figure 1-3: Across the aerospace industry there are fewer program opportunities for young engineers to gain systems-level experience.

experience by learning from the the experience and mistakes of others? Two natural solutions arise from this quandary: 1) place engineers in teams where individuals can leverage each other's experience and 2) codify experience-based knowledge into standard process.

By nature of the size and complexity of aerospace systems, team-based engineering has been a de facto norm since the early 1990's when integrated product teams became popular. Teams offer an opportunity to have each detail and decision reviewed by many eyes, thus bringing to bear multiple sets of knowledge and experience. For this reason, teams are demonstrably better than individuals at making safety-critical decisions [125]. Through interacting, team members are able to develop pointers to knowledge held by other team members. This is called transactive memory [151] and enables teams to develop informal webs of knowledge. However, teams are not without faults and team dynamics and culture can lead to groupthink or other forms of dysfunction. It is therefore of value to identify which team traits (e.g. culture and demographics) promote the exchange of tacit knowledge and therefore enable teams to engage in team, or collaborative, systems thinking.

Standardized process offers an opportunity to codify best practices and facilitate effective coordination among individuals and groups working on a complex problem. As systems engineering practices have matured, standards and frameworks have developed to help structure and evaluate a given organization's systems engineering practices. These standards can be as simple as specifying what information should be presented at a gate review (e.g. Mil Standard 1521B) or as complex as specifying the steps and necessary interactions during the design process (e.g. EIA 632). The emphasis on standard process is also driven by contract requirements. The Air Force estimates greater than 35% of program cost growth and schedule slips are caused by failures to follow systems engineering practices and principles [87]. Many aerospace and defense contracts now require some minimal level of process maturity in an attempt to reverse decades of cost overruns and schedule slips. One such process capability maturity index is the Software Engineering Institute's Capability Maturity Model Integration: CMMI®. However, standard process is best applied to routine tasks and many aerospace programs are novel concepts dealing with problems and technologies without precedent. The art to process is determining when to standardize and when to innovate. By better understanding how process is used to promote systems thinking, process can then be better designed with that goal in mind.

1.2 Research Questions and Objectives

As motivated above, focusing on teams offers a new way to explore and understand systems thinking. Because teams are comparatively stable units within programs, an investment in a systems thinking team should have longer lasting benefits than a transient systems thinking individual.

1.2.1 Research Objectives

This research began with a simple question: What is the structure and behavior of systems thinking teams within the aerospace industry?

The primary objective of this research is therefore to describe collaborative systems thinking as observed through case studies of aerospace engineering teams and explored further through interviews with aerospace engineers and managers. By combining these field observations with insights from literature, a definition of collaborative systems thinking was developed. An early definition of collaborative systems thinking was used to focus the general inquiry and was refined over the course of research.

The second objective is to identify heuristics for collaborative systems thinking. While still descriptive tools, the heuristics provide guidance to teams seeking to engage in collaborative systems thinking within aerospace teams. These heuristics were derived directly from field observations and validated through a set of interviews with aerospace engineers.

The third objective is to put together a theory explaining the influence of team traits (e.g. demographics and culture) and process usage in enabling collaborative systems thinking. Whereas heuristics are tied to specific contexts, a descriptive theory generalizes across observed contexts to provide some explanation for the role of team traits and process on a team's collaborative systems thinking abilities.

To summarize, this is the first known research to explicitly look at engineering team systems thinking. This research builds upon past work on engineering systems thinking and draws insights from a wide body of literature. This research also varies from the majority of engineering team research because of its use of practicing engineers. Much engineering team literature relies upon student teams for data despite some concerns over the applicability of student-derived results to professional contexts.

1.2.2 Research Questions

As discussed above, this research is driven by one central question:

How do teams engage in systems thinking and what traits are common to these systems thinking teams?

To guide this exploration, three secondary questions are also considered.

1. What is collaborative systems thinking and how does it differ from individual systems thinking?

2. What are the empirically generalized (i.e. commonly observed) traits of systems thinking teams within the context of the aerospace industry?

3. What observed mechanisms best predict collaborative systems thinking?

A set of quantitative and qualitative approaches were used to address these questions. The resulting theory is validated empirically via a small number of predictive case studies.

1.3 Unique Relevance to Aerospace

This research belongs in an aerospace setting for two reasons: 1) aerospace engineers are a self selecting and unique subset of the population and 2) the most fruitful areas for research are those that cross traditional discipline boundaries.

1.3.1 Aerospace Engineers as a Unique Population

While other engineering fields face similar workforce issues, aerospace engineers are a unique group as defined by their behavioral preferences. The Myers-Briggs Type Indicator is an instrument for measuring behavioral preferences [29]. Databases of personality types are maintained from which characteristics of professions may be deduced. For instance, while 30% of the general population and 47% of the greater engineering population prefer “intuitive perception” behaviors, fully two-thirds of aerospace engineers exhibit this behavioral preference. Characteristics of “intuitive perceivers” include the tendency to think in abstractions and to see the ‘big picture’ [112]. Because collaborative systems thinking is likely dependent on the thinking preferences of the individuals within the team, it is important to note that aerospace engineers have different thinking and personality tendencies than other engineering disciplines. To further emphasize the uniqueness of aerospace engineers, only one percent of the general population are Myers-Briggs type INTJ (Introvert-iNtuitive-Thinking-Judging) [74]; about 3% of civil engineers are INTJ [141]; and 20% of aerospace engineers have the INTJ personality type [141].

The INTJ preferences for complexity, following sensible rules, and focusing on the “what can be” rather than “what is” [74, 112] show in how aerospace engineers work (e.g. in inventing new tools, rules and systems for manned space flight). However, the INTJ type also is characterized by a desire to explore new ways of completing a task and a resistance to following past procedures [29]. These seemingly contradictory preferences may explain why engineers exhibit resistance to the use of standard process, which is emphasized throughout the industry. NASA emphasizes systems engineering through its handbook [129] and through initiatives at its research centers to continuously improve systems engineering practices [70]. The US Department of Defense is striving to improve systems engineering practices across its purview [87, 105]. Industry too is looking toward developing better systems engineering practices and more senior systems engineers [35, 65, 118]. By understanding the specific relationships between aerospace engineers and process usage, processes can then be tailored to complement their thinking preferences.

1.3.2 Innovation Occurs at Intersections

While the majority of aerospace research will and should continue within the traditional analytic fields, there is much to be learned by looking at the intersection of aerospace-specific knowledge and other disciplines. These innovations are originating in finance, psychology, cognitive science, management, and political science [37, 45, 49, 61, 89, 112, 139, 141].

The results are visible in the inclusion of real options to generate more flexible designs and the use of cognitive sciences and human factors analysis to improve both design practices and human-system interactions. From management and psychology literature comes knowledge on how teams interact, patterns of behavior, and team roles [16, 61]. From psychology and cognitive science, lessons on non-verbal thinking inform how engineers construct shared conceptualizations of a system [45, 49]. From political science and economics engineers can learn to leverage ambiguity in the decision making and consensus building processes [37, 139].

In addition to learning from the theory and literature of other disciplines, there is value in adapting their research methods as well. The strength of combining qualitative and quantitative research methods is that a greater richness of data can be collected and analyzed. In addition, the data collected are grounded in practice and are therefore of immediate value and applicability to industry. To use a systems analogy, leveraging social research methods allows for viewing the engineering team as the system. By looking for ways to understand how the system works and ways to affect positive change within the system, these methods bring a human factors approach to engineering design. Such research focuses on the social problems inherent in engineering and the relationship between social and technical problems, the skills that enable design, and the ways in which engineers think and interact.

1.4 Thesis Outline

The following five chapters, as shown in Table 1.1, outline the relevant literature, the research methodology utilized, and results, contributions, and conclusions. Chapter 2 outlines past similar research and other pertinent inputs, defines the four critical research constructs, and introduces two frameworks used to develop research tools. The research methods used are discussed in Chapter 3. Particular attention is paid to the concept of grounded theory methods and the use of both qualitative and quantitative data in a series of interviews and case studies. The second half of Chapter 3 outlines the actual research instruments used in said interviews and case studies. The first part of Chapter 4 presents examples of data analysis from each stage of research. The second part of Chapter 4 synthesizes the results of data analysis to address each research question and objective, as introduced in Chapter 1. Chapter 5 is a brief chapter highlighting the results of a set of validation case studies. Finally, contributions to practice, implications for industry and academia, and directions for future work are presented in Chapter 6.

Table 1.1: Thesis Outline

Chapter	Content
Chapter 1: Introduction	Introduce Research Questions and Objectives
Chapter 2: Literature Review	Survey of Related Literature
	Introduce Important Research Constructs
	Proposed Literature Framework
Chapter 3: Research Methods	Introduction to Grounded Theory Methodology
	Discussion of Quantitative and Qualitative Methods
	Outline of Research Tools and Development
Chapter 4: Analysis and Results	Examples of Data Analysis
	Answers to Research Questions
	Address Additional Research Objectives
Chapter 5: Validation	Results of Validation Activity
Chapter 6: Conclusions	Summary of Contributions to Practice
	Implications of Research for Industry and Academia
	Future Work

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Chapter 2

Literature Review

Aeroplanes are not designed by science, but by art in spite of some pretence and humbug to the contrary. I do not mean to suggest that engineering can do without science, on the contrary, it stands on scientific foundations, but there is a big gap between scientific research and the engineering product which has to be bridged by the art of the engineer.

–British Engineer to the Royal Aeronautical Society, 1922 [148]

2.1 Background

Systems engineering was developed by the aerospace industry in response to the growing complexity of its products [66, 72]. Systems engineering provides a link between the science and art of engineering [59] and is therefore an enabler of systems thinking. The following is a brief discussion of the history of engineering, the origins of the 'two cultures of engineering,' and the subsequent development of systems engineering.

2.1.1 A Brief History of the Engineering of Systems

The foundations of modern engineering were laid over thousands of years by the Greek mathematicians and philosophers and Roman architects. These early engineers wrote about their engineering success and failures, developed heuristics for design, and attempted theories to explain why their machines did or did not work. Figure 2-1 is a graphical counterpart to the following discussion of engineering history.

The ancient Greeks were philosophers. They developed the foundations for democracy, geometry, and physics [102]. A practical people, the Greeks sought to apply their scientific knowledge [76] in the pursuit of architecture (e.g. the Parthenon) and war machines (e.g. the Helepolis). Many of the well-known Greek engineers were trained as philosophers or mathematicians (e.g. Aristotle, Archimedes and Hero of Alexandria). Among their contributions to engineering are the steam engine, the scientific method, and the Archimedes screw.

The Romans were the heirs-apparent to the Greek tradition, but their approach to engineering was markedly different. The Romans were developers rather than innovators in their own right [76]. Their greatest contributions were in water engineering and building. Vitruvius, an engineering architect of the Roman period, wrote what are considered the first books on engineering. In these texts are early case studies of design failures [114]. The Romans produced such engineering marvels as the Roman baths, the first vaulted ceilings, and the Pantheon–still the largest un-reinforced concrete dome.

After the fall of the Roman Empire, most of Europe fell into the Dark Ages, or Middle Ages. During this time, the torch of scientific inquiry was passed to the eastern expanse of the former Roman Empire. This is the height of the Byzantine empire and the Islamic Golden Age. During this period, there was a separation of cultures. Western civilization remained under the influence of Roman ideals of engineering. Their aims were practical and focused on building [76]. It is during this time that many of Europe's great cathedrals were built. Roman knowledge of vaults, arches, and domes was utilized to create these soaring stone structures. At the same time, Eastern civilization was influenced by Greek ideals on science and technology [76]. During this time Arabic numbers replaced Roman numerals and prominent Arab artist/engineers published texts on mechanical devices.

However, it was not until the 14^{th} century that engineering as known today was developed. Engineering development was spurred in large part by the use of mechanical

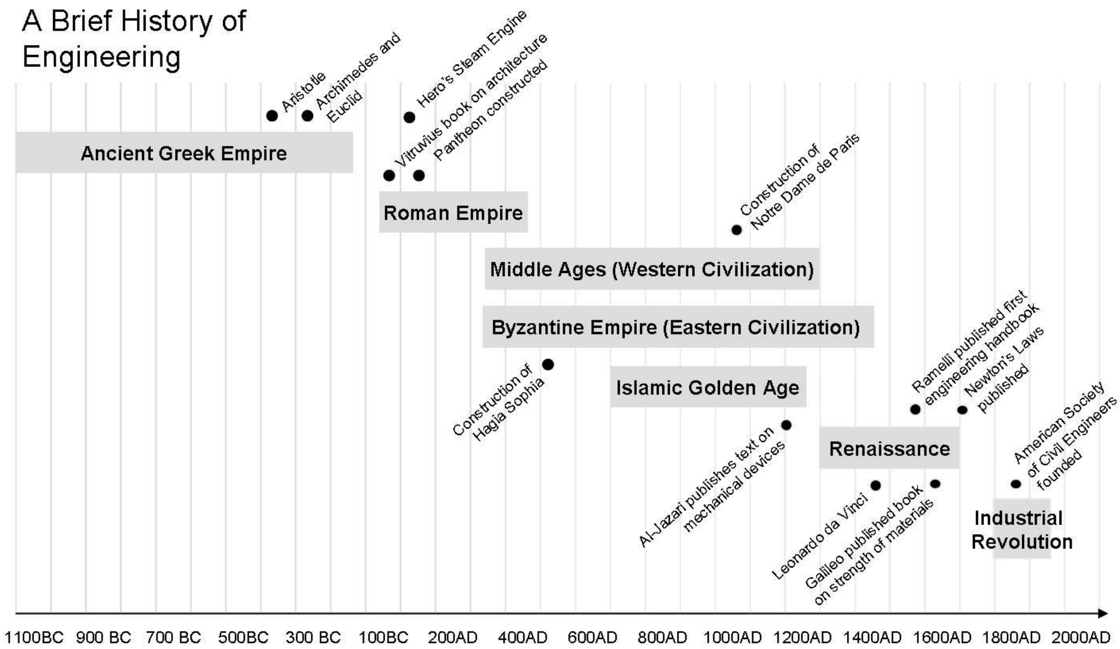
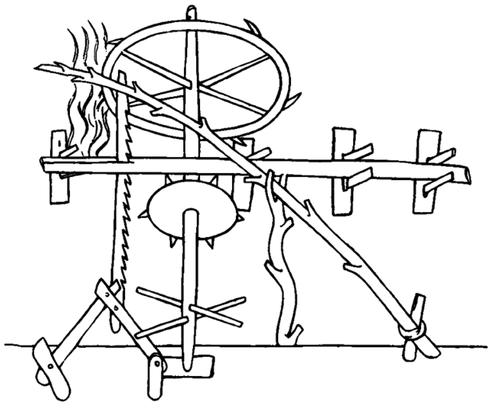


Figure 2-1: Highlights in the development of engineering.

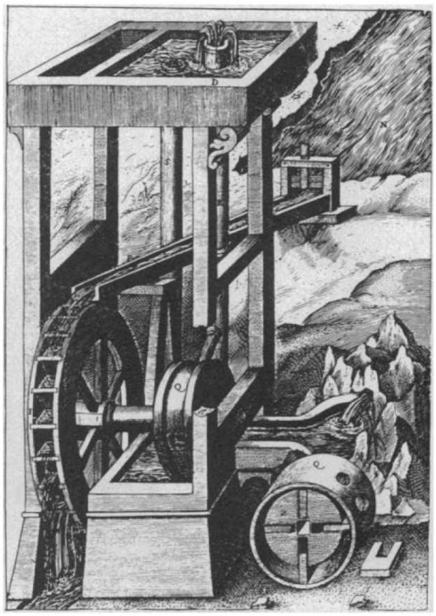
power in place of human (mostly slave) power for the implementation of engineering feats [76] and by the intersection of cultures, science, math, and the practical arts. At this time, transmission of knowledge between the East and West created a fusion of knowledge that launched the Renaissance, a period of great innovation in art and engineering [76].

The Renaissance was a perfect storm of influences. Just as Eastern writings reintroduced the West to the Greek writing on science and math, the printing press permitted greater distribution of ideas, and advances in art enabled richer technical communication. In the mid-1400's the invention of perspective drawings enabled engineers to effectively convey three dimensions in a two-dimensional sketch [49], shown in Figure 2-2. Once perspective was included in mechanical drawings, technical information could be more widely shared and improved upon. The sharing of technical information is evidenced by the contemporary appearance of similar drawings, often with modifications and improvements, across large distances [49].

In 1420 Brunelleschi, an Italian artist and architect, designed and built the Dome of Santa Maria del Fiore, using drawings and scale models to guide construction



(a) 13^{th} century sawmill drawing. (From the Smithsonian Institution collection)



(b) 16^{th} century rotary pump drawing by Ramelli. (From the Hagely Museum collection)

Figure 2-2: An example of how the use of perspective enabled more accurate technical drawings.

[53]. In the early 1500's Leonardo da Vinci further perfected the use of perspective with his exploded view drawings, showing how his fanciful creations worked and were constructed. The exploded view enabled even more technical information to be encoded in a drawing. Individual components and their relative position could be conveyed. Figure 2-3 is an excellent example of da Vinci's use of exploded drawings, in this instance showing a weight-driven rachet device. Among da Vinci's engineering legacy are a 720 foot-span bridge design that has been used in modern construction and a codex on the flight of birds [53]. In 1588 Ramelli published what is regarded as the first engineering handbook. Shortly thereafter, Descartes developed the Cartesian coordinate systems and Galileo published the first book with analytic expressions for the strength of materials.

These improvements in drawings enabled contemporary inventors to communicate their ideas to others and for ideas to be subsequently improved upon by others. The Renaissance was a period in which engineering transitioned from an empirical field to

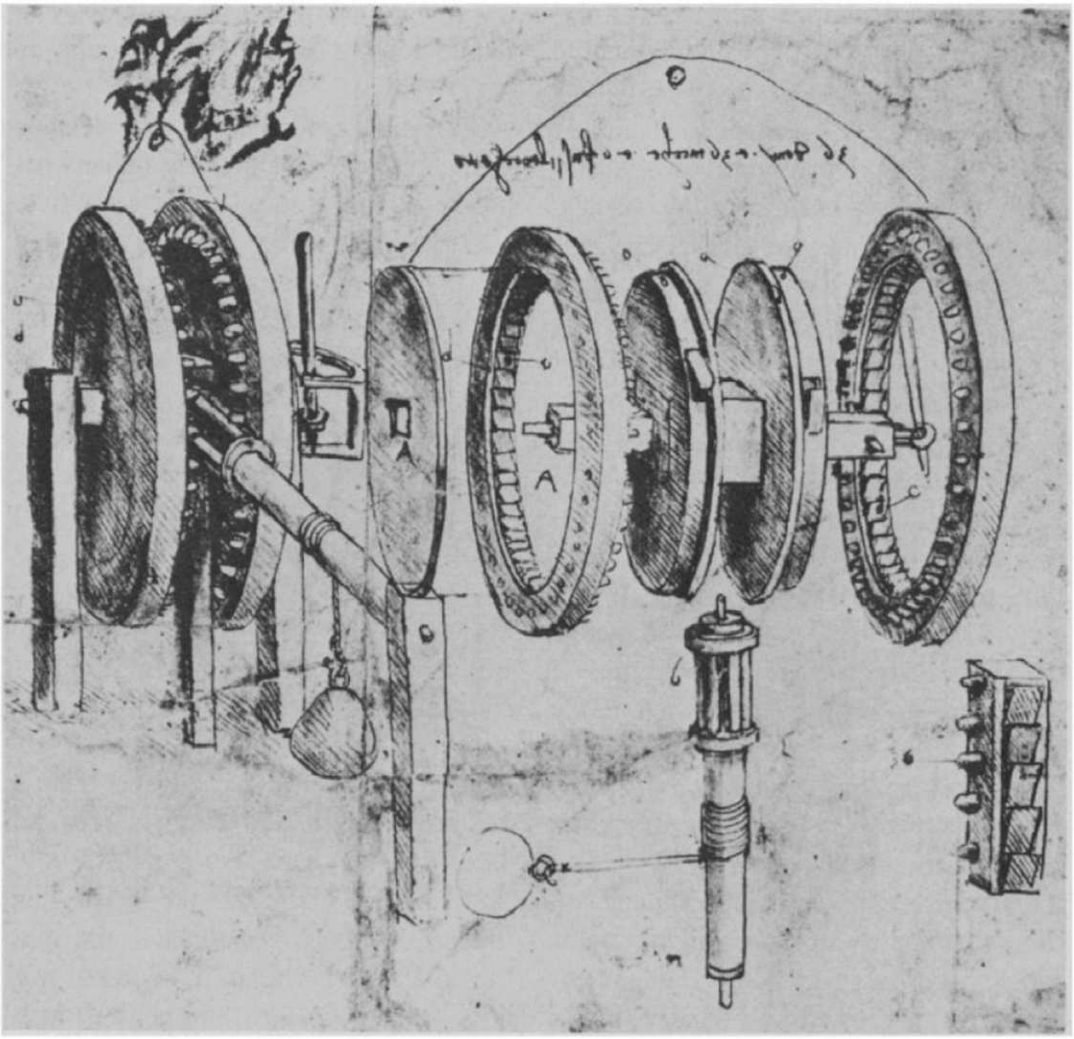


Figure 2-3: An example of da Vinci's use of exploded drawings to convey technical information. (From the University of Delaware Library collection)

a learned and studied field. In the three subsequent centuries, advances in design were complemented by striking advances in mechanics and analysis by the likes of Isaac Newton and Joseph-Louise Lagrange, which laid the foundation for the spectacular engineering accomplishments of the industrial revolution.

Up to this point in history, it is noteworthy that the great engineering accomplishments come from men trained not as technologists or engineers, but as artists, philosophers, and inventors. As engineering entered the Industrial Revolution, this paradigm shifted. During the 19^{th} century, engineers craved greater social standing and differentiation from technicians, mechanics, and skilled craftsmen [15]. While science and math training were already essential components of the engineering toolbox [49], engineers sought to align themselves more tightly with science to capitalize upon it's growing respectability within gentrified society [15]. While the shift in emphasis ensured engineers' professional status, this transition came at the neglect of engineers' social, political, and non-verbal skill sets [15, 49]. Culturally, "hard thinking" has come to be seen as superior to soft skills because of its objectivity and transparency. As a result, most engineering research in academia focuses on furthering analytic tools and capabilities: the *science* of engineering [49]. Among the recent advances in engineering analysis are computational fluid dynamics, finite element models for structural analysis, optimization algorithms and complex system-level models. Most engineering research addresses technical problems with technical solutions.

However, much of design is ill suited to verbal and mathematical expression [49]. Design, once taught through apprenticeships, has become only a small portion of today's engineering curricula in part because much of design is not easily reduced to words, but is better represented by pictures and visual images: art, not science [49]. From this change in engineering education–this shift from emphasizing perception, mind experiments, and non-verbal communication as part of engineering to an emphasis on objectivity and scientific analysis–come the two cultures of engineering to which Griffin refers [59]. For centuries, engineering was both an art and science, and only in the past 200 years has science trumped the role of art and creativity. Advances in analysis have allowed for systems so complex that engineering's ability to manage the design process is strained, resulting in miscommunication, team dynamics issues, and new and unanticipated modes of systems failure, often brought about by a failure to consider the social aspects of a system. This is in part because many of the intellectual components of technology are nonscientific and nonliterary [49]. Only a small fraction of engineering decisions are based on analytic calculations, the rest requiring consideration of social, political, and environmental issues that are difficult to quantify [15].

Following the historical pattern that great engineering occurs at times when art, science, and design merge, the next generation of engineers must bridge the science-design gap in order to successfully address the difficult problems facing today's engineers [15, 59].

2.1.2 The Development of Systems Engineering

Systems engineering is a set of engineering practices used to define a system configuration to meet an operational need: it is an evolutionary process that transforms abstract notions into defined functions and forms [21]. Former NASA Administrator Michael Griffin refers to systems engineering as the bridge between engineering science and design [59], allowing for the use of creativity and intuition in the engineering process.

First developed by scientists and engineers, systems engineering grew out of the coordination of large-scale technology development projects [73]. Early practices were developed by scientists and engineers as a means to coordinate efforts on large projects. These practices borrowed from those already in use at Bell Labs and Western Electric, which defined formal specifications and structured relationships between engineers and manufacturers [73]. Developed during World War II and championed by the likes of Bernard Schriever, systems engineering was adopted by the military [66, 72]. Previously, military aircraft were purchased and then retrofitted with weapons and other modifications. It was Bernard Schriever who first thought to design 'entire systems' [72]. This required close coordination between the military and industry and exposed the need for a process to coordinate and standardize efforts. Schriever found the solution in systems engineering, the benefits of which were documented and recognized in the 1949 Ridenour Report [73]. The development of systems engineering coincided with a period of dramatically increasing complexity. The number of parts in a gas turbine engine increased 120% between 1946 and 1957, while the engineering hours required to design a fighter aircraft increased by a factor of 82 between 1940 and 1955 (from 17,000 hours to 1.4 million hours [72]). Systems engineering offered a way to manage this complexity at a time when the increased knowledge required for systems design was forcing a shift to multidisciplinary teams, thus creating more social complexity in the design environment. This balance was referred to by Simon Ramo as a race of "systems engineering versus the increasing complexity of technological civilization" [72].

Schriever and his group adapted and improved upon systems engineering practices throughout the intercontinental ballistic missile (ICBM) program, although it wasn't until 1956 that the Air Force Western Development Division and contractor Ramo-Woolridge came to an agreement about what systems engineering actually entailed [73]. Despite this, the first courses in systems engineering were taught at MIT in 1950 and by 1962, several prominent colleges were offering graduate degrees in the discipline. In 1957, the government mandated cost estimation as part of systems engineering, establishing the practice as part of the entire product lifecycle [73], and the first text on systems engineering was published by Harry Goode and Robert Machol [72].

By the 1960's, there was a widespread consensus that design was poorly understood and had become a bottleneck within system development, and research to identify systematic procedures, or the first standard processes, began [19]. However, adoption of systems engineering practices remained scattered at best. Wernher von Braun and the Marshall Space Flight Center (MSFC) did not embrace systems engineering methods until 1968 [73]. This close-knit group had worked together for over 30 years and understood not only the technical component of their task, but the social dynamics of their group. This made formal coordination unnecessary until contractors were brought in to assist on the Saturn V project. At this point, von

Braun recognized the need for formal planning, and systems engineering practices were integrated [73].

In 1991 the International Council on Systems Engineering (INCOSE) was founded to advance the practice and knowledge of systems engineering. In 1997 and with interest from the Office of the Under Secretary of Defense, one of the largest projects to standardize and assess systems engineering process maturity was begun: the Capability Maturity Model Integrated (CMMI®) Project [23]. Even after the CMMI® maturity model became the standard for measuring systems engineering capability maturity, one study estimated greater than 35% of cost growth and schedule slips in the aerospace industry were due to failure to follow established systems engineering practices [87] and the National Defense Industries Association cites an industry wide failure to recognize the importance of systems engineering or use consistent definitions and approaches [105].

Systems engineering is one of the most significant advancements in modern day aerospace design [98]. Engineering science and design are not ends in of themselves, but powerful components of the engineering process that are integrated by systems engineering practices [98]. The framework provided by systems engineering focuses engineering effort: emphasizing creativity and iteration early in design and structured analysis and decision making during detail design. This 'normative' design process runs counter to the reactive tendency of engineers, but has been shown to better handle complexity in design [136].

2.2 Insights from the Literature

[A]irplane design, in common with most modern engineering practice, must be fundamentally viewed as a social activity wherein, technology, processes and people must be treated as a unified whole – a true "systems perspective".

–John McMasters and Russ Cummings

Engineering is a socio-technical activity [63]. While commonly viewed as a technical activity, the social component of engineering is an important contributor to how decisions are made, new ideas accepted, and ultimately design is executed. This section focuses on insights from the literature, many of which come from the intersection of disciplines, and a framework for structuring further inquiry.

2.2.1 Contributing Factors to Engineering Team Performance

Team performance is linked to many variables. There is a positive relationship between the average abilities of a team's members and overall team performance [157]. Perhaps more important is that a team has members with differing and complementary skills and knowledge and a strategy to capitalize on those skills and knowledge [86]. Teams also require support from the surrounding environment in the form of clear delineations of authority, coaching, and clear and consequential goals [61]. Finally, teams must be motivated to perform. Fundamentally, individuals are motivated by achievement and conformance [64]. In a team setting some level of conformance motivation is required to get members to move in the same direction. However, engineering culture is typified by achievement motivation, thus identifying a potential cultural barrier to effective engineering teams [84].

Tools and processes also contribute to team performance. Teams are supported in their work by a variety of information technologies. These enable greater access to information necessary to explore the solution space and make design decisions [91]. The reduction in communication costs has enabled teams to more easily exchange information and also enabled team membership to change more frequently [91]. Flexible team membership has become one way in which knowledge is transferred between teams [85]. While this membership transfer helps to spread knowledge between teams, for any given team these comings and goings can negatively impact a team's transactive memory, or shared pool of knowledge and references to with whom that knowledge resides [151].

Some types of team knowledge can be standardized across teams. Often this knowledge takes the form of processes that list expectations or specify in what order steps occur. Such standards reduce the amount of team-specific knowledge and allow individuals to quickly and efficiently transition between teams without the need to learn new design practices. The movement of individuals across team boundaries also allows for the sharing and testing of team-specific standards, which helps to innovate and justify the existence of standards [61]. As such, standards facilitate individuals working across multiple teams, and individuals working across multiple teams facilitate identifying and sharing the best team practices.

Engineering Cultural Influences

There are many stereotypes about engineers, images that engineers themselves subscribe to. These typologies form the basis for engineering culture, thus influencing ways in which engineers interact with one another and affecting team performace. The three main components of engineering culture are that it is technology centered, that engineers equate success with organizational power, and that engineers have self-centered tendencies [97]. The result is a group who is typified by non-communicative members who prefer to work alone and yet recognize the need to work in teams and communicate [84].

The five engineering archetypes are the Maverick, the Expert, the Macho, the Technophile and the Non-Communicator [84]. These archetypes are discussed below.

The Maverick The maverick typifies the engineer's desire for autonomy and his belief in the importance of the lone engineer. These beliefs defend late nights at work, a preference for individual work over team work, and an ethic that relies on the individual, making it at times difficult to rely on others' results and contributions.

The Expert The expert typifies Griffin's engineering science culture. This archetype is based on the belief that 'real engineering' requires a rigorous theoretical background and is expressed in the enjoyment engineers derive from talking about their work in scientific terms. The pitfall of the expert is an inability to communicate with non-engineers, an inability to admit mistakes and a tendency to engage in overt displays of their expertise. The "expert" archetype explains the chain of events that led to the fateful decision to launch the Challenger in January 1986 [84]. Because the aerospace culture is comprised of many specialists [17], the expert archetype explains why multi-disciplinary work is difficult in the aerospace engineering culture. This tendency towards specializations makes the transfer of tacit knowledge across boundaries (cultural or functional) more difficult [156].

The Macho The macho archetype is linked to the "Right Stuff." Macho engineers find strength in masculine ideals and believe there is only one "right" answer. Tendencies towards dominance, aggression, and a constant need for respect typify the macho and are linked to the evaluation of one's technical competency. Macho's are achievement motivated, competitive, but also arrogant. Teamwork is a large hurdle for the macho [84]. Because the aerospace culture is linked to the military and defense [115], the macho best typifies the aerospace engineering culture.

The Technophile The technophile experiences an inherent conflict between the craft nature of engineering and the academic rigor of engineering. Technophiles enjoy engineering in part because of the prestige that comes from working with technology. In fact, their love for technology drives technophiles to work late nights and to bring their work home with them, habits not widely accepted in most professions [84].

The Non-Communicator The non-communicator does not value communication. This archetype is closely related to the technophile, and as such, time spent communicating is seen as negative because it is time away from technology. Because non-communicators spend so much time with technology, they tend to perceive human interaction as systematic and routine, much like the natural laws that govern technology [84]. This archetype is linked to the prototypical nerd as portrayed in movies and on television.

In his study of engineering culture, Paul Leonardi observed that while engineers recognize process as an important part of being an engineer, they believe these rules should be derived by the engineers, thus justifying their habitual tendency to deviate from standard process [84]. This matches with the types of beliefs and behaviors suggested by the predominate Myers-Briggs personality type within aerospace engineering: Introverted-iNuitive-Thinking-Judging. Additionally, Leonardi found that engineers are habitual procrastinators, tend to be achievement motivated, and derive satisfaction not from the process, but from the final product and whether the "right answer" was found [84]. Yet, engineers state preferences for completing work in advance, are often motivated by fear of failure, express a desire for ownership of their results and recognition for their accomplishments [84], and state a preference to work in an environment with moderate coordination [111].

In a world of increasing complexity, teamwork and standard process are essentially mandated to cope with complexity. These archetypes suggest common beliefs and behaviors among engineers that are inconsistent with teamwork. For example, typical engineering stereotypes emphasize working alone, working long hours, and promote a sense of competition over finding the "right" answer. While much anecdotal evidence exists to support these engineering cultural typologies, the fact is that many programs exhibit positive examples of teamwork and program success. Therefore these typologies provide caricatures of a subset of perceived and self-identified engineering behaviors. In actuality, many engineers embrace teamwork, willingly share data, and recognize the importance of technical and social skills.

Examples of Engineering Team Failures

It has been said that more is learned through failure than success because it is easier to identify reasons for failure. However the reasons for failure are often treated as closely-held secrets; causes for embarrassment; liabilities. For these reasons, the best analyses of aerospace failures come from NASA accident investigation reports. Being a publicly funded entity with a congressional mandate to report out its failures, NASA reports provide detailed information on the team and organizational dynamics surrounding its three deadly system failures.

The Apollo 1 accident was technically caused by a spark that ignited a fire in a pure oxygen environment. The fire was fueled by flammable materials within the capsule and efforts to extinguish the fire were stymied by an inward opening capsule door [9]. From a design standpoint, the failure was caused by a failure to imagine what *could* happen to the system. A pure oxygen environment and inward opening hatch were used on both Mercury and Gemini. Because these programs succeeded, fundamental assumptions in their design were not questioned [9]. Operationally, emergency test procedures were not in place. Emergency fire, rescue, and medical teams were not present at the test. Additionally, NASA had 'go-fever' and was willing to take greater risks in order to achieve its goal. This meant there was a cultural pressure to *not* ask important systems level questions if the answers to those questions might further delay the program. A result of the accident was the creation of the Aerospace Safety Advisory Panel to oversee human spaceflight systems procedures and management policies [30].

In the case of the Challenger accident, the technical reason for failure was a leak in the o-ring of the solid rocket booster. However, the Rogers Commission Report cited the original o-ring design process and the NASA launch decision making process as contributing factors. The shuttle o-ring design is based on the Titan III. This successful and reliable design was 'improved upon' by the addition of a second seal. This design change gave a false sense of improved reliability [114]. The Rogers Commission Report cited a decision making culture at Marshall that sought to "contain potentially serious problems...rather than communicate them forward." This meant that initial Thiokol concerns about launching were not conveyed to the final decision makers [116], thus inhibiting a decision made on complete systems information. Another finding faulted the NASA team as a whole for failing to consider the role of icing on crew safety. NASA put the burden of proof on showing that conditions were unsafe, rather than safe. Despite hazardously icy crew evacuation slide-wire baskets, this higher-level systems concern was ignored in favor of a go-for-launch decision [116]. Again, a culture of 'go-fever' contributed to this system failure. Strong pressure to launch enabled groupthink that led to a go-for-launch decision.

Columbia is the most recent of the NASA accidents and had theoretically benefited from the recommendations of previous accident reports. Yet, the Columbia Accident Report cites a continued trend to underemphasize safety and risk management as contributing to the Columbia accident [30]. Other contributing factors cited in the report include 1970's design practices and a failure to investigate both why foam separated from the main tank and any possible implications of foam impacts [30]. The 1970's design procedures depended on relative functional isolation with late-stage design integration. As a result, issues in the main tank design were not identified during design. Previous shuttle flights (80%) experienced foam loss. Engineers were aware of the situation, but did not ask if this presented a threat to the orbiter. The predominant issue then was not an over-eagerness to launch, but a failure to recognize that a small failure could have such large systems implications.

A common theme across these examples is a myopic tendency to ignore higher-level systems issues or to ignore lessons learned on past systems. This failure to learn from past design paradigms is the reason that human error in anticipating design failure is the single most important factor limiting systems reliability and safety [114]. It is for this reason that systems thinking is important for engineering aerospace systems.

2.2.2 What is Systems Thinking?

Systems thinking is an age old concept. Eastern philosophies emphasize the importance of wholes and the multitude of interconnections that exist in nature. In the modern sense, systems thinking has its roots in the development of systems theory in the 1930's. Systems dynamics, systems science, and systems engineering all lay claim to definitions of systems thinking. The commonalities between these definitions include an emphasis on wholes, system-level issues, and some derived ability to judge and choose between alternatives based on their system-wide impact [1, 7, 70, 127, 133, 142, 149].

Generic definitions of systems thinking vary, defining the skill as the use of one's abilities to apply sound reasoning in a given situation [42], to the application of different types of thinking. Russell Ackoff defines systems thinking as a systemic mode of thinking based on holistic as opposed to reductionistic methods [1]. By his definitions, reductionistic thinking begins by analyzing the parts of a whole, and from the properties of the parts, deriving the properties of the whole [1]. By contrast, holistic thinking begins with the system, and derives the parts from the properties of the whole [1]. Given that systems by their nature are greater than the sum of their parts, this definition elucidates the benefits of applying systems thinking to engineering systems. Another definition of systems thinking emphasizes the role of understanding interactions within complex systems as a departure from linear thinking rooted in simple cause and effect logic [149].

Systems thinking definitions derived from systems dynamics include and build upon the components of the generic definitions, emphasizing the role of holism, interactions, and dynamics. Definitions based in systems dynamics are typified by an emphasis on identifying patterns of behavior and representing these patterns through cause-effect relations [122]. 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" [127]. One such tool is systems thinking diagrams, a method of visualizing system behavior through a series of feedback loops, stocks (accumulations), and flows (actions that influence stocks) [127].

Figure 2-4 shows five different systems thinking definitions and the common themes among them: complexity, interrelationships, context, emergence (or dynamics) and wholes.

Systems Thinking within Engineering

While systems thinking within the engineering community is still concerned with the system as a whole and elucidating patterns of behavior and interactions, engineers' goals are primarily to manipulate technology, manage systems with ill-understood cause and effect relationships and to apply systems thinking before the system is realized, thus limiting their ability to learn through observing the system. As such,

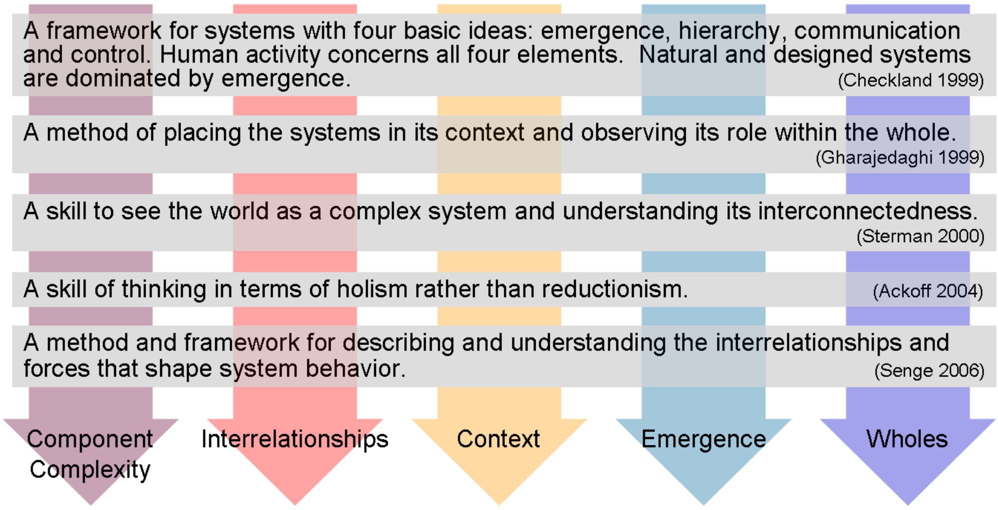


Figure 2-4: Common themes across systems thinking definitions. [1, 28, 54, 127, 138]

the engineering definitions of systems thinking place a greater role on interactions and interfaces because these contribute to emergence.[1]

Dr. Moti Frank was one of the first people to identify systems thinking within engineering as a concept distinct from systems thinking within systems science. Through examination of literature and interviews with engineers, Frank derived 30 laws of engineering systems thinking [52]. These laws, tailored to the challenges, tools and context of engineering, include awareness of the implication of breaking a problem or systems into smaller parts, an emphasis on the interactions between systems elements, and specifically mention the role of the designer and operator as critical components of the system. Included in Frank's laws for engineering systems thinking is an acknowledgement that multiple individuals are required to understand an entire system [52]. This statement links the concepts of systems thinking and teams.

A second definition of systems thinking applied to engineering contexts was developed by Dr. Heidi Davidz through a series of interviews with over 200 practicing engineers. Beginning with a baseline definition, Dr. Davidz solicited feedback on what systems thinking meant in practice. The definition that emerged from her research is that systems thinking is "utilizing modal elements to consider the componential,

[1]From this point onward, the term 'systems thinking' refers exclusively to systems thinking as a skill expressed by a single engineer

relational, contextual, and dynamic elements of the system of interest" [35]. In other words, effective engineers use a variety of tools, methods, thinking styles, models and processes to enable consideration of the context, interrelationships, and dynamics of a system and its elements. Further, this research identified a set of enablers and barriers to systems thinking development. Key among these are individual characteristics, experiential learning, and an environment that values systems skills [35]. This research established that there exists consensus on these key enablers of systems thinking development [35].

Traits of Systems Thinking in Practice

In modern engineering, social skills are just as important as technical skills. 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 [15].

The skills and benefits of systems thinking enhance problem solving ability [70]. Traits of systems thinking include the ability to understand dynamic systems behavior and to identify patterns resulting from interactions [122, 142]. The identification of feedback processes, or closed-loop thinking, is used to explain the observed patterns of behavior [122, 142], thus enabling action to influence behavior. The ability to recognize stocks and flows, sometimes referred to as structural thinking, is also a skill of systems thinking [122, 142]. Systems thinkers are also able to identify and understand the impact of time delays between system inputs and reactions, enriching their understanding of feedback loops [122, 142]. Recognizing the limits of assumptions and presence of non-linearities in a system are also crucial to effective systems thinking [142]. Finally, to be an effective systems thinker, one must be familiar with the specific knowledge required by the problem's context and have the ability to leverage both quantitative and qualitative data towards its solution [142].

Influences on Systems Thinking Development

It has been shown that environment affects an individual's perceptions and relationships with the surroundings, thus impacting thinking style [110]. Within a given context, an individual's thinking style can be influenced and modified through interventions [110]. Individual traits, such as personality type, are also thought to influence behavior preferences [147] and therefore affect systems thinking ability [112]. Within the personality-as-influence school of thought, intuitive thinkers are particulary suited as systems thinkers. Intuitive thinkers prefer to work with abstract concepts, exhibit creativity, enjoy complex problems and are considered 'big picture' thinkers [15]. By this model, systems thinking is not a natural mode for engineers, who tend towards rational thinking [149]. Within engineering rational thinking, dominated by analysis and data, has a tendency to overrule intuitive thinking. In reality, both are necessary for systems design [149]. Models, causal loops, interaction matrices, requirement nets and behavioral diagrams are a few of the many tools developed to assist with systems thinking within the context of engineering [64].

2.2.3 Extending Thinking to Team Settings

Thinking is a mental process, defined in large part by its outcomes: the actions and positions that result from thought. According to the Merriam-Webster dictionary, "to think is to form an opinion, or an intention to act." Within an engineering context, thinking is purposeful, reasoned and goal-directed action towards the solving of problems. The elements of thinking in this context are decision making, problem exploration (creativity), judgement of alternatives, and ultimately problem solving [6]. The process begins with an ill-defined problem and uses recalled knowledge (memory) and other inputs towards solving the problems.

Thinking can be a team activity, the result of social interactions through which team members take in information, interpret that information, and recall past information as a group [6]. Because teams have multiple people contributing their knowledge and interpretation of that knowledge, teams are deemed better at making decisions, especially in safety critical situations. However, team skills are more difficult to develop , requiring practice as a team [127].

Team thinking is like having parallel processors: it only works with communication between the processors [100]. Team thinking emerges from the intersection of individual team members' thinking, their behaviors and team processes [31]. The result is greater than the sum of the individual thoughts [31], enabling a team to deliver more value than a group of individuals. Throughout the process of problem solving, teams use communication to stimulate their thinking and handle uncertainty inherent in design. Brainstorming, team norms, and processes enable this communication [6].

While there are no agreed upon measures for team thinking, there is consensus that process and culture are influences [47]. Shared mental models do not represent an effective way to measure team thinking as the strength of team thinking is in the heterogeneity of team member knowledge, and shared (or team) mental models measure the level of shared knowledge [31]. Good measures of team thinking will address its holistic nature, respect unique individual knowledge in deriving collective knowledge, and address the dynamic nature of team knowledge [31].

Design Thinking in Teams

One focus of team 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.

The design process has five basic elements: analysis of the need of problem (exploration of problem space), generating ideas to address this need (the creative process), evaluation of those alternatives (comparison and selection), initial design, and final detailed design [143]. Within engineering, this process is systematic and developed by designers to aid in the design of systems or processes that satisfy an end user's needs within a set of constraints [45].

During the design process, several types of thinking are engaged. Roughly, these thinking types can be categorized as either divergent or convergent. Divergent thinking operates in the concept domain, encapsulating the steps of generation and exploration [45, 136]. Convergent thinking operates in the knowledge domain and consists of comparison and selection [45, 136].

While the creative process requires both divergent thinking to explore the problem space and convergent thinking to act upon that exploration, the majority of engineers express a preference for convergent thinking [44, 136]. 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 [55]. This situation is common in engineering even though purely convergent thinking can lead to lower quality outcomes.

Therefore, effective design thinking includes both convergent and divergent components, enabling the exploration of the problem space and critical analysis of the solutions space [136]. 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 the multiple languages of design [45]. The references to big picture thinking and tolerating uncertainty draw clear parallels between design thinking and systems thinking. Further, design thinking specifically references the ability to think as a team, making it 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.

Normative Design Process as an Enabler of Design Thinking

Research into design theory and thinking follows three paths: normative, empirical and design-as-art [136]. Normative research tends to propose systems methods for engineering design: processes that are based in rational analysis. By contrast, empirical research shows the methods prescribed by normative research are rarely followed in practice, resulting in a rejection of the belief design can be modeled. The design-as-art camp falls somewhere in the middle recognizing designers need flexibility in approach to react to context, but gain efficiencies by borrowing from pre-established procedures [136]. Which of these perspectives works best depends on the problem.

As Einstein said, imagination is more important than knowledge. Consistent with this belief, Einstein advocated for an emphasis on capacity building rather than information gathering [137]. Being creative is, after all, a skill or capacity; a way of thinking rather than a knowledge base. Exploration and concept generation are among the first steps in the design process, and both require divergent thinking and creativity. A creative environment facilitates design by enabling teams to break with previous patterns of thought to explore new regions of the goal space [143]. Yet, engineers often have a "them vs. us" attitude that inhibits their own creative environment [152].

Observations of teams given design problems shed some light on effective patterns and maintaining a creative environment for complex systems design. These teams spent on average two-thirds of their time addressing the content of the design problem and one-third addressing the process by which to address the design task [136]. The most time was spent on analysis, or examining the elements of the design space and their interrelationships. Consequently, very little time was spent generating solutions based upon this analysis. Rather, following human tendencies towards satisficing, some workable solution is quickly passed through analysis, and only after it fails is the goal space further explored [136].

Out of these observations came two natural design processes. The first process most resembles the natural thinking of an engineer. The process relies heavily on convergent thinking, narrowing the design space early by failing to ask questions early, thus maintaining harmony within the team. While the process is quick, it does not handle complexity well because of a rush to evaluate the first design proposed rather than engaging in analysis of the problem [136]. The second process more resembles the processes defined by normative design theory. The second process is more time consuming and requires more team interaction. However, because more time is spent up front on analysis the quality of designs are better, and the process can better deal with complexity [136].

The difference between the two processes is whether the team asks a lot of questions up front. Early questioning, in turn, is most likely in heterogeneous groups with a culture that is receptive to questioning and divergent thinking styles [136]. This example shows the constructs of team thinking, culture, and process usage are tightly intertwined.

2.2.4 Frameworks Supporting Further Inquiry

Two frameworks are provided here; compilations of the above insights from literature. These frameworks are used to focus the research instruments discussed in Chapter 3.

A Framework Linking Culture and Process

Culture is an abstraction used to describe and explain a group's behavior. Three levels of characteristics can be used to describe a group's culture. These are a group's artifacts, its jointly held and vocalized beliefs and values, and the assumptions, subconscious or take-for-granted, that underly the group's behavior [126].

Supplementary to an organization's culture are its structures and procedures, or processes. When these two together act in a consistent manner ambiguity within the organization is reduced, and behavior is more predictable. However, when culture and process are inconsistent, the result is a weakened culture [126]. Within an organization, a strong culture is important because it contributes to motivation, orientation and control of the organization [38]. For example, individuals are motivated by two goals: achievement and conformance [64]. Therefore a culture that stresses achievement may find it more difficult to get engineers to follow strict processes, while a culture that stresses conformance may not be as innovative.

A study of new product development showed that the difference between successful products and those which failed was linked to the "organic" relationships formed on the successful teams [43]. The organic relationships and subsequent changes in communication norms and methods in the successful teams are an example of how culture influenced a team's process and improved its success rate. The teams that maintained traditional defined rules and limited themselves to the organization's established process were less likely to succeed in part because the culture and process did not enable enough transfer of information for the teams to design successful products [43]. Because culture is deeply ingrained in groups, it is easier to change processes than culture [150] and therefore links between culture and process help with identifying leverage points when tailoring process to a given culture.

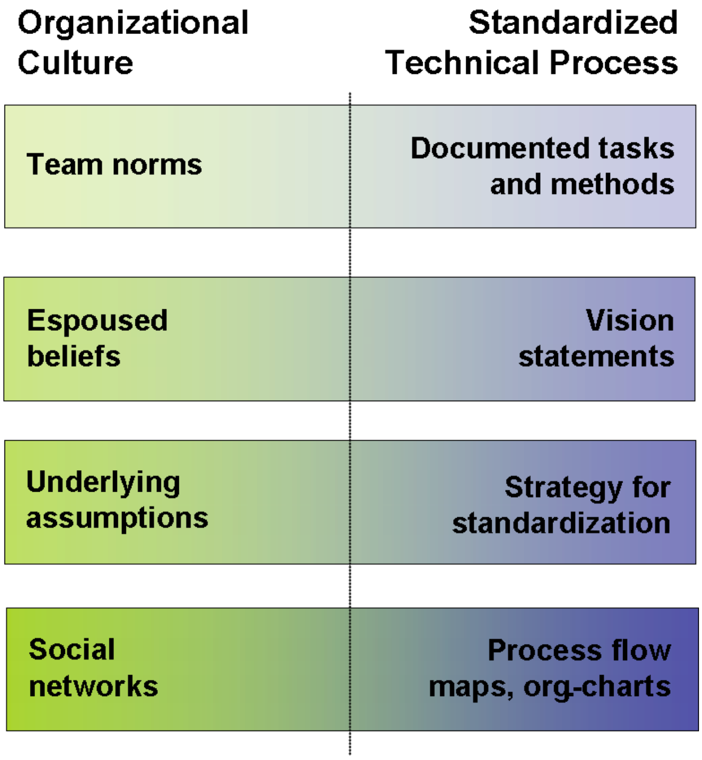


Figure 2-5: Framework linking aspects of culture and process.

Figure 2-5 shows a proposed set of ways in which culture and process are linked. The left column of the figure is based on Schein's framework for cultural characteristics: team norms, espoused beliefs and underlying assumptions. To these three traits social networks have been added with the justification that culture is the result of interactions between people. The right column represents those aspects of process (both the artifacts and strategies) that parallel culture. These relationships between culture and process are described below.

Undocumented team norms vs. Documented tasks and methods Norms, tasks, and methods are all observable behaviors. Team norms are emergent behavioral tendencies of groups, part of their culture. Process-related behaviors are specified top-down via required tasks and recommended methods for completing those tasks. When behaviors on both sides are complementary, it follows that teams should be successful. Likewise, if team norms are acting at odds with the process's tasks and methods, the team will be dysfunctional.

Espoused beliefs vs. Vision statements/strategic goals Espoused beliefs are shared and articulated values and beliefs a team has about its environment, goals, etc. These beliefs develop within a group as a result of shared experiences. Vision statements articulate the goals and beliefs of a group. In this research context, the espoused beliefs of interest are those of the engineering culture and unique team subculture. The vision statement is a product of the organizational culture. When a team is operating with a set of goals and values that conflict with the organization at large, the team is not likely to be effective. This is not to say the team's beliefs must be the same as the organization's, just that they should not conflict with the organizational values.

Underlying assumptions vs. Strategy for standardization The underlying assumptions are difficult to observe, but inform team beliefs and behaviors. Likewise, the reason an organization institutes standard design processes may be multi-faceted and go far beyond the obvious reasons. Partnerships, contract bids, and politics are all reasons why an organization might pursue process standardization. While not inherently poor reasons, if employee stewardship and a genuine desire to improve the product or service are not high among the organization's reasons for standardizing process, the changes are likely to fail to result in meaningful improvements.

Social networks vs. Process flow maps and organizational charts Culture is the result of human interactions. Therefore the web of interconnections and interactions within a group impact culture. Likewise, process flow maps and organizational charts are developed to explain the way people *should* interact both from a social, hierarchical standpoint (org. charts) and in terms of completing a task (process diagrams). As with the previous comparisons, the cultural element is emergent and bottom-up, while the process element is consciously constructed and top-down. Process maps, while useful, cannot contain enough specific information to drive all necessary design interactions. "Short-cutting" a social network enables innovation within both the product and process.

Framework For Exploring Team Traits

In addition to the interactions between culture and process, insights from the literature suggest that team characteristics may influence team-level systems thinking. Figure 2-6 shows team traits included in the exploration framework. Below is a description of each component within the framework.

Team Diversity Heterogeneity is a team asset and is linked to better team performance [61]. Diversity also limits the risks of groupthink [69]. Pertinent elements of this concept are the diversity of degrees awarded to team members and the number of different disciplines represented on the team.

Team Experience Experience is an enabler of systems thinking [35]. The ability to leverage a greater body of past experiences is one reason teams are a better decision making unit than individuals in safety critical situations [124]. This research is focused on the relevant engineering experience of the team members.

Team Environment The concept of creativity is closely linked with systems thinking [143]. Tangible and intangible components of the work environment contribute to creativity. Using multiple levels of abstraction to communicate within a team is linked with good engineering design thinking [45]. The tools and physical spaces available to a team will dictate with what means they communicate (e.g. 'war rooms' provide an informal venue to share and interact with pictures and sketches whereas teams using virtual shared spaces may lack the ability to jointly manipulate images and ideas).

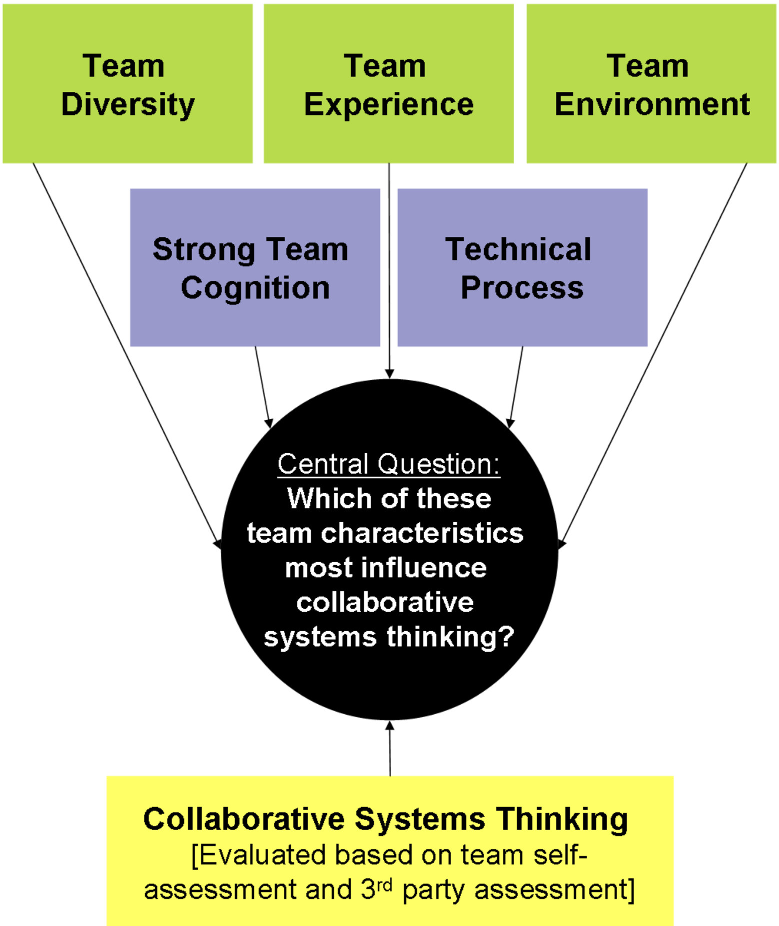


Figure 2-6: Framework showing team traits explored as possible contributors to collaborative systems thinking.

Team Cognition Collaborative systems thinking is an instantiation of team thinking. Team cognition is a logical pre-requisite with a set of literature-identified traits [124]. Testing for the presence of these traits will help in evaluating whether the observed behaviors are the result of team-level systems thinking or strong individual systems thinking. Such traits include valuing teamwork, having a strong sense of team, and good mutual awareness of other team members.

Technical Design Process Well designed, mature technical processes have certain consistent components. A concentration on analysis before evaluation enables better handling of complexity [136]. These processes also enable individual and teams to identify and understand their place and role within the organization and process as a whole. Additional research suggests the act of discussing and agreeing upon additional communication processes within a team improves a team's odds of success [43]. Metrics such as CMMI® capability maturity are an indicator of good process design, but not necessarily an indicator of good process implementation. Measures of actual process usage, process tailoring, and team-agreed upon practices round out the evaluation of technical process.

2.3 Critical Research Constructs

When undertaking exploratory research it is important to first identify, define and explore key constructs pertinent to the topic. Within the context of a single dissertation, only a small realm of aerospace engineering design can be addressed. Given the recent industry emphasis on process and capability maturity, a growing realization of the impact of 'soft' issues, and a desire to further explore systems thinking within teams, the following four research constructs were identified: collaborative systems thinking, teams, process, and culture.

A natural working unit within large, complex projects, teams may offer an opportunity to leverage scarce systems thinking resources more efficiently. By expanding research on engineering systems thinking to the team level, additional knowledge will be generated to help design more effective methods for fostering systems thinking skills within the aerospace workforce.

The following are discussions of each of the four critical research constructs. Included in each discussion is a construct definition, examples of the construct in an aerospace context, a brief treatment of any validity concerns, and a list of construct-related metrics. The one exception is that no examples are provided for the collaborative systems thinking construct as this is a previously unexplored construct. The three types of validity addressed are construct, convergent, and discriminant. Construct validity is defined as the ability to clearly and unambiguously define a construct. Convergent is defined as consistency in a construct definition across organizations. Discriminant validity is defined as the ability to clearly discriminate between constructs. Additional threats to validity will be discussed relative to research methodology in Chapter 3.

2.3.1 Construct 1: Collaborative Systems Thinking

Science is a way of thinking much more than it is a body of knowledge.

–Carl Sagan

Engineering is also more a way to think–an approach problem solving–than a body of knowledge. This premise is well illustrated in research showing that upwards of 70% of the knowledge required for a relatively simple system is undocumented [41]. This indicates the majority of knowledge required for systems development comes from experience; experience that informs the way engineers approach and solve problems; experience that is an important enabler of systems thinking development [35].

Defining Collaborative Systems Thinking

As established in Section 2.2, systems thinking is one mode of thinking engineers engage in when designing complex systems. Systems thinking enables engineers to better handle complexity, make better design decisions, and to consider the dynamic interfaces and interrelationships of a system [35].

Recent empirical research resulted in the following definition of systems thinking:

> *Systems thinking is utilizing modal elements to consider the componential, relational, contextual, and dynamic elements of the system of interest* [35].

This definition applies to systems thinking in individual engineers and will be used as a starting point for developing a definition for collaborative systems thinking. Within this definition the words componential, relational, contextual, dynamic, and system correspond to the five systems thinking definition themes of interrelationships, component complexity, context, emergence and wholes.

Thinking is a mental process defined by the Merriam-Webster dictionary as forming an opinion or an intention to act. Within an engineering context, the elements of thinking are decision making, problem exploration, judging between alternatives, and problem solving [6]. The process begins with an ill-defined problem and uses recalled knowledge (memory) and other inputs towards solving the problem. Within a team context, thinking occurs as the result of social interactions (transactions) by which team members share knowledge, create pointers to knowledge held by others, and interpret and recall information as a group [6, 151].

Successful design teams engage a variety of thinking styles and use a variety of means to communicate [6, 45]. These teams show curiosity towards the problem space, generate large numbers of alternative solutions and then engage in evaluation [6], following the normative design process [136]. By engaging in analysis before evaluation, these teams spend more time engaging in divergent thinking. As stated earlier, cycling between divergent and convergent thinking is an enabler for team success [45]. The willingness to ask questions, and thus engage in divergent thinking, is an indicator of a culture that supports learning. Finally, for a team to effectively communicate, multiple design languages are needed. The languages of design include text and speech, graphics (e.g. sketching and part drawings), shape grammars, executable mathematical models, and numbers [45]. Communicating enables teams to keep a clear vision of the mission [150]. While shared mental models are often touted as a means to support system-level design, collaborative systems thinking aims to leverage areas of expertise and knowledge not shared by the entire team. Thus shared mental models, which have not been shown to positively impact team performance [101], are not an effective vehicle for exploring collaborative systems thinking.

In addition to input from the literature discussed above and in Section 2.2, feedback from research interviews and case studies was used refine the collaborative systems thinking definition. The majority of feedback centered on the similarities in goals and purpose between individual systems thinking and collaborative systems thinking. The majority of respondents had simple, functional definitions for team-based systems thinking; definitions that emphasized the whole, the entire lifecycle, interfaces (technical and social), and context (which most defined as including the engineers themselves). Among the few specific differences consistently cited is the stipulation that while individuals contribute to a design, teams are responsible for delivering products.

Taking these inputs, the following definition for collaborative systems thinking is derived:

> *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 systems attributes, interrelationships, context and dynamics towards executing systems design.*

Like Davidz's definition of systems thinking [35], the definition of collaborative systems thinking contains the five themes consistent across definitions of systems thinking: complexity, interrelationships, context, dynamics, and wholes. The above working definition was used to execute field research. Chapter 4 includes a detailed analysis of how data collected influenced this definition.

Validity Concerns

Because collaborative systems thinking is a new construct introduced through this research, validity is a concern. By starting from a definition of systems thinking grounded in industry practice and modifying it to apply to teams based on discussions with industry and literature on team-based thinking and design thinking, threats to construct validity are minimized. Convergent validity, while a concern, is somewhat inapplicable to the construct of collaborative systems thinking. This construct is not currently recognized within organizations, and therefore the definition cannot vary between organizations. However, differences in the ways organizations react to, interpret, or modify the definition may be threats to convergent validity. Finally, discriminant validity will be addressed by asking each individual for his or her definition of systems thinking and collaborative systems thinking to gauge the ways in which collaborative systems thinking varies from similar constructs such as individual systems thinking.

Proposed Collaborative Systems Thinking Metrics

The traits, processes, and cultural characteristics explored as potential enablers and barriers to collaborative systems thinking are drawn from existing literature and metrics on team thinking, design thinking, and multiplicity of literature on team performance and management. These are areas that may influence collaborative systems thinking and are therefore worth exploring. Analogous to the enablers and barriers to individual systems thinking development (individual characteristics, experiential learning, and supportive environment [35]), team preferences and behaviors, cumulative experience, and environment (real and virtual) guide the inquiry into collaborative systems thinking. The metrics and traits proposed below come from literature on team cognition and team management. These represent existing theory on enablers and barriers to team thinking and the behaviors of effective teams.

A Strong Team Cognition

Strong Team Identity Teams with a common goal better maintain their focus. Shared beliefs that enable risk taking foster a climate characterized by trust and mutual respect [147]. These traits enable free communication which reinforces a team's goal. Teams with a strong and consistent identity may be said to have a more well defined team culture.

Engage in Critical Analysis Empirical research has shown that teams engaging in early analysis of the problem engage in early divergent thinking, ask more questions, better explore the goal space and consequently are better able to deal with system complexity [136]. As such, an ability to step back and analyze the problem or need before rushing to find the "right answer" helps teams better understand the system.

Leverage Multiple Thinking Styles Early in the design process divergent thinking results in a greater exploration of the problem space [136]. This is enabled by processes that emphasize insightful questioning rather than seeking early answers [92]. In later stages of design, convergent thinking is required to resolve trade studies and drive design decisions.

Mutual Awareness Mutual awareness is a measure of how aware team members are of each other's activities within the design context. Teams with a greater mutual awareness communicate more efficiently [100].

Situation Awareness Teams that better understand their situation and the task at hand perform better. Situational awareness measures a team's collective awareness of their environment, tools, and procedures [31]. Situational awareness may also include the ability to place the team's contribution, or component, within the overall system. For instance, a team working on an impeller would be explicitly aware of the engine type and interface with the impeller.

Implicit vs. Explicit Coordination Coordination is marked by the management of dependencies between tasks, resources and people. Explicit coordination is accomplished through process, consensus and top-down management. Implicit coordination is more subtle and relies on leveraging social and knowledge networks within an organization to gain access to expertise, collective understandings of team tasks and the anticipation of other's needs [31].

B Team Interaction Traits

Effective Team Communication Effective team communication is necessary to keep teams moving in the same direction. As such, teams need to be aware of how they are communicating. Teams with a majority of introverts need to be cautious of an overreliance on email, because while email offers an efficient way to transfer information, it is not an effective way to communicate [29]. Indicators of mature and effective communication are the ability to clearly articulate ideas, provide compelling reasons, listen to others, and provide constructive feedback. Mature communications enable higher levels of team understanding [147]. The use of sketches and other nonverbal communications improve this common understanding [45, 49].

Interaction Styles Complement Team Preferences Studies have indicated that most aerospace engineers have a Myers-Briggs[2] type of ISTJ or INTJ [141]. The result is that despite having long attention spans, engineers require time to digest and assimilate new information. Situations that require engineers to act upon new information without a period of reflection is stressful and unproductive [29]. While measuring personality types is impractical in the context of this research, individuals can be asked about their comfort with team processes and interactions.

Mutual Respect and Trust among Team Members Trust is at the base of successful interactions [86]. Mutual respect enables collaboration and communication within a team, thus facilitating knowledge sharing and team thinking.

Consensus Decision Making Ownership over a decision is a powerful empowerment mechanism [10]. The inclusion of many different voices in a decision creates a sense that all have been heard and contributed to the final decision [70]. This creates a sense of inclusion and collaborative progress. Experience has shown collaborative multidisciplinary teams have worked rather well in the aerospace industry [98].

Consistent Time Horizon Because teams work with schedule pressure, it is important for team members to operate on similar schedules. Differences in time orientation among team members result in stress and conflict [126]. These differ-

[2]Myers-Briggs is a measure of personality type with four dimensions. Dimension 1: Extraverts (E) vs Introverts (I). E's are oriented to the outer world, whereas I's are oriented to their own inner world. Dimension 2: Sensing (S) vs Intuitive (N). S's are in touch with their five senses, whereas N's are big picture thinkers who rely on their memory and associations. Dimension 3: Thinking (T) vs Feeling (F). T's use logical analysis for decision making, whereas F's apply personal priorities to decision making. Dimension 4: Judging (J) vs Perceiving (P). J's are goal oriented where as P's are curious and open-minded.

ences are one of the key reason industry and academic collaborations fail [156]. The balance between short and long term visions also impacts decision making, planning and goal setting [38].

Additional details into the methods used for determining collaborative systems thinking ability are discussed in Chapter 3.

2.3.2 Construct 2: Team

Clearly no group can, as an entity, create ideas. Only individuals can do this. A group of individuals may, however, stimulate one another in the creation of ideas.

–Estill I. Green, VP Bell Labs

Definition of *Team*

In its most simple incarnation, a team is a group of individuals working together. As the quote above implies, the power of groups is in interactions that facilitate creativity and better decision making. In most engineering organizations, teams are an important organizational tool [61]. Teams bring to bear a greater breadth of knowledge to a problem than can a single individual. This makes teams particularly effective in situations where important decisions, such as safety critical decisions, must be made [125].

There are many formal definition for teams. One such definition specifies four necessary conditions: a team task, clear boundaries, specified authority, and membership stability [61]. Recognizing that group work can be designed to be decomposed or integrated, Richard Hackman differentiates teams from co-acting groups by also requiring the tasks to be integrated, thus involving team member interaction [61]. Within teams, traditions and values develop over time that facilitate members working together [104]. Another conceptualization of a team relies on blurred boundaries and flexible membership to accomplish a task. These so-called "X-Teams" have the benefits of scalability and leverage both strong and weak interpersonal bonds to gain team visibility across an organization, obtain resources, and find necessary information [8]. Whatever the definition, there are certain common factors within all teams. These factors are the people who compose the team, the way tasks are designed (*process*) and the norms that develop with the group to support interaction and task completion (*culture*) [104].

The main function of teams is to execute work, or in engineering, to design systems and their components. Within engineering, team design occurs when a group of individuals work together cooperatively and share their unique expertise, knowledge, and ideas towards the design of products or processes [111]. Systems design is particularly suited for teamwork because it requires coordinated inputs from several specialities [61]. To be successful, teams require a clearly defined task or problem, sufficient time and resources, the latitude to make decisions, and some means of feedback [61, 111]. Additionally, healthy debate and dialogue within a team is important to encourage participation and ensure the solution space is well explored [111].

A diverse team membership is one way to ensure healthy debate [61]. A heterogenous team is less likely to succumb to groupthink, a condition where team members' desire for harmony blurs their ability to objectively and critically consider alternatives [69]. There are several rules of thumb for team composition. At a minimum, the team needs members representing the different disciplines required to design the system. However, there are multiple ways to construct and analyze teams. One method emphasizes the importance of team heterogeneity in addition to coaching on effective team norms, which often run counter to human tendencies [61]. Effective team norms emphasize proactively seeking less obvious causes and solutions and thinking critically when dealing with deadlines and political or social pressure in order to avoid groupthink [61].

A second and more structured approach to team building is based on balancing team composition in terms of set team roles. Clear team role assignment is important for coordinating group efforts and for allowing individual team members to leverage others' expertise [86]. Team roles may specify administrative or technical contributions. R. Meredith Belbin's nine team roles, shown in Figure 2-7 is an example of one functional team role structure. Belbin's framework is based on the assertion that individuals are more or less adept at certain roles and that team composition should consider an individual's contribution to team functioning in addition to her technical contribution [16].

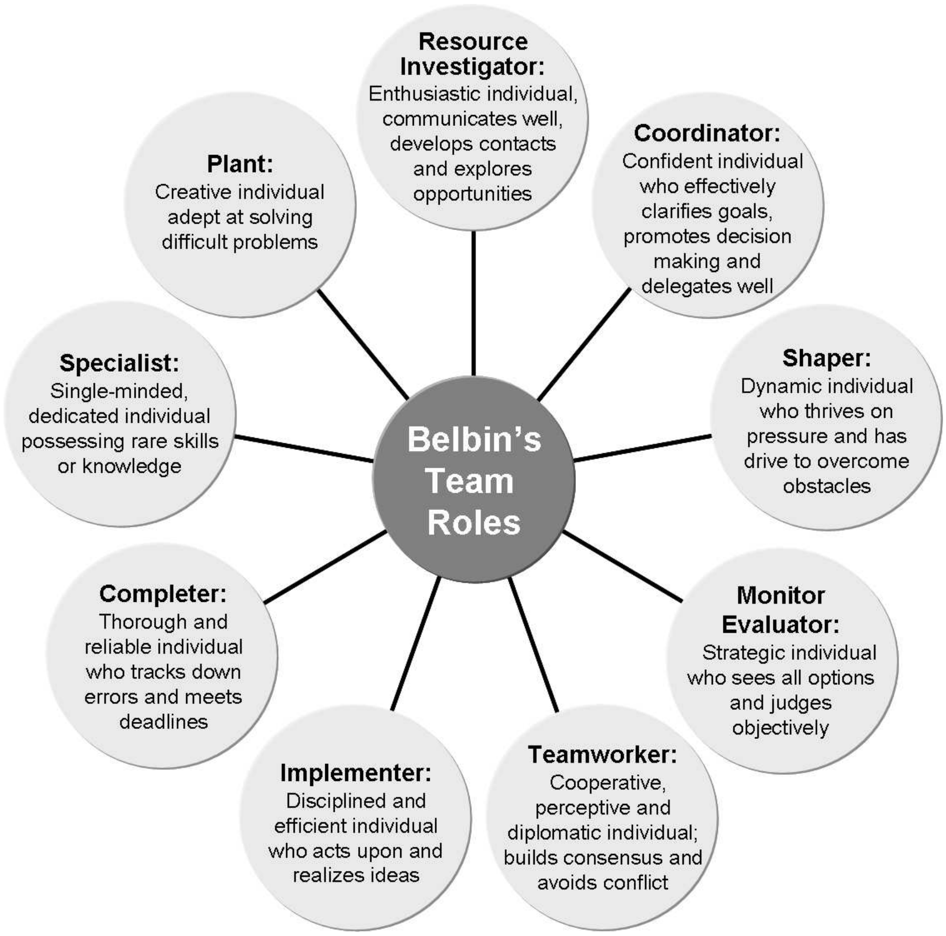


Figure 2-7: R. Meredith Belbin's nine fundamental team roles. Figure adapted from [16].

Deborah Ancona's 'X-Team' framework is a third take on team composition. Within 'X-Teams' there are three tiers of team membership: core, operational, and outer-net. Member of each tier have different roles and responsibilities relative to team functioning. Core members are responsible for maintaining the team's history and making important decisions [8]. Operational members are similar to Belbin's 'completers,' executing most of the teams tasks. Operational members are generally focused on some subset of the team's overall task [8]. The outer-net members are generally specialists and others who are brought onto the team when needed either for their experience or expertise [8]. While Hackman's definition of a team would exclude outer-net members, this tier's membership contributes materially to a team's ability to complete work.

Examples of Teams in Aerospace

The aerospace industry has a heritage of functional, or single discipline, teams [17]. As such, the move towards multi-disciplinary teams is representative of a change in the way work is decomposed; shifting from linear, decoupled tasks to more iterative and integrated tasks [19]. This shift follows a transition from concentrating on primarily convergent methods towards including divergent-convergent cycles (e.g. spiral development) that require a fundamental difference in the way teams work and relate to each other.

Concurrent engineering is the umbrella term given to multi-disciplinary product development teams and came into use in the 1980's [51]. The objective of concurrent engineering is to get concurrent participation by a variety of disciplines throughout product development: from conception through to realization [27]. Concurrent engineering also places an emphasis on considering the entire product lifecycle during initial design [33], motivated by studies showing 66% of the lifecycle costs are decided by the end of conceptual design.

Integrated product teams (IPT's) are one instantiation of concurrent engineering used within the aerospace industry. By bringing together different disciplines early in design, system requirements are matured more quickly and the design space is opened through cross-discipline discussion [117]. The result of this early interaction is greater efficiency and shorter development times [62]. Both IPT's and concurrent engineering practices reduce the likelihood of failures due to poor communication [109].

The following two examples of aerospace teams show dramatically different ways of implementing concurrent engineering within the aerospace industry.

The first team is a high-performing software team responsible for writing and maintaining code for the Space Shuttle [50]. This team is characterized by relatively stable membership. The team is large (260 people), and members have individual offices. The low error rates necessary for manned space flight are maintained by following strict procedures and maintaining team stability and professionalism. The team is split into two parts: coders and verifiers. A healthy competition between the two drives programmers to find and fix problems at their root cause, rather than superficially. Group meetings are held regularly and serve as a means to surface and address issues as well as keep the team on schedule. There are no freelancers or heroic coders on the Shuttle team. Rather, the team is structured and tasks split so as to be dependent on no single person. This structure purposely limits creativity, because creativity is not the team's core value, perfection is. The resulting team has been in operation for decades producing the industry's most reliable code [50].

A striking contrast to the Shuttle software team is the Jet Propulsion Laboratory's (JPL's) use of integrated concurrent engineering (ICE) [25, 26]. ICE teams are small by comparison, consisting of no more than 20 individuals representing several disciplines, the customer, and a facilitator. These individuals are co-located in a single room during the short and intense ICE sessions. The team hierarchy is flat, and 'sidebars' are used to resolve design issues while a number of independent tasks are addressed simultaneously. The working environment subjects team members to multiple conversations at once, requiring them to filter and identify information pertinent to their task. Because of the intense, psychologically draining atmosphere of ICE, the sessions are short and the team members' ability to handle the environment must be considered when building teams. The accelerated pace of ICE teams, finishing early-phase design in one-tenth the time of most teams at JPL, leaves team members susceptible to groupthink, which helps to accelerate the process at the cost of critical evaluation of alternatives. ICE teams work together for no more than a few weeks, and the format itself is relatively new. However, the proof is in the product and ICE teams have proven successful at producing initial designs at substantial time and cost savings over traditional IPTs [25, 26].

These teams differ in structure, size, and process; yet the basic knowledge underlying both teams' tasks (e.g. propulsion, orbital mechanics, and thermodynamics) is the same. Because many teams are required for large complex systems, training, standardization (of both processes and conventions), information technology and co-location all offer benefits for teams working together [22]. The constructs of process and culture are important components of this team-team interaction.

Validity Concerns

For the purposes of this research, a team is an 'established and defined group of individuals working together on an integrated multi-disciplinary engineering task.' This simple definition establishes construct validity. Because the form and function of teams differ across organizations, the concepts of 'defined group' and 'integrated multi-disciplinary task' will be used to enforce convergent validity. Teams of interest will be working in the design phase, have at a minimum a core with identifiable and stable membership, and be involved in cross-disciplinary work. Organizational charts and survey and interview questions can be used to ensure these conditions are met. The research-specific discriminant validity of the team construct is ensured in that no competing or conflicting constructs are included in the research protocol.

Relevant Team Metrics

Teams can be described and quantified in a number of ways. Experience is an important contributor to systems thinking, and team heterogeneity is an enabler of creativity. Therefore, measures of team diversity and experience are of greatest relevance to an inquiry into collaborative systems thinking. The following proposed metrics are accepted measures of team diversity and past experience. These metrics provide an insight into those team traits identified in the literature as influencing systems thinking.

A Team Diversity

Degree Concentration and Discipline Degree concentration and discipline are indicators of the type and variety of specialized knowledge on a team.

Job Title Job title is an indication of the types of functional roles represented on a team.

Personal Preferences Crude measures of team members' preferences give an indication of team heterogeneity from a personality standpoint.

Team Roles Team roles, as defined by Belbin, show how well balanced a team is from an functional/execution perspective.

Team Tenure The relative length of time team members have been together is an indicator of team maturity and how long teams have had to form transactive memory.

Individual Systems Thinking Capability Because it is unknown if individual systems thinking is a prerequisite for collaborative systems thinking, first and third party assessments of individual systems thinking capability will clarify the relative importance of individual systems thinking for CST.

B Team Experience

Level of Education The number of advanced degrees on a team is indicative of the depth of knowledge represented.

Corporate and Industry Tenure The number of years spent in the aerospace industry and with the current company are proxies for depth of experience and familiarity with corporate procedures.

Number of Past Similar Programs The number of past similar programs worked is a direct indicator of the breadth of experience represented on the team.

2.3.3 Construct 3: Process

Most accidents are not the result of unknown scientific principles but rather of the failure to apply well-known, standard engineering practices.

–Nancy Leveson in *Safeware*, 1995

Definition of *Process*

Process is a logical sequence of tasks performed to achieve an objective, a way of decomposing a large task into smaller subtasks. Process defines what is to be done without specifying how [93]. Processes take many forms. Processes may be standardized across an organization, agreed upon within a smaller group, or unarticulated sets of common assumptions [91]. Within engineering, standardized processes are used to decompose large technical problems into smaller tasks and facilitate collaboration (social interaction) among teams and individuals addressing each task. Facilitating communication is one of the most important roles of process [119] and is accomplished through rules and guidelines that ensure information is not lost or omitted [63].

Engineers are the most variable component of the design process [96]. Introducing standard ways of executing tasks helps to reduce variability and facilitate scheduling and cost estimating. Standards support engineering excellence by saving engineers from 'reinventing the wheel,' and preserving their efforts for true innovation [56]. The "art" of process standardization is to find the right level of standardization in order to facilitate design without being overbearing. Rigid processes inhibit flexibility and the ability to capitalize on new situations [91]. Some process advocates insist the development process should be tailored to the specific product under development [93]. Others promote more universal standards to facilitate collaboration among disparate teams and organizations. Because engineering systems blends routine and novel activities, no single process can cover every conceivable inevitability and some amount of process tailoring is necessary [119]. The traits of well designed process are therefore clear ownership and traceability [119] and promoting responsibility and initiative rather than solely emphasizing compliance [56].

Within the context of systems thinking development, the systems engineering process is the most relevant body of engineering processes. The goal of the systems engineering process is to, in a systematic way, address problems across a system's entire lifecycle. The basic steps in the systems engineering process are the following [21]:

Systems Engineering Process

1	Define the problem	7	Complete requirements analysis
2	Perform feasibility analysis	8	Oversee design optimization
3	Determine systems operation requirements	9	Facilitate design integration
4	Develop the maintenance and support concept	10	Conduct systems test and evaluation
5	Identify and prioritize technical performance measures (TPMs)	11	Oversee production
6	Perform functional analysis	12	Support product during operation
		13	Plan for and execute systems retirement and disposal.

Despite the documented benefits of standardized system design processes, resistance to their use still exists. Anecdotal evidence suggests that engineers feel restricted by processes, preferring to instead work in their own ways. Others resist on the basis that they and the tasks they complete are non-routine and therefore above or outside the process [128]. Yet others use standard design processes as checklists, a defined minimum of acceptable effort [128].

Even when standard processes are in place and used, design success is not guaranteed. Some say emphasis on process is misplaced and that process advocates are confusing the abstract entity of the process with the actual execution of the process by an individual or group, placing their emphasis on the object of documentation rather than the act of execution [113]. While process aims to reduce the variability introduced by engineers enacting design [96], engineering is inherently a creative process, and the skills and contributions of the engineer cannot be separated from the act of engineering. In one study of product development teams, those who interacted beyond the process were more likely to succeed than those whose interactions closely followed specified processes [43]. By this argument, process enables positive practices and behaviors, but the true success comes from teams who use the process and innovate where necessary to ensure good communication during the design process.

Process standardization, like laws and rules, exist with tension between precision and flexibility [139]. A rigid process enables the process to be independent of the individual executing it, but too severely limits flexibility. This is especially true in engineering where the problems faced are often not routine and require flexibility and creativity to solve.

Examples of Standardized System Design Process in Aerospace

Systems engineering processes are standardized at several levels from enterprise-specific handbooks to universally accepted process models such as ANSI\EIA 632 and process capability maturity models such as CMMI® [93, 94, 129]. Most systems engineering standards come from a common heritage, Military Standard (Mil-Std) 499; an early standard aimed at helping in the development of a project's systems engineering management plan (SEMP) [94]. Modern standards are maintained by a variety of organizations and provide varying levels of detail for processes spanning the entire product lifecycle. One such modern standard is ANSI/EIA 632. Developed by the Electronic Industries Association, ANSI/EIA 632 is an example of a standard prescribing normative functionality–that is what processes, or steps, should be performed during product development. Figure 2-8 shows a graphical interpretation of the standard.

Other examples of well known systems engineering standards include the International Council on Systems Engineering (INCOSE) Handbook and the NASA systems engineering handbook [93, 129]. The INCOSE systems engineering handbook is an example of a standard, or process framework, developed by a professional society with inputs from many organizations and industries. The handbook includes an overview of the systems engineering process as well as in-depth 'how-to' information for the types of analysis necessary to execute systems engineering [93]. The major steps in

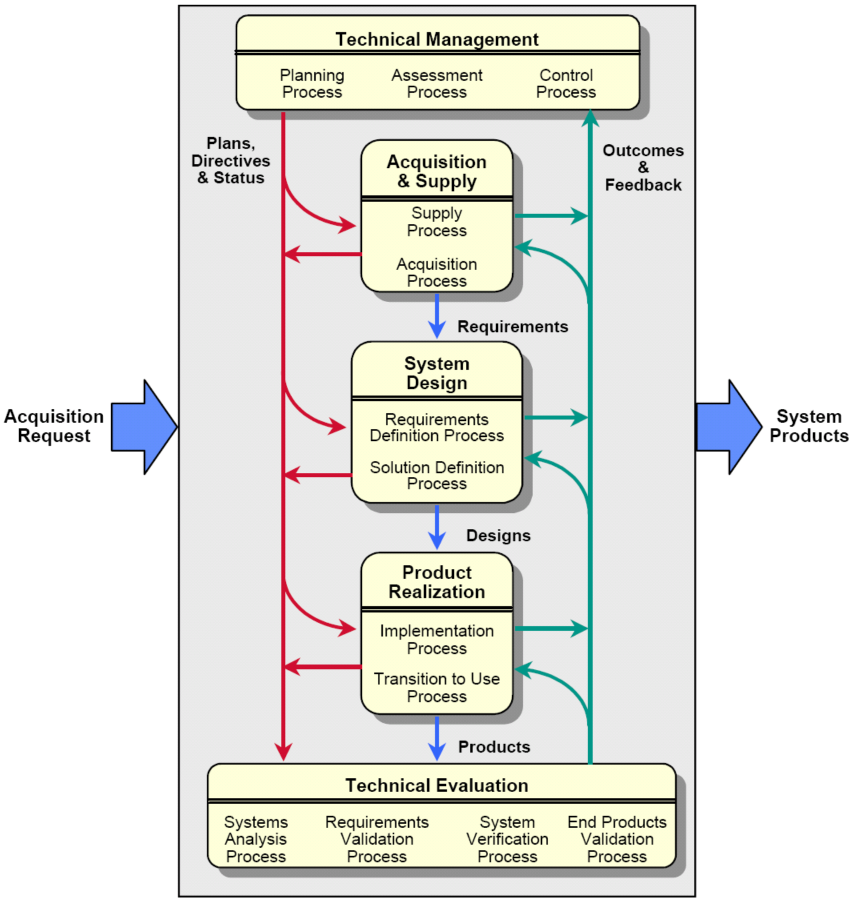


Figure 2-8: Top level view of the ANSI/EIA process for systems engineering. (From ANSI/EIA-632-1998)

the systems engineering process as specified in the handbook are similar to those in the ANSI/EIA 632 standard and include concept exploration, program definition, engineering and manufacturing, and production and field support. In contrast, the NASA systems engineering handbook is specifically tailored to the types of programs NASA works on and the methods and artifacts in use at NASA. However, the main steps remain the same: advanced studies, preliminary analysis, definition, design, development, and operation.

While not a standard in its own right, maturity models such as the Software Engineering Institute's CMMI® provide frameworks for systems engineering standards and specify practices and behaviors that should be in place for a systems engineering process to be mature and effective. The belief is that a mature design process will produce higher quality designs and mitigate risks such as cost and schedule [132].

Within the aerospace industry, the NASA systems design process is among the most well documented of design processes. The following examples show that even within a single set of design process guidelines, several different approaches are possible.

The first example comes from those who write software for the Space Shuttle. This mission critical component of human space flight is kept safe and reliable through a set of processes that include developing clear requirements and complete specification, intense testing, validation, and verification, and maintaining a comprehensive database so accurate and up-to-date information is always available [50]. The second example is integrated concurrent engineering (ICE), a co-located, intense engineering practice used on some projects at the Jet Propulsion Laboratory (JPL). ICE is not only a set of procedures used to solve a design problem, ICE is an environment that facilitates communication and the ability to solve problems rapidly [26]. The third example also comes from JPL in the form of its systems engineering advancement (SEA) initiative. SEA aims to go beyond just the process of systems engineering to include education, training and communication as explicit components in its architecture [70]. Driven by recent high profile failures, the goal is to improve systems engineering practices by addressing people and technology in addition to process [70].

Validity Concerns

Process is one of the most overused words within the engineering community. 'Process' means many different things to different people, thus adversely affecting construct validity. For purposes of exploring CST, process is defined as 'organizationally standardized tasks or steps taken by the team (or its members) towards the completion of systems design.' The definition is precise enough to require that the process be documented and utilized at a level higher than the team, while still allowing flexibility in how individual organizations implement their process. Within the research instruments, construct validity is addressed by using common touchstones such as the process terminology used in CMMI® and the INCOSE systems engineering handbook. Such steps will also ensure convergent validity. Clear terminology, and tightly worded questions will be used to address discriminant validity. Questions will focus on key elements of process (e.g. decision making, conflict resolution, and the degree of iteration). By intelligently framing the question, ambiguous words can be removed while maintaining sufficient generality to ensure the question is valid across organizations and contexts.

Relevant Standard Design Process Metrics

Several traits of process may affect collaborative systems thinking. Process standards are often proprietary and may be highly tailored to the individual team's task. The process metrics specified concentrate on more transcendent aspects of process to enable comparison across teams and organizations.

Existence of Standard Process Not all organizations have a standard process as defined above. The first step is to ascertain if the team is using a standard design process.

Use of Normative Process Structure While the details of individual design processes vary, there are empirically validated rules of thumb for design processes. This metric seeks to identify if the concepts of early design iteration and analysis before evaluation are incorporated in the standard process.

Understanding Role of Process within System and Organization This question should reveal information about a team's understanding of the role of standardization. The extent of convergence or divergence in responses is of great interest.

Ability to Tailor Process This metric is based on the suggestion that successful product development teams are such because they innovate beyond the standard process. This metric gauges the ability of a team to tailor the standard process and the extent to which the team does tailor the process.

Actual Rate of Process Usage A metric of team or individual process compliance. The traits of a standard process are of no influence to a team's performance if the process is not actually utilized.

Perception of Process This metric measures team member perceptions of the usefulness and applicability of the standard process.

Usefulness of Process Artifacts (e.g. process flow maps and organizational charts) Process flow maps and organizational charts are tools to help people make the connections necessary to execute design and understand their role within the overall task. A measure of how useful these artifacts are will gauge their effectiveness at representing the actual design process.

2.3.4 Construct 4: Culture

The practices of engineering culture uphold the importance of the individual and of autonomy, and such rituals appear in two important places: On the job and in the engineers education.

Because of the nature of most rituals in engineering culture, rituals that emphasize technical skill and individual work, engineers often understand themselves to be autonomous individuals and regard themselves as mavericks.

In engineering culture showing strength is often linked to masculine ideals that create a culture of the right answer.

–Paul M. Leonardi, excerpts from "The Mythos of Engineering Culture"

Definition of *Culture*

Culture is a property of groups; an abstraction for explaining group behavior [126]. In a bid to take a systems approach to understanding the relationship between the social and technical aspects of engineering, the environment and therefore the cultural values of the team must be understood [61]. The following are commonly used definitions of culture.

1 Detert, Schroeder and Mauriel define culture as a set of expressive symbols, codes, values and beliefs. These are supported by information and cognitive schemata and expressed through artifacts and practices [38].

2 Gerry Johnson sees culture as a web of values, norms, rules, beliefs, and taken for granted assumptions that define the way the world is and should be [71].

3 Edgar Schein defines culture as a shared pattern of basic assumptions learned by a group by interacting with its environment and working through internal group issues. These shared assumptions are validated by the group's success and are taught to new members as the "correct way to perceive, think, and feel in relation" to problems the group encounters [126].

4 Paul DiMaggio sees culture existing in inter-personal interactions, shared cognitions, and the tangible artifacts shared by a group [40].

These definitions share the common features of identifying culture through properties, tangible and intangible, that represent shared thoughts or assumptions within a group, inform group member behavior, and result in some type of artifact visible to members outside the group. These features are influenced by a group's history, are socially constructed, and impact a wide range of group behavior at many levels (e.g. national, regional, organizational, and inter-organizational) [38]. Culture can also be considered at smaller levels. For instance, a team may have its own subculture within an organization: heavily influenced by the overall organizational culture, but nuanced by the individuals and experiences on a given team [126].

At each level of culture there are cultural characteristics with varying degrees of visibility to outside observers. The most visible characteristics are the artifacts to which the culture definitions refer. Artifacts may include visible organizational structures and documented processes. The lesser visible characteristics consist of the consciously supported beliefs and values within a group (e.g. strategic goals) [126]. While not directly visible, espoused beliefs and values may be uncovered through observing and interacting with members of a group. The least visible characteristics of culture are the basic underlying assumptions of a group. These include perceptions, thoughts, feelings and taken-for-granted beliefs [126] and are difficult for a group member to articulate, let alone for an observer to observe.

In addition to being a property of distinct social units, functionally aligned groups may also be said to have a unique culture. Examples include groups aligned with specific technologies (products or programs), corporate divisions, or professions (e.g. operators, engineers, and executives) [126].

Within an organization, culture originates with the beliefs, values and assumptions of the founder. Likewise, within a team, much of the tone is set by the team leader and those who have been with the team the longest. Once established, a group's culture is tempered by shared experiences and by the past experiences of those who later join the group, bringing with them new beliefs, values and assumptions [126].

In the context of this research, the most significant cultural influences are likely the organizational unit, the engineering culture, and any product or program specific identity or culture.

Culture is both deep and broad within a group. Culture is a deep and often unconscious influence on groups, covering nearly all of a group's functioning [126]. In an engineering context, this means a team's culture impacts its creativity, problem solving, and ability to generate new concepts [63]. In fact, group norms, one of the characteristics of culture, are key to group performance [61]. However, efforts to alter group norms can be confounded by culture. New behaviors or processes introduced to a group will fail to catch on if they go against the prevailing culture [61]. This is because one characteristic of culture is its stability within a group

[126]. The formation of culture begins with the formation of a group, and mirrors the stages of groups formation: forming, storming, norming and performing [144]. Once a group is formed, group norms begin to develop through conflicts, attempts to achieve harmony, and the eventual focus on a mutual goal throughout the execution of which the team matures, adapts, and innovates, constantly testing and updating its behaviors, assumptions, and artifacts [126].

While culture is a powerful predictor of group behavior, it is also a barrier to the introduction of new methods, tools and processes [17]. However, culture can also be a motivator for change. So-called 'cultures of change' empower members to seek out new methods and ideas to solve problems [36]. It is evident then that organizational culture is a contributor to team success [111]. Because trust is at the base of successful interactions [86], organizations can emphasize positive team norms and create a cultural context that supports team success [92] by fostering and sustaining intellectual curiosity, effective communications and the keeping of thorough documentation, or artifacts [58].

Examples of Cultural Influences within Aerospace

The aerospace engineering culture is influenced by its origins (nonconformist bicycle makers) and historic association with the defense industry. Borrowing from Leonardi's engineering cultural archetypes, these suggest a tendency for aerospace engineers to follow the 'maverick' and 'macho' engineering archetypes. Both archetypes are characterized by a resistance to team work. In contrast, the NASA culture is more accurately described by the 'technophile' archetype and is characterized by the tensions between academic rigor and the craft nature of engineering. Technophiles enjoy the prestige that comes from working with the technology (e.g. manned spaceflight).

Because culture affects the behavior and the way groups work, it ultimately impacts the systems being developed [134]. The aerospace industry cultural heritage shows a resistance to teamwork, while at the same time enjoying large and complex engineering problems. The following are a few observations from the literature on desirable cultural traits for aerospace engineering teams. From observations of integrated concurrent engineering teams, it has been determined that successful design teams have a culture that enables autonomy while facilitating frequent and detailed team reviews of design choices[25, 26]. To enable this seeming dichotomy, a trusting, respectful and egalitarian culture is needed [25, 26]. Within JPL's Team-X, these traits are achieved by keeping a flat team hierarchy, using a team room, and engaging in frequent sidebar conversations to resolve problems and avoid groupthink. In an attempt to revise systems engineering practices at NASA's JPL, it has been recognized that the inherent desire to focus on the technology must be balanced by an increased emphasis on people. This necessitates a new look into the training and behavior of the engineers in order to create a more people intensive culture [70]. This JPL effort shows that even in highly technical organizations, systems engineering is best executed in an environment that places equal emphasis on technical and social skill development. The third insight comes from the space architecture community. When balancing multiple divisions or disciplines (e.g. architects and engineers when developing space habitats) it becomes more difficult to consciously steer a system's development. In this situation, a culture that supports spatial communication and transparency in decision making helps [149].

Validity Concerns

Cultural analysis is subjective and time consuming. Data collection constraints require that cultural data be collected primarily through surveys and interviews. The sensitive and/or proprietary nature of most aerospace programs means direct team observation is difficult. Because culture is an abstraction, construct validity is a concern that must be addressed by carefully specifying what is meant by culture. As such, this research will limit the construct of culture to more observable characteristics such as group norms (e.g. decision making processes), artifacts (e.g. team documentation), and espoused beliefs about the teams purpose and objectives. By focusing on a well-defined subset of cultural traits, convergent validity is addressed. While a vague term like 'culture' may have subtly different meanings across organizations, the elements upon which this research focuses are consistent in form and definition across organizations. There is no one universally accepted definition of culture, and some explanatory data are likely lost by not considering the "unobservable" components of culture. To address potential issues of discriminant validity, the word 'culture' is not used in any of the case study instruments. Rather, the questions aimed at understanding an organization's and team's culture use more precise words that focus on the observable characteristics of interest.

Relevant Aspects of Culture

The following cultural characteristics are based on the intersection of Detert's eight dimensions of organizational culture, common behaviors and beliefs based in engineering culture, and the behavior, value and structural components of the proposed process-culture interaction framework, discussed in Section 2.2.4.

A Team Environment

Collocation Teams dynamics are affected by team geography. The further apart team members are situated, the less likely they interact [22]. Collocation also affects the types of media used to communicate.

Collaboration Tools Information sharing is central to the effectiveness of engineering teams. This metric identifies any special tools or communication methods the team uses to complete its work.

Team Spaces Team spaces include any special team rooms or other team spaces, virtual or physical, that aid the team in completing its tasks. The physical environment of a team impacts the team's interactions as do functional, hierarchical and organizational levels and boundaries [32]. Team member impressions of the role of environment gauge both the extent to which the environment is an enabler or barrier and also the extent to which team members are aware of the influence of their environment.

Enablers of Creativity A creative environment supports cycling between the divergent and convergent thinking styles: valuable in engaging teams in early analysis and critical questioning. In a review of creativity principles as applied to engineering, the following enablers and barriers were identified [143].

Enablers to Engineering Creativity

1. Freedom to make meaningful decisions
2. Access to sufficient resources (physical, financial, and time)
3. Collaborative atmosphere
4. Recognition for accomplishments and contributions
5. Tasks and projects that provide a stimulating challenge

Barriers to Engineering Creativity

1. Misalignment between goals and rewards
2. Excessive constraints
3. Resistance to change, exploring new ideas and ways of doing things
4. External and critical evaluation
5. Bureaucracy and organizational disinterest

Communication Preferences A team's environment impacts the frequency and means through which team members interact. As was discussed in Section 2.3.1 communication should engage the multiple design languages: verbal, mathematical, pictorial, model, simulation, etc. Also, the medium of communication is important. While email is great for transferring information, it does not necessarily facilitate communication [29].

B Team Norms

Decision Making Decision making is an important team activity. While humans tend towards satisficing solutions [130], engineering design is inherently about finding good or optimal solutions. Descriptions of decision making processes show perceptions of how inclusive team decisions are and how conflicts within the team are resolved.

Team Atmosphere Teams with an egalitarian atmosphere where individual contributions are well accepted and logical and reasoned discussions prevail are more likely to elicit good ideas and support critical evaluation of ideas. This ability to engage in free discussion encourages systems analysis [136]. By contrast, teams that move quickly to conclusions may miss important aspects of the problem and end up with a poorly optimized solution.

Team Role in Process Selection/Tailoring Many teams have the ability to tailor existing standard processes. This metric is based on the assertion that teams which 'own' their processes perform better.

Role of Social Networks A complement to process flow diagrams and organizational charts, social networks help people obtain information necessary for task completion. This metric gets to the role informal social relationships play in obtaining necessary information and making new connections that facilitate work within a team.

C Espoused Beliefs

Team Goals The consistency of team goals across team members is a good indicator of how well a team understands its purpose and how unified the team is relative to accomplishing that goal.

Team Identity Team identity gets to how a team sees itself. These metrics measure how team members view each other in terms of perceptions of the heterogeneity or homogeneity of the team, the extent to which team members share these perceptions and the accuracy of these perceptions.

Value of Teamwork Attitudes towards teamwork will be influenced by the organization's culture and reward systems. Cultures that espouse teamwork, but exclusively reward individuals will promote teams in name only. The complex nature of engineering work requires true teamwork.

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Chapter 3

Research Methods

That's all very well in practice, but how does it work in theory?

–Groucho Marx

The nature of this research is such that established practices are being probed to describe the phenomena of collaborative systems thinking. The logical outcome is a theory. This type of research is different in nature than most engineering research, which is deductive; starting with and testing a hypothesis based on existing theory. While this research utilizes social science methods, grounded empirical research has a rich heritage in science and engineering. In the 17^{th} century, Johannes Kepler developed the laws of planetary motion to explain his observations of planetary transits and Sir Isaac Newton developed the laws of universal gravitation after purportedly watching a falling apple. In modern research, genetics and biological engineering often utilize grounded empirical methods to gain insight into disease vectors and answer other questions about human health and wellbeing.

3.1 Exploratory Research

Exploratory research methods offer a means to collate observations of practice into new theory. Whereas traditional deductive research starts with a hypothesis and then seeks evidence to prove or disprove the hypothesis, exploratory research starts with an interesting question or area of inquiry and ends with a set of hypotheses that form the basis for new theory [57]. Exploratory research is useful in situations where the phenomena being observed are not well understood or insufficient theory exists to form a testable hypothesis. Its strengths include examining the phenomena in context towards generating explanations or theories [77, 123].

With the goal of uncovering new ideas and explanations, exploratory research is inductive [135]. Unlike deductive inquiries, there are no control variables in exploratory research. Rather, such control variables, or 'handles,' are the outcome of exploratory research and the inputs for future research [77]. These generalizations help in understanding the teams and processes being studied [135].

A weakness of exploratory research is it sometimes fails to produce conclusive results. Smart sampling that represents variation within the sample population helps reduce inconclusiveness [135]. Validity is also a concern with exploratory research. The inclusion of qualitative data allows for a more complete description of the phenomena under consideration, but leaves room for researcher bias to enter during data analysis. The use of recognized techniques and tools and a well designed research structure helps address validity concerns. Grounded theory is one such method of exploratory research wherein a well-established framework for interpreting results is provided.

3.1.1 Grounded Theory Research

Scientific inquiry is predicated on empirical observation [131]. The scientific method as taught in most science and engineering classes begins with a theory and ends with a set of observations. The grounded theory method starts with observations out of which generalizations are made and theory is formed. Figure 3-1 shows how both paths of scientific inquiry combine to form the scientific process.

Grounded theory research is characterized by concurrent and systematic data collection, analysis, and theory development [57, 140]. Grounded theory development involves the collection of data from several sources including, but not limited to, surveys, interviews, focus groups, field observations and primary documents. From

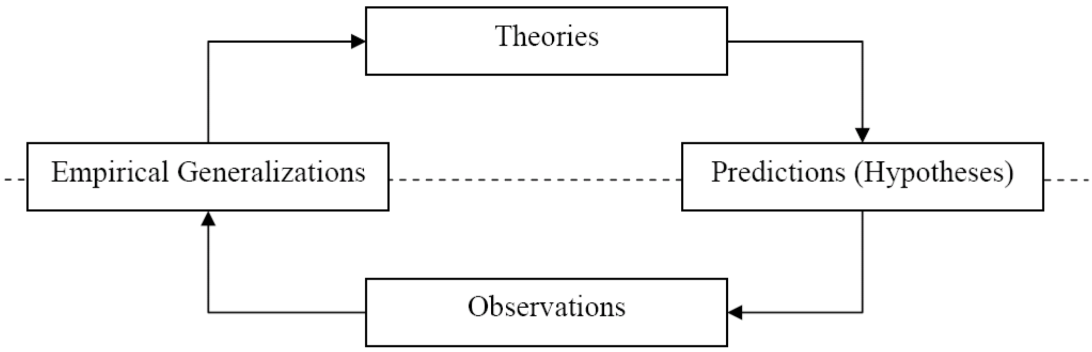


Figure 3-1: The scientific process as defined by Singleton and Straits [131]

these sources, concepts, and categories are identified and linked to form patterns. Theory is then formulated based on observations of the patterns [140]. The formal coding process used in grounded theory builds up categories and constructs. Data from several sources are compared and contrasted to find repeated patterns, apparent contradictions, and holes within the data. Contradictions and holes in the data drive further data gathering and subsequent analysis. This process is shown in Figure 3-2. Because grounded theory research utilizes a systematic process to collect and analyze data, it leads to a more accurate process of discovery; less influenced by researcher biases.

The goal of theory is to provide explanatory power in a specific, practical situation. In researching systems engineering, the goal is to explain the process by which engineers execute systems engineering and to predict and explain which behaviors and activities are helpful or harmful. Grounded theory provides a rigorous framework within which to collect and analyze data and avoid the pitfalls of revelation and intuition which threaten to relegate systems engineering and related fields to a philosophy rather than a science [146].

3.1.2 Grounded Theory Procedures

Grounded theory specifies a set of procedures and techniques for data collection and analysis. These steps lead the researcher through decomposing the data, forming

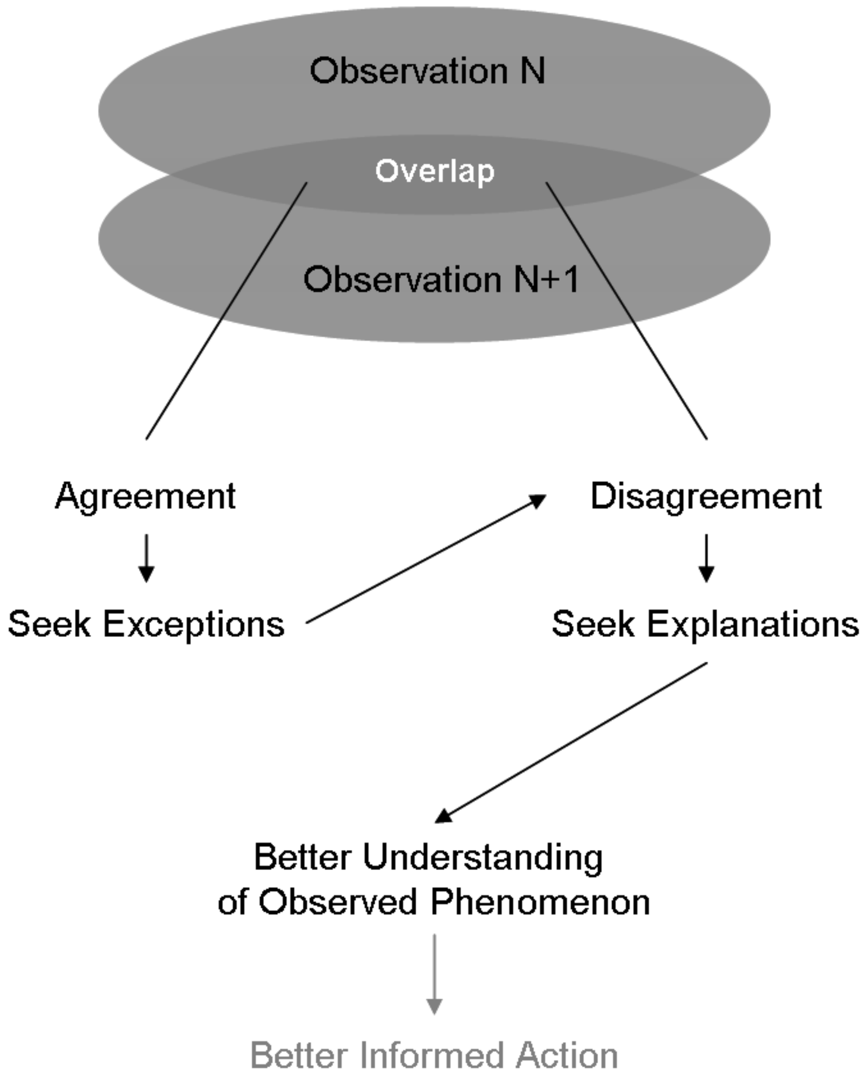


Figure 3-2: Diagram of the grounded theory analysis process. Adapted from [39].

conceptualizations and then integrating to form theory [140]. The goal of these procedures is to inspire insights into the data while maintaining a level of objectivity in the way the data are manipulated. While some advocate beginning with a clean slate to avoid researcher bias, it is beneficial for the researcher to have some theoretical insight into the phenomenon being explored [57].

Grounded theory procedures require the researcher to step back and critically analyze the situation being explored, to recognize and avoid her own biases, to think abstractly, and to have a vision that ultimately guides the research direction [140]. The researcher then must go into the field and sample until obtaining theoretical saturation: the point at which new observations fail to add additional explanatory power [57].

The steps taken along this journey include description, conceptual ordering, and theory building.

Description Description is the use of words to describe a mental image of a person, place, thing, experience, etc. [140]. In field work, descriptions may come from the researcher's observations or participants' past experiences in the form of interview transcripts or responses to survey questions.

Conceptual Ordering Conceptual ordering is the organizing of data according to some specified set of properties and their dimensions [140]. Conceptual ordering is a key component of data analysis in grounded theory. Coding and memo writing are two techniques to manage conceptual ordering and stimulate the researcher to see connections between concepts supported by the data.

Theory Building Theory is a set of related concepts which together provide a framework suitable for explaining or predicting the phenomenon of interest [140]. Theory is the end goal of grounded theory research. Just as coding and memo writing facilitate conceptual ordering, the later stages of coding support identifying and defining the relationships between concepts which ultimately form theory.

3.1.3 Qualitative versus Quantitative Data Collection

One strength of the grounded theory method is that both qualitative and quantitative data may be used [77, 135]. Using multiple types and sources of data facilitates triangulation [123] and bolsters the validity of results. Additionally, different types of data are suited for illuminating differing aspects of a phenomenon under observation. For instance, quantitative data are better for structural aspects of observed phenomena and qualitative data are better for flexible research designs and those dealing with process. Combining the two may allow for statistical generalizing of results [123].

Traditional engineering research is dominated by quantitative research methods. Numerical models and controlled experimental environments lend themselves to description by measures and statistics. These measures and statistics then inform or validate a-priori hypotheses [77]. The relative strengths of quantitative research come from its repeatability. Because the researcher controls the experimental environment, the experiment can be re-produced to validate results. Quantitative data is also objective and able to support direct comparisons. The numerical nature makes results easy to report and easy to verify. However, quantitative data collection is rigid, and does not allow the flexibility often required for field data collection.

Qualitative research allows for a richer set of data, including verbal descriptions of events. Additionally, qualitative research methods lend themselves to situations with poor or no experimental control and use tools and techniques to develop a-posteriori hypotheses to explain observed patterns of behavior [77]. Qualitative research methods are flexible, can accommodate uncontrolled environments, and are suited for describing complex personal and interpersonal situations. However, qualitative data require interpretation and are therefore subject to researcher bias [77].

Mixed methods combine the data collection flexibility and descriptive richness of qualitative methods with efforts to objectively quantify results through the use of surveys and coding interview data.

Qualitative Data Analysis

Qualitative data may come from many different sources: e.g. interview transcripts, surveys responses, and primary documentation. These are text-based sources. The objective of qualitative data analysis is to extract data from text that supports comparisons and conclusions. These data are referred to as codes and memos. Several commercially available software tools can be used for qualitative data analysis.[1]

Within the grounded theory framework, there are two important components of qualitative data analysis: coding and memo writing. These are part of an iterative process; refined with each new piece of data. The following is an introduction to both coding and memo writing.

Qualitative analysis is by nature descriptive. The outputs of qualitative analysis (e.g. code frequencies) may be quantified and used for descriptive and inferential quantitative analysis.

Coding Coding can take many forms, but the common idea is to break down textual data into a group of central ideas, eventually creating a relational structure that supports interpreting the data and provides explanation for the observations [77, 140]. These textual data are interview transcripts, open-ended survey responses, and primary documentation.

Concepts are the primary building block of theory, and their identification and classification is the primary goal of coding. Categories are used to classify important or major concepts. Subcategories delineate concepts that clarify and explain the categories. Categories also have properties and dimensions that provide meaning to the constructs and describe in what ways the properties vary [140]. Part of coding is the identification of interesting and relevant material. Therefore, identified concepts should contribute to the understanding of the phenomenon under investigation. Because coding recognizes variability within categories, case studies should be selected to include variability on key concepts so that the resulting theory will include and explain the impact of such variability [140].

[1]This research used the MaXQDA software package for qualitative data analysis.

Three types of coding are used to transition from raw textual data to structured relationships between concepts. The first step is open coding, the step during which categories and their properties are initially identified. The second step is axial coding. In axial coding, concepts and categories are reordered to find the central phenomena and identify potential causal conditions, contexts, and consequences. The final step is selective coding during which the resulting categories of axial coding are integrated, and an explanatory theory results [123]. The use of visual representations such as matrices, network diagrams or other graphics are often used during axial and selective coding to facilitate the identification of concept relationships [77]. The coding steps are not discrete but overlap and repeat as necessary, driving both future data collection and theory generation. Figure 3-3 shows an example of open and axial coding from the pilot interviews. The diagram shows the codes identified within the pilot interviews and the frequency of occurrence of each code within each document. The codes were then organized into a hierarchy of related groups of enablers and barriers to collaborative systems thinking. The hierarchy groups similar codes and provides context through which to interpret the results. Notice that some codes (e.g. Shared Taxonomy) are cited many times within one interview and other codes (e.g. Creativity) are cited less often but appear in nearly all the interview transcripts. The names, or titles, for the codes, come from the interview transcripts during open coding and are condensed, integrated and renamed during axial coding.

Memo Writing Memo writing creates a second set of textual data that both drives the research as well as shapes the theory generated. Memos contain a record of data analysis as well as researcher thoughts, interpretations, and questions about the data. Reviewing and sorting memos is another way to identify the central category [140]. These stream of consciousness commentaries about field observations push researcher thinking by asking questions that identify 'holes' in the emerging theory and drive theoretical sampling [46].

The basic types of memos include code notes, theoretical notes, operational notes, and diagrams. Code notes contain the outcomes of coding. Theoretical notes sum-

Figure 3-3: An example of coding from the pilot interview analysis. Dot size (and color) indicates the frequency with which a code is cited in a given document.

marize research thoughts and ideas about future sampling. Operational notes contain procedural directions and reminders. Diagrams are the sketches and pictures used to describe relationships between concepts [140].

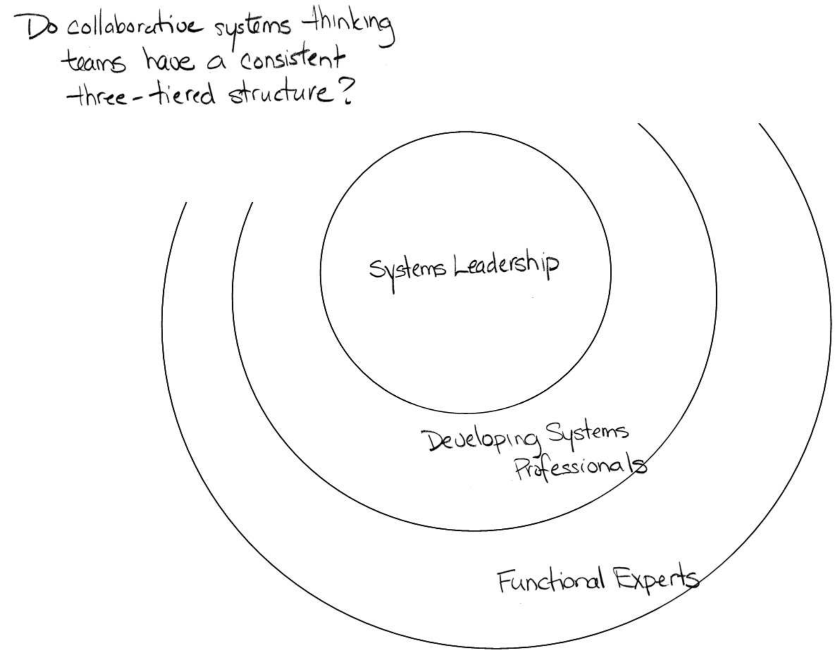
Figure 3-4 shows two examples of theoretical memos used to drive data collection. The first memo is a result of an interview from a case study in which it was suggested that collaborative systems thinking teams had three membership categories. The memo captures the concept in a question and accompanying diagram that were used to drive conversation in subsequent case study interviews. The second memo is the result of a comment that systems thinking serves differing purposes throughout the design process. This memo captures the core of the idea and includes a diagram based on several sketches by interviewees. Both memos resulted in new questions being asked during subsequent interviews.

Quantitative Data Analysis

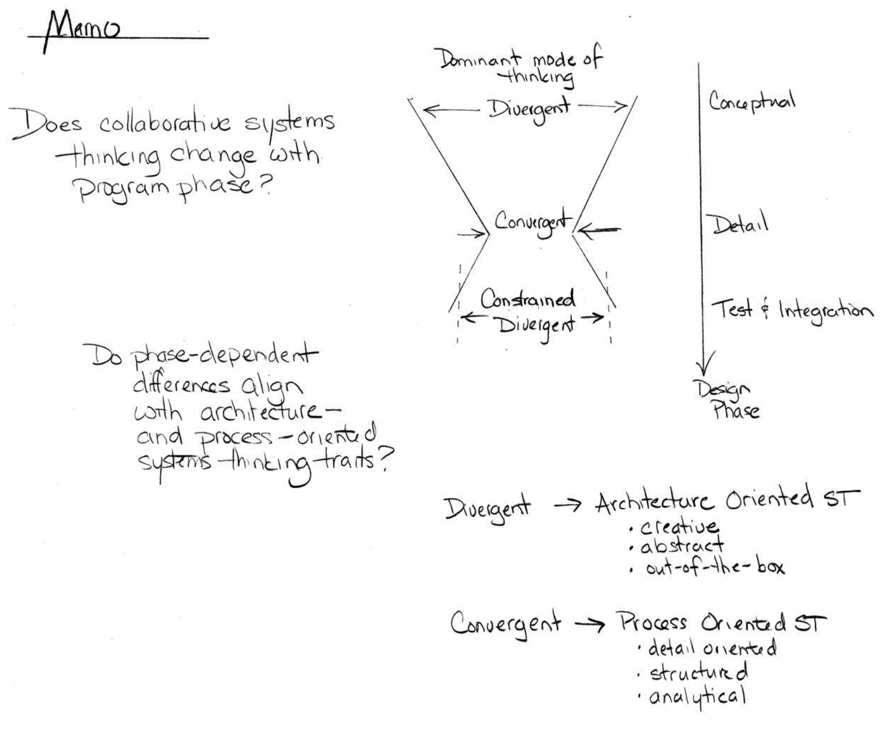
Quantitative methods are also used within grounded theory. Whereas qualitative methods are primarily descriptive, quantitative methods are used both to describe the observations and to make models to help infer relationships among observed variables. Quantitative data come from surveys and include such parameters as years of experience, number of past programs, and quantified data on perceptions in the form of Likert scale responses to questions that gauge an individual's perception or opinion.

Descriptive Analysis The purpose of descriptive analysis is to use quantitative methods to characterize and describe the data collected. Descriptive analysis enables further generalizations and quantitative modeling. Two types of descriptive quantitative data analysis are used: descriptive statistics and cluster analysis.

Descriptive Statistics The ultimate objective of this research is to identify the enabling conditions for collaborative systems thinking. To that end, a set of measures were taken to describe the group and the individuals within the group. The objective



(a) Memo 1: Comments on collaborative systems thinking team structure



(b) Memo 2: Thoughts on linkages between systems thinking styles and program phase

Figure 3-4: Two examples of memos, both theoretical notes.

of descriptive statistics is to smartly choose measures to represent pertinent group properties. These descriptive statistics become the inputs to the cluster analysis and regression analysis, discussed below.

Common descriptive statistics include measures of central tendency (e.g. mean, mode, and median), measures of variability (e.g. range, standard deviation and variance), and measures of relationship (most commonly referred to as correlation) [77]. Measures of central tendency and variability are used to group individual responses into team descriptions. The team surveys collect a mix of interval and ordinal data. Interval data come from those questions with answers that represent numerical quantities with equal intervals (e.g. years worked, number of past program experiences, relative percentages). These data are also sometimes referred to as cardinal or ratio data. Ordinal data come from questions with answers that represent represent ordered data (e.g. Likert scale responses and rank-ordered lists). While all the above discussed measures of central tendency and variability are applicable to cardinal data, only mode, median and range are suitable metrics for ordinal data. Likewise, the most common measure of relations for cardinal data is the Pearson correlation coefficient, whereas the Spearman's ρ correlation coefficient is more appropriate for ordinal, or ranked order, data. These two measures of relationship are used as appropriate to identify those team properties most correlated with collaborative systems thinking.

As with statistical analysis, the teams studied represent a small sample of a much larger population–that of all aerospace engineering teams. As such, aggregate measures that seek to generalize across teams have an associated uncertainty relative to the entire population. Aggregate measures describing the composition and traits of one team do not have associated uncertainty as the team surveys sample the entire (or near entire) population within a given team. The resultant descriptive statistics therefore are not from a small sample of a larger population, but from an entire population: the team membership.

The output of descriptive statistical analysis is a set of vectors of metrics describing each team. From these vectors, the correlation coefficients are calculated between each independent metric and a team's reported collaborative systems thinking ability.

From this, generalizations can be made as to which traits (i.e. metrics) best predict a team's collaborative systems thinking.

Cluster Analysis Cluster analysis is a method by which to classify data. The cluster analysis used in this research is based on calculating the distance between case studies and then using the complete linkage method to identify which cases are most similar [14]. Equation 3.1 shows the distance matrix used for cluster analysis. The distance between cases i and j, δ_{ji}, is calculated using equation 3.2, where x_k is the k^{th} element of the vector of P case study parameters [14].

$$\begin{pmatrix} - & \delta_{12} & \delta_{13} & \cdots & \delta_{1j} \\ \delta_{21} & - & \delta_{23} & \cdots & \delta_{2j} \\ \delta_{31} & \delta_{32} & - & \cdots & \delta_{3j} \\ \vdots & \vdots & \vdots & - & \vdots \\ \delta_{j1} & \delta_{j2} & \delta_{j3} & \cdots & - \end{pmatrix} \tag{3.1}$$

$$\delta_{ji} = \sqrt{\sum_{k=1}^{P} (x_{ik} - x_{jk})^2} \tag{3.2}$$

From the distance matrix, the closest cases are identified and grouped, and their distance is noted. The process is repeated until there is only one cluster, as shown in Figure 3-5. The complete linkage method is used, where the distance between clusters is determined by the greatest distance between cases within those clusters. The dendrogram is used to show that case studies cluster according to self-reported collaborative systems thinking ability.

Inferential Analysis and Modeling Inferential analysis is a branch of statistics used to reach conclusions beyond those from descriptive analysis. Using the vectors of metrics identified during descriptive analysis, regression analysis is used to determine both the relationships between the regressor, or independent, variables and the dependent variable, collaborative systems thinking, and the relative strength or im-

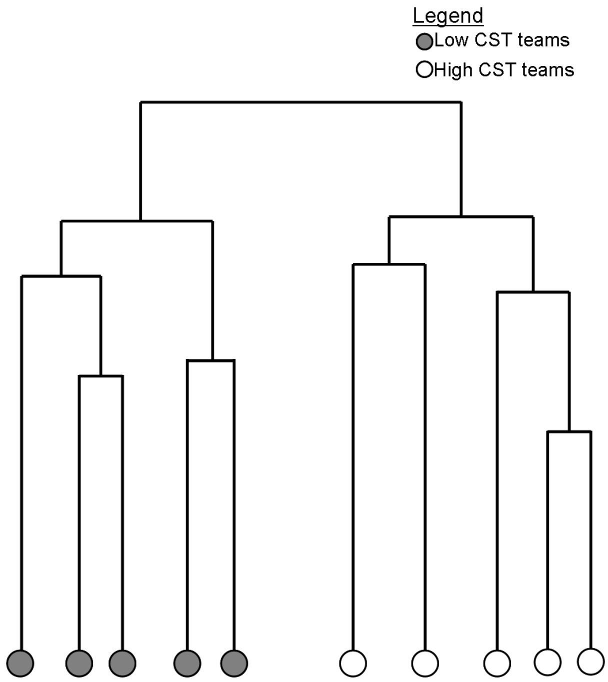


Figure 3-5: A dendrogram shows similarity by showing the distance between case studies and clusters of like case studies

portance of the regressor variables in terms of their ability to explain the observed variance of a team's collaborative systems thinking self-assessment.

A Recap Regression Analysis The following description of regression analysis is based on the following references: [14, 77, 123].

Equation 3.3 describes the linear relationship between the observed independent and dependent variables, where α describes the line's intersect and β describes the line's slope. The residual error, $e_i \sim N(0, \sigma^2)$, is the variability, or dispersion of the observed value of the dependent variable (y_i) relative to the fitted value ($\hat{y}$). The residual error of each observation is independent, but with constant variability.

$$y_i = \alpha + \beta x_i + e_i \tag{3.3}$$

When using regression analysis, a few assumptions must be met. First, the observations need to be independent. Second, the observed variable (y_i) must be linearly related to the regressor variable(s) (x_i). Finally, the conditional distribution of the observed value (y_i) about the fitted value ($\hat{y}_i$) given x_i is assumed to be both normal, with variance σ^2, and constant.

Independence of observations is established through data collection protocol. Because data were taken from teams from different organizations and programs, the observations can be assumed independent. A scatter plot of data can be used to check that there exists an approximate linear relationship between variables. Finally residual plots of the standard error, introduced in equation 3.7, can be used to check that the residual error is normally distributed with constant variance.

In practice, the data used in regression analysis represent only a small sample of a larger population. Thus, the regression equation is re-written to show the parameters used to describe the regression relationship (a and b) are approximates of their actual values (α and β). This is shown in equation 3.4, where $\hat{y}_i$ represents the fitted, or predicted, value of y_i given x_i. The constants of a and b are calculated by minimizing the sum of the square of the errors between y_i and $\hat{y}_i$.

$$\hat{y}_i = a + bx_i \tag{3.4}$$

The goodness of this estimate is represented by R^2, a measure of how much of the observed variability of y_i is explained by the regression relationship.

$$R^2 = \frac{\sum_{i=1}^{n}(\hat{y}_i - \overline{y})^2}{\sum_{i=1}^{n}(y_i - \overline{y})^2} \tag{3.5}$$

Another indicator of the strength of the relationship comes from estimating the variability about the regression line. The unbiased estimator, calculated in equation 3.6, is an estimate of the distribution of the residual error.

$$\hat{\sigma}^2 = \frac{1}{n-2}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 = \frac{1}{n-2}\sum_{i=1}^{n}(y_i - a - bx_i)^2 \tag{3.6}$$

As stated above, b is an estimate of the actual regression slope, β. Presuming a sampling distribution of $b \sim N(\beta, \frac{\sigma^2}{\sum_{i=1}^{n}(x_i-\bar{x})^2})$, the standard error of b can be estimated using the unbiased estimator, as shown in equation 3.7.

$$s\hat{e}(b) = \frac{\hat{\sigma}}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}} \tag{3.7}$$

Using the estimated standard error of b and t^* (the upper 2.5 percent of the Student's t-distribution) a 85% confidence interval for b is calculated as shown in equation 3.8. Using this range, the null hypothesis(that $\beta = 0$ and there is no relationship between y_i and x_i) can be tested.

$$(b - t^* \times s\hat{e}(b), b + t^* \times s\hat{e}(b)) \tag{3.8}$$

Multivariate Regression Analysis In the above discussion of regression analysis, x_i is presumed to be a one-dimensional variable. In practice, multiple variables may contribute to the observed variance in y_i, and by including multiple regressor variables a better estimate of y_i can be obtained. As with single-variable regression, the ideal relationship between the regressor variables and the observed variables is described by equation 3.9.

$$y_i = \alpha + \beta_1 x_{i1} + \beta 2 x_{i2} + \ldots + \beta k x_{ik} + e_i \tag{3.9}$$

As with the single variable regression, estimates of the intercept of partial regression coefficients are calculated by minimizing the sum of the square of the errors between the observed and fitted values of y. The fitter, or predicted value of y is calculated as shown in equation 3.10.

$$\hat{y} = a + b_1 x_1 + \ldots + b_k x_k \tag{3.10}$$

In multivariate regression, the unbiased estimator, shown in equation 3.11, is calculated as the sum of the square of the errors between the observed and fitted value divided by the number of degrees of freedom in the model, $n - k - 1$, where k represents the number of regressor variables used. This constrains the number of regressor variables used to $n - 2$.

$$\hat{\sigma}^2 = \frac{1}{n-k-1}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 = \frac{1}{n-2}\sum_{i=1}^{n}(y_i - a - bx_i)^2 \tag{3.11}$$

Likewise, the form of the goodness of fit measure is adjusted to account for the use of multiple regressors. The adjusted R^2 ($adjR^2$) only increases with each additional regressor variable if the extra regressor reduces the residual variance, $\hat{\sigma}^2$, and therefore improves the accuracy of the regression model prediction.

$$adjR^2 = \frac{(n-1)R^2 - k}{n-1-k} = 1 - \frac{\hat{\sigma}^2}{\sum(y_i - \bar{y})^2/(n-1)} \tag{3.12}$$

The assumptions and null hypothesis test described above apply to multivariate regression analysis with x_i replaced by the vector of values, $\vec{x}_i$.

Selecting and Comparing Regressor Variables The number of regressors used is constrained to $n-2$, e.g. for 10 case studies, a maximum of 8 regressor variables may be used. When selecting regressor variables from a large pool of potentials, it is best to use theory when applicable and to choose variables that show a high independent correlation to the dependent variable, as visible through a simple scatter plot. As there is no existing theory on collaborative systems thinking, correlations identified in the descriptive analysis will be used to choose regressor variables.

When using multivariate regression analysis, it is also desirable to compare the relative influence of each regressor variable. Equation 3.13 divides each regressor variable by its estimated standard deviation and multiplies each coefficient by the corresponding standard deviation, $b_j^* = b_j \times s_j$. The resulting beta-weights, b_j^*, allow for a more direct comparison of the contribution of each regressor variable.

$$\hat{y} = a + b_1^*\frac{x_1}{s_1} + b_2^*\frac{x_2}{s_2} + \ldots + b_k^*\frac{x_k}{s_k} \tag{3.13}$$

However, the beta-weights do not necessarily allow for conclusions to be drawn about the relative importance of each regressor variable. If regressor variables are correlated, their relative influence will also be correlated, and thus their beta-weights are not independent. It is therefore desirable, when possible, to select regressor variables that are uncorrelated or loosely correlated. The stipulation of weak or no correlation will help when down-selecting regressor variables.

Limitations on Quantitative Analysis Quantitative methods are especially useful for making comparisons between pre-identified groups. When groups are pre-identified, statistical tests can be used to demonstrate differences between the groups from which theory can be developed. Because the concept of collaborative systems thinking is introduced through this research, it was not possible to pre-identify groups based of differing collaborative systems thinking ability.

The other strength of numerical methods is the ability to calculate confidence interval for results. Large sample sizes result in smaller confidence intervals, thus strengthening the conclusions made. For example, Davidz used Chi-square tests to show statistically significant differences between pre-identified groups of engineers and scientists [35]. However, she had 200 data points upon which to draw. Given the relatively much larger efforts required to gather data on one case study (5-10 interviews, 10+ surveys, plus primary documentation), including a large number of case studies within the context of a single dissertation was infeasible. Therefore, tests of statistical significance are difficult to use in the context of this research.

Given these caveats the quantitative analysis performed is best interpreted as describing the conditions and traits observed. These methods are well aligned with the research objectives of exploring and identifying the traits of collaborative systems thinking teams. More data and further numerical analysis are required to narrow the bands of statistical confidence, thus allowing for more powerful statements of relationship and the use of methods, such as path analysis, to identify causal relationships.

3.1.4 Threats to Validity

As with all research there are threats to validity, or strength of conclusions, that must be addressed through the research methodology. In grounded theory research, the primary threats are construct, convergent, discriminant, external, and internal validity [146]. The first three types of validity concern the constructs used to build theory and were addressed in Section 2.3. The remaining two types of validity are external and internal validity.

External validity addresses whether or not results are generalizable. Choosing a representative and adequately sized sample help with external validity [146]. For case study based research, reaching saturation determines the necessary number of case studies. Saturation occurs when with each new case study, the observed patterns and concepts are the same as those observed in past case studies. For most research, saturation occurs after $\sim$10 case studies [158]. Additional considerations taken to ensure a representative sample are discussed in Section 3.2. Internal validity is achieved when a study eliminates extraneous variables as contributing to the phenomenon under observation. Triangulation, or using multiple sources to corroborate a piece of data, bolsters internal validity. Additional steps taken to validate this research are discussion in Section 3.2 and Chapter 5.

3.2 Research Design

This research is based on data collected through interviews and case studies aimed at exploring collaborative systems thinking within aerospace teams. This section describes the steps and tools used to gather these data. Figure 3-6 shows the data collection methods in relation to each other temporally and in terms of theory generation. The following section describes the level and units of analysis and the four phases that comprise the research design: the literature review, pilot interviews, case studies, and validation activities.

The latter three phases of the research design utilize interviews and surveys for data collection. These were conducted in accordance with the MIT Committee On the Use of Humans as Experimental Subjects (COUHES) guidelines and in accordance with Federal mandate (The Common Rule 45 CFR 36). A copy of the consent form signed by all participants is included in Appendix A.

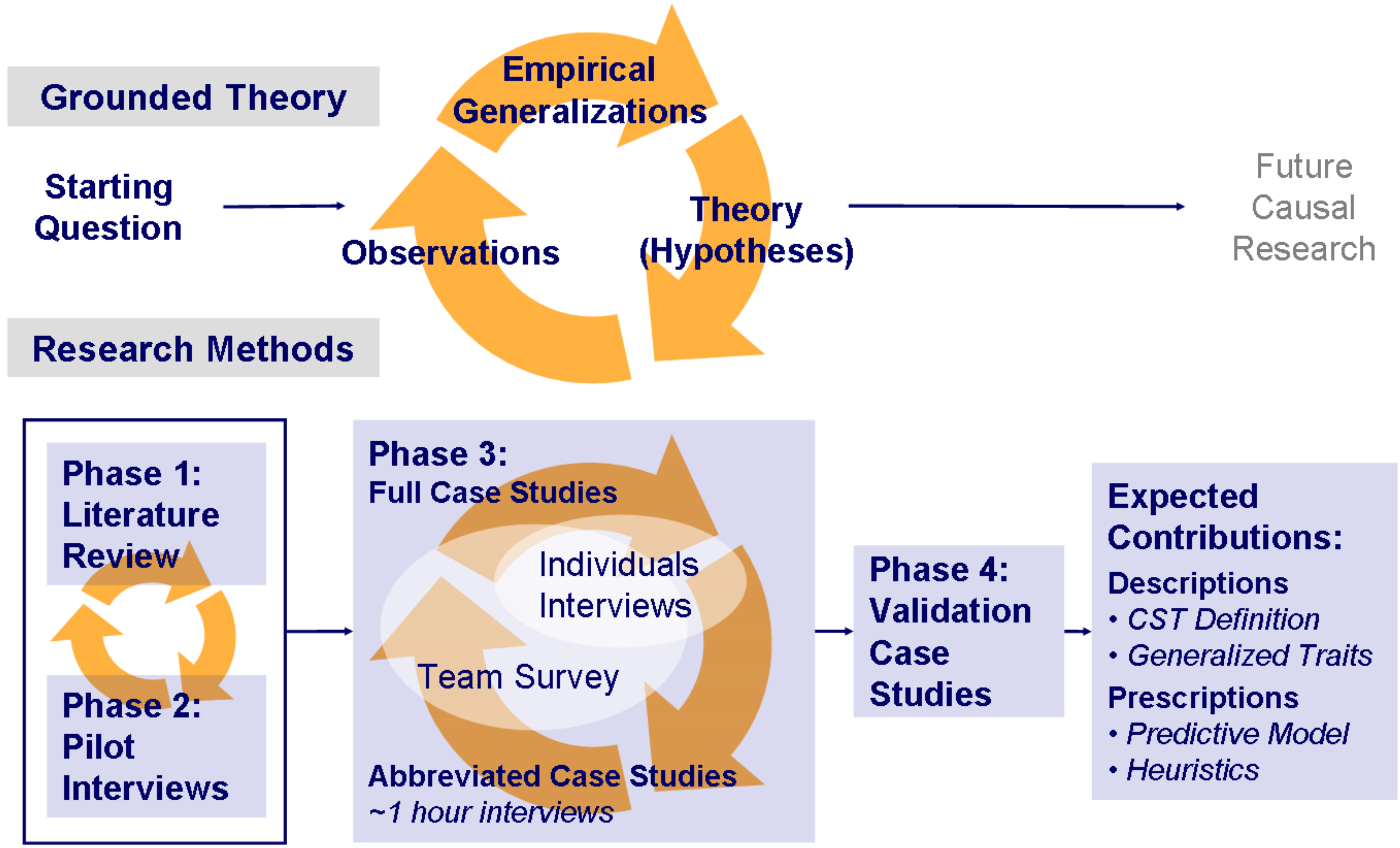


Figure 3-6: Diagram of methods used in research design.

3.2.1 Level and Units of Analysis

Social research methods define four common levels of analysis: individuals, groups, organizations and environments [95, 146]. Systems engineering research often deals with inter-level interactions [146]. The primary level of interest and any inter-level interactions are important to consider, both when choosing the constructs upon which to focus and when designing research tools.

Collaborative systems thinking is by definition a team property, and therefore this research focuses on the group level of analysis. The group level was chosen both because of the recent focus on team-based design (e.g. [34, 45, 68, 111, 147]) and to complement research on systems thinking at the individual level (e.g. [35, 52]).

Units of analysis may consist of individuals, roles, social artifacts, process models, or relationships [95, 146]. The units of analysis are sources of data that support the levels of analysis. Relevant units of analysis include individuals, their experiences and perceptions of team performance, and primary documentation. Such data can be collected both directly from team members and from team observers through interviews and surveys. To facilitate triangulation and comparison across case studies, it is important to define units of analysis that are comparable across organizations and contexts [146].

3.2.2 Literature Review

The literature review, Chapter 2, served to both direct the final topic of research and identify fruitful areas of exploration therein. The primary contributions of the literature review are the identification of four critical research constructs (collaborative systems thinking, team, process, and culture), definitions and metrics for these four constructs, and two frameworks used to summarize literature-based relationships between process and culture and team traits likely to influence collaborative systems thinking.

3.2.3 Pilot Interviews

Pilot interviews offered an opportunity to gain insight into the constructs of interest [146]. Pilot interviews occurred in parallel with the literature review, resulting in an iterative process whereby pilot interviews helped identify additional sources for inclusion in the literature review.

Eight pilot interviews were conducted to elicit feedback on the definition of collaborative systems thinking; to validate the emphasis placed on culture, process and team as critical enablers of collaborative systems thinking; and to provide feedback on case study tools. Participants in the pilot interviews were selected based on recommendations from committee members. The majority of interviewees were management or executive-level members of the aerospace industry with program oversight experience. Their backgrounds include experience in space, defense, and avionics. Their work experiences cover industry and government organizations. One architect (i.e. designer of buildings) was included to provide a breadth of perspective and because he is a principal in a firm that emphasizes holistic design methods.

Pilot interviews consisted of a twelve question semi-structured interview with an average duration of 60 minutes. The pilot interview questions may be found in Appendix B. Results of the pilot interviews are presented in Section 4.1.1.

3.2.4 Case Studies

Case studies were used to collect the majority of research data. Flexible and effective means to gather many types of information, case studies are well suited for exploratory research [158]. Case studies utilize both structured (e.g. surveys) and unstructured (e.g. open-ended interview questions and observations) data collection methods. Smartly chosen case studies are helpful in establishing external validity and ensuring results are generalizable [158].

Two types of case studies were used to explore collaborative systems thinking within the aerospace industry and are aimed at gathering data with both breadth and depth of detail. Full case studies consist of surveying and interviewing multiple people

Table 3.1: Case Study Selection Dimensions

Selection Dimension	Allowable Values
Industry Sector	Aircraft
	Spacecraft
Customer Base	Government
	Commercial
	Private
Team Size	Small (< 10)
	Large (≥ 10)
Design Phase	Conceptual
	Detail

on the same engineering team. Ten full case studies were conducted. Abbreviated case studies consist of interviewing one member of an engineering team about his or her team experiences. Sixteen abbreviated case studies were conducted. Combined, the data represent twenty-six different aerospace teams. These cases were chosen along selection parameters discussed below.

Case Selection

This research uses a cross-section design, taking snapshots of several teams at a single point in time. The objective when choosing case studies is to identify teams that are representative of the entire population as determined by a few key dimensions, shown in Table 3.1.

The four selection dimensions and allowable values were chosen based on applicable literature. Systems thinking within a team requires communicating technical information through multiple means and levels of abstraction. Because hardware and software are engineered at different levels of abstraction, only teams working predominantly with flight hardware were considered. Both aircraft and spacecraft teams were considered, but are differentiated between because the two industry sectors have distinct cultural traits, visible even within a senior-level college design class. The customer base is important because government customers exert influence via government regulations, some of which require a minimum level of demonstrated process maturity. By contrast, private consumers have relatively little influence over how the product is engineered. Companies selling to private consumers also tend to be comparatively smaller organizations. Team size is important from a communication standpoint. The objective of collaborative systems thinking is a communal systems awareness, and the number of people participating in the team could have a large influence on the ability of the team to engage in collaborative systems thinking. Finally, the program design phase is an important selection criteria because different types of information flow and interactions occur in different design phases. For instance, one might expect a conceptual design team to be engaging in more brainstorming, sketching, and abstract thinking. By contrast, teams in detail design should be more detail-oriented and may be using more detailed equations or models to convey design information.

Theoretical sampling was used to select case studies along the above dimensions. Within theoretical sampling, cases are chosen for their ability to help in formulating theory. Cases are selected to provide variation along characteristics thought important to the theory and to guarantee certain properties are explored [123]. Theoretical sampling is superior to convenience sampling because the results are more generalizable. Results can be made even more generalizable through the inclusion of an extreme case [123].

Figure 3-7 shows the actual case studies completed relative to the selection parameters. Both full and abbreviated case studies are shown. There are no companies currently selling spacecraft to private consumers, hence this combination is blocked out in Figure 3-7.

Full Case Studies

Ten full case studies were conducted. These consisted of a survey administered to all team members and interviews with a subset of team members and one non-team member familiar with the team's work. The full case study was designed to be

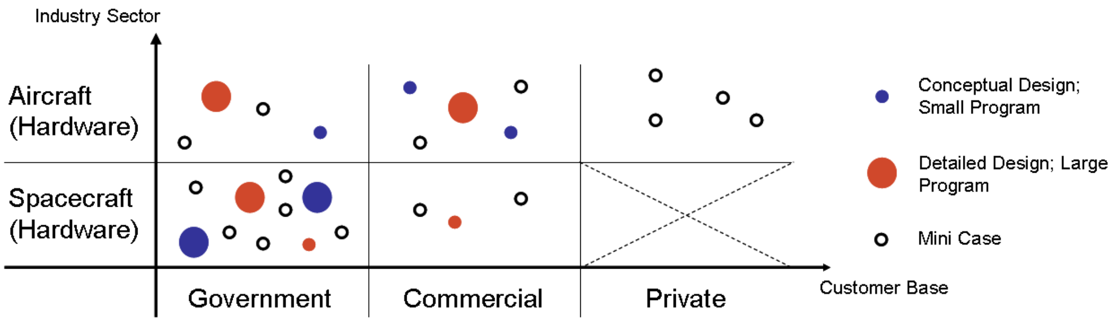


Figure 3-7: With ten full and 16 abbreviated case studies, the sample set of teams well represent the selection parameters.

conducted in approximately two days and require no more than two hours of any given engineer's time so as to comply with government time reporting requirements where applicable.

A sample full case study agenda consisted of a ten minute presentation to the team followed by ten minutes for team members to ask any questions they may have about the research. At this point, the team survey was administered and completed surveys were collected after about 30 minutes. On the second day of the case study, three or four team members participated in a one-on-one interview and a third party familiar with the team was also interviewed for purposes of obtaining another point of view on the team's systems thinking abilities.

Influence of Literature on Case Study Tool Design The case study instruments were designed around the literature frameworks presented in Section 2.2.4. These frameworks were expanded upon using the proposed construct metrics in Section 2.3. The case study survey and interview questions were designed to probe these metrics.

Figure 3-8 shows the intersection of the research instruments and the Culture-Process Framework proposed in Section 2.2.4. The matrix shows the tracing of each survey and interview question to the framework metrics. Additionally, the matrix shows how data from primary documentation (D) and observation (O) contribute to the characterization of teams within the case studies.

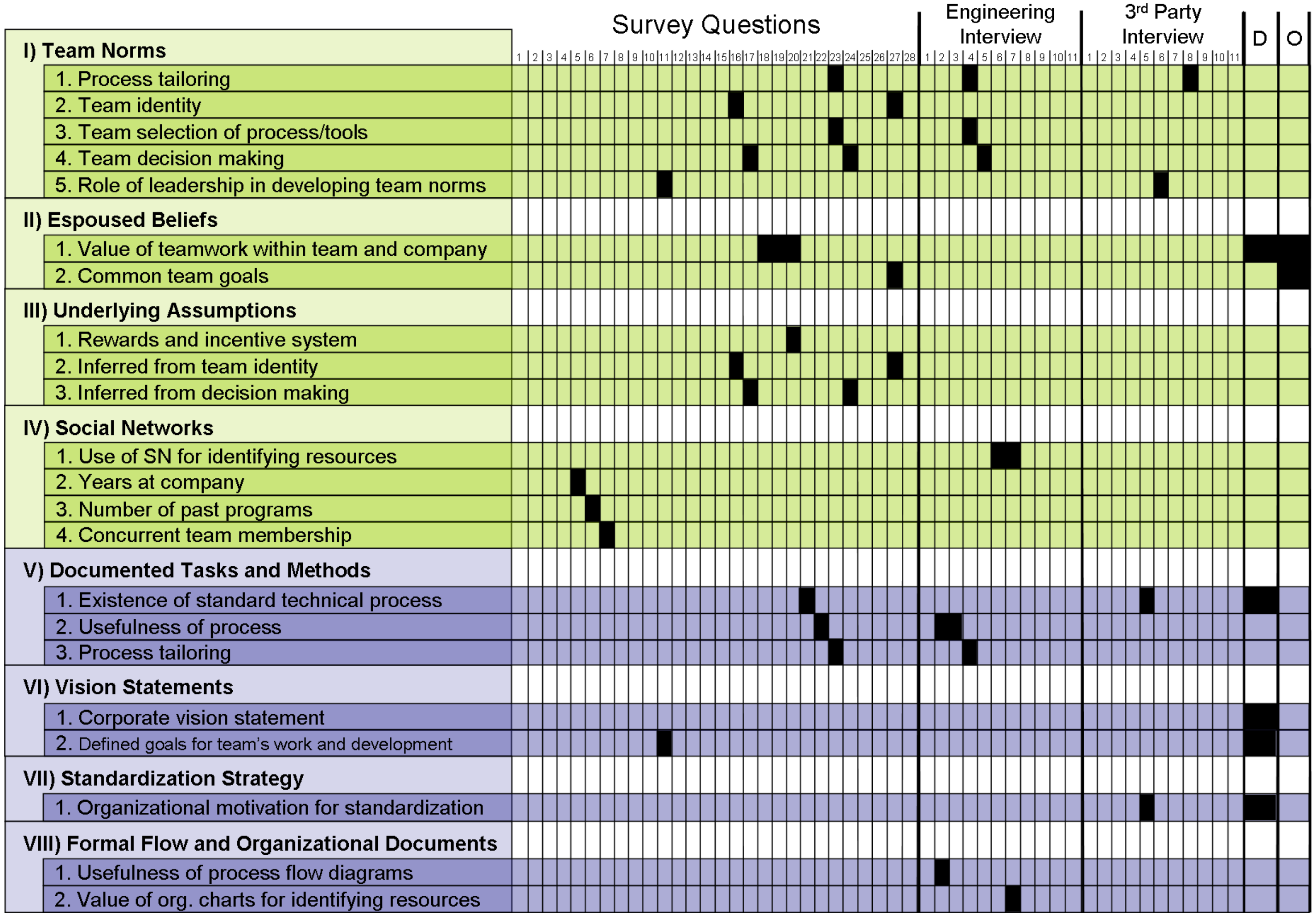


Figure 3-8: Matrix showing the links between the Culture-Process Framework proposed in Section 2.2.4 and the case study instruments.

Figure 3-9 shows similar information for the Team Traits Framework described in Section 2.2.4. As with Figure 3-8, Figure 3-9 shows how each survey and interview question is used to gather pertinent data for the case studies.

The survey and interview questions and guidelines for gathering data from primary documentation and observation provide multiple sources for each metric, facilitating triangulation. In the case of the surveys and engineering interviews, these instruments are administered to multiple people within each team, also facilitating triangulation. The design of each case study instrument is discussed in more detail below.

Survey Design Surveys are an effective method for gathering data on demographics and short answer responses from large numbers of individuals. In the context of this research, surveys was used to collect data driven by the Sections 2.3.2, 2.3.3, and 2.3.4 and the pilot interview results.

Within each case, a survey was used to collect data from all team members. Many teams had ten or more members and the survey facilitated collecting demographic data and individual opinions on aspects of team process usage and culture in an easily reducible format. A combination of multiple choice, numerical answer, Likert scale and short answer style questions are used. The survey was designed to last no more than 30 minutes (with an average actual duration of 25 minutes). Survey questions are shown in Appendix B.

Interview Selection and Design Interviews are an effective way to gather longer responses to questions about more abstract topics like work environment and team culture. Because interviews are more intensive, only a few engineers within each case study were interviewed. In the context of this research, interviews were used to collect data driven by Sections 2.3.1, 2.3.3, and 2.3.4. The interviews were especially useful in fleshing out detail behind the survey trends for process usage, decision making, and for obtaining an assessment of the team's collaborative systems thinking.

A semi-structured interview protocol with 11 questions was used. The average interview lasted about 60 minutes. The first part of the interview gathered descriptive

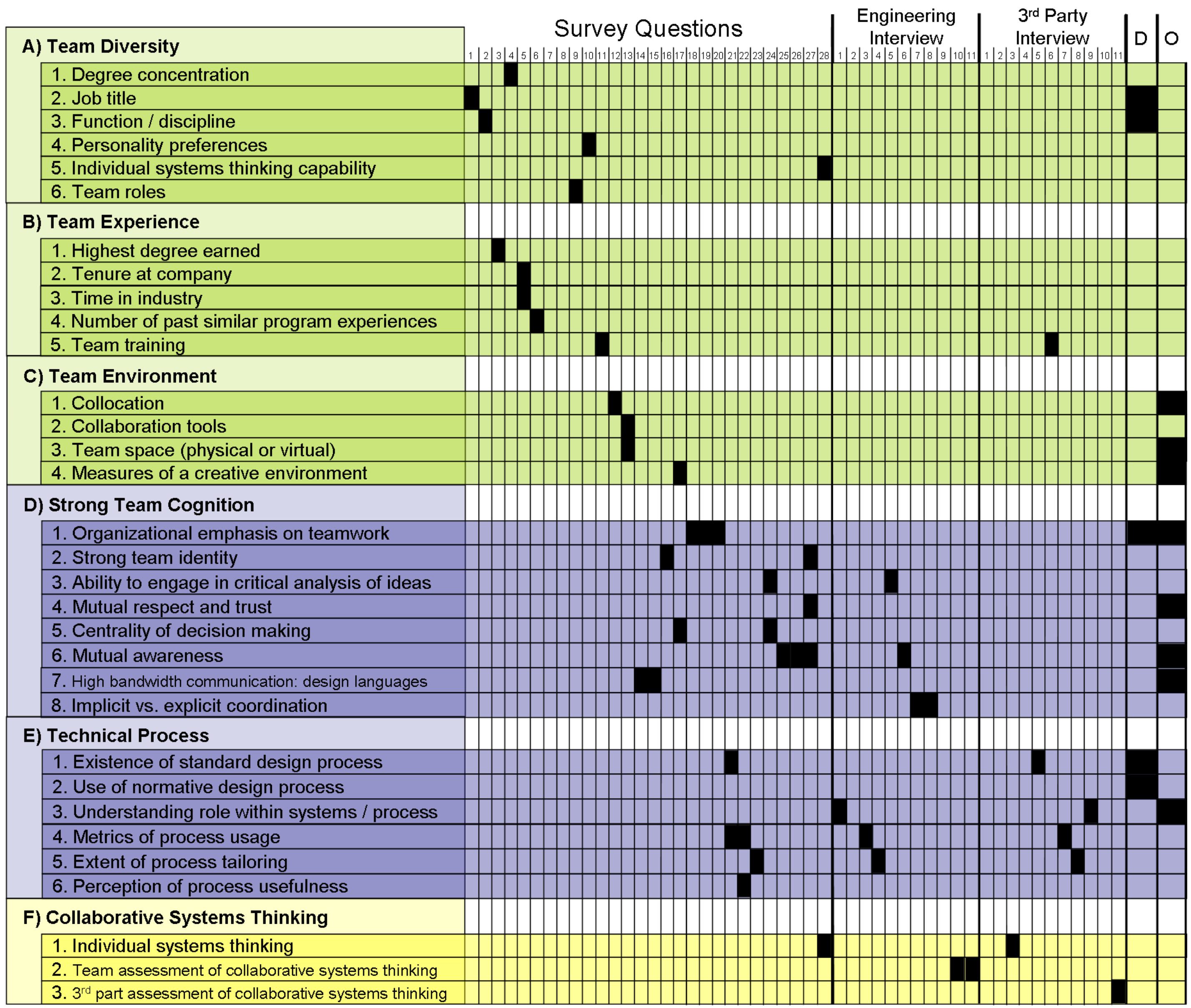


Figure 3-9: Matrix showing the links between the Team Trait Framework proposed in Section 2.2.4 and the case study instruments.

data to complement the survey results. The latter portion of the interview concentrated on systems thinking. Participants were asked to define systems thinking as an individual and team property. If their definition lacked any of the important components of the definition of collaborative systems thinking, a brief discussion ensued to sensitize the interviewee to the standard definition used in this research. At that point, the interviewee was asked to rate his or her team's collaborative systems thinking ability.

To avoid bias, interviewees were selected in advance by the case study contact. In general, a sampling of more and less experienced team members was requested. One interviewee familiar with, but not on, the team was also requested to participate in a modified interview to obtain a 3^{rd} party perspective on the team.

The interview protocol for both engineering participants and 3^{rd} party participants is shown in Appendix B.

Primary Documentation Primary documentation represents an artifact of the values, structures, and behaviors an organizations wishes to encourage among its employees. When considering the relationship between culture, process, and systems thinking, artifacts such as process documentation, organizational charts, and training materials are of interest. Primary documentation came from teams and from program and organization websites. In the context of this research, primary documentation was used to collect data driven by Sections 2.3.2 and 2.3.3.

Access to primary documentation was limited as many teams were not at liberty to provide access to their organizational charts or process documentation. However, valuable online documentation was found for each program, providing the researcher with a reasonably good understanding of each team's task and the technical context of their work.

Observation Because of the proprietary, and at times sensitive, nature of aerospace work, few opportunities were provided to directly observe team members. The role of observation is to provide baseline data to allow for comparisons between teams.

Data from team members are the richest source of culture and process usage data. However, these internally generated data may confound efforts to compare across teams. Observation by a third party, in this case the researcher, provides the context necessary to compare teams. Within the context of this research, observations were driven by Sections 2.3.2 and 2.3.4.

The predominant observation time was while administering the survey. Notes were taken on the team's physical surroundings and any observed team interactions. A field notes guide, shown in Appendix B, was used to help organize and record observations.

Abbreviated Case Studies

Abbreviated case studies were used to improve the distribution of samples within the target population of aerospace engineering teams. One-hour semi-structured interviews, the abbreviated case studies offered an opportunity to question and explore ideas captured in memos during the full case studies. The data from abbreviated case studies are qualitative and anecdotal, but help in deciding which explanatory variables are likely to be more generalizable across contexts. The abbreviated case studies also provide data for vignettes to better illustrate the results and conclusions of this work.

Questions asked in the abbreviated case study centered around an individual's definition of systems thinking, discussion to introduce the interviewee to the working definition of collaborative systems thinking, questions about interviewee team experiences, and reflection upon what traits enabled or prevented these teams from engaging in collaborative systems thinking. Questions based on theoretical memos from the full case studies were used when appropriate.

3.2.5 Validation Activities

Validation is difficult with grounded theory research. One method proposed by proponents of grounded theory is to take the resulting theory back into the field and to validate the results through testing the theory's explanatory power on a new case [140]. While not a foolproof method of validation, using the results of additional case studies to validate the regression model is a powerful way to show the results are relevant and generalizable. As such, eight 'predictive' case studies were used to validate this research. The case studies consisted of a survey and interview with individuals from teams not involved in the initial research. These abbreviated cases addressed the subset of measures found most important through regression analysis. A short interview was then used to gauge the team's self-assessment of its collaborative systems thinking ability and the results were be compared to the regression analysis. Results falling within the 90% confidence range of the regression model provide further data to support the generalizability of this research. Results falling outside of the 90% confidence range point to limitations in generalizing this research. Validation case studies were chosen from within the aerospace industry, but from combinations of industry, customer, and program phase not seen in the full case studies so as to push boundaries to which this research may be generalized.

Validation strategies employed by past similar research include the use of control groups and 'blue chip.' While the use of control groups is considered desirable from a validation standpoint, the number of case studies required is infeasible. 'Blue chips' experts are individuals with backgrounds that place them in positions to knowledgably comment on the phenomenon under observation. In this context, individuals in charge of systems engineering training or development within large aerospace and defense companies would be well suited to comment on the results. The use of 'blue chip' experts is a viable way to circumvent the small sample size, but the opinions of 'blue chip' experts are still subjective and do not demonstrate in a concrete manner the relevancy and generalizability of results.

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Chapter 4

Analysis and Results

4.1 Analysis

The following are examples of data analysis for each data source: pilot interviews, full case studies, and abbreviated case studies. The outputs of qualitative data analysis and descriptive quantitative analysis are presented and discussed. These outputs, combined with inferential analysis and modeling, are presented in Section 4.2 as answers to the original research questions and objectives.

4.1.1 Pilot Interviews

Eight pilot interviews were conducted to elicit feedback on the definition of collaborative systems thinking, to validate the emphasis placed on culture, process, and team as critical enablers of collaborative systems thinking, and to provide feedback used in development of case study tools.

The first step in analyzing the pilot interview data was entering the transcripts into MaxQDA for text analysis. Commonly occurring phrases and ideas were tagged, organized, and combined when appropriate, resulting in a set of commonly cited codes. After a set of unique codes was identified (open coding) the codes were reorganized into categories (axial coding), grouping similar code constructs and providing greater explanatory power. All codes identified are emergent, that is they emerged from the transcripts. Axial coding resulted in three main categories: definition-related, enablers, and barriers. Within the enablers and barriers categories, codes were further subdivided into subcategories of culture, standard process, and team traits as informed by the critical constructs identified in the literature review. The construct of leadership emerged as an important factor during the case studies and is included within the team traits subcategory. Figure 4-1 shows the resulting code hierarchy and code frequencies for each pilot interview.

As can be seen in Figure 4-1, far more enablers than barriers were identified. Within the enabler category, the number of different codes identified are evenly split among the subcategories. However, the majority of identified barriers to collaborative systems thinking were cultural. As part of the pilot interviews, interviewees were asked in what ways collaborative systems thinking differed from individual engineering systems thinking. These responses are coded in the definition-related (and general comments) category. These comments center on using a holistic approach to understand the problem and achieve product success.

Table 4.1 shows examples of raw text supporting eleven of the most common codes identified in the pilot interview transcripts. Each code was cited between 6 and 12 times across the 8 pilot interviews. Text supporting the remaining pilot interview codes is included in Appendix C.

Figure 4-2 shows the codes organized by the number of times cited across all pilot interviews. The six most frequently cited codes relate to those process and team traits seen as enabling collaborative systems thinking. It is worth noting that many of the most frequently cited codes refer to an engineer's (or team's) soft skills and culture or environment. Nine of the 32 most frequently cited codes refer to technical aspects of engineering a system: e.g. management, technical depth of teams, producing a product, or finding interfaces and interconnections. The remaining 23 codes (representing over two-thirds of commonly cited codes) refer to communication, team interactions, and social leadership. This balance emphasizes the fact that collaborative systems thinking is a social phenomena and is greatly influenced by the dynamics and personalities on a given team.

Figure 4-1: Results of open and axial coding from pilot interviews.

Table 4.1: Supporting Text for Selected Pilot Interview Codes

Definition Codes

CST Involves Producing a Product	"Teams must realize successful products"
	"The idea of producing a product is absent from the systems thinking definition"
CST Involves Understanding the Problem	"In a group it is important to understand the problem at hand"
	"Program teams focus on understanding problems"

Culture-Related Codes

Creativity and Multiple Thinking Styles Enable CST	"Metaphorical thinking allows for exploring and making connections"
	Teams need "innovative individual thinking"
A Supportive Environment Valuing Systems Thinking Enables CST	"Teams require constant reminders to stay in a systems thinking mode"
	"Individual team members must listen, understand, and make value-add comments to the team"
A Willingness to Ask and Answer Questions Enables CST	"Teams must be constantly questioning"
	"A managerial culture where people can raise their hands and ask for help when in trouble"
	"Teams must be willing to answer questions"

Process-Related Codes

Shared Language and Taxonomy Enable CST	"Process enables communication"
	"Process provides a mutually agreed upon taxonomy"
	"Shared reference frame," "Shared framework"
Knowledge Management Enables CST	"Need to share experiences on a diverse set of missions"
	"Tools should support frictionless data flow"
Tools to Promote Systems Thinking Enable CST	"Standard process provides a tool to promote systems thinking"
	Process is a "reminder" and "companion" for systems thinking

Team Trait Codes

Socialized Experts/ Shared References Enable CST	"Teams need many experts–well socialized"
	"Mature teams have socialized members"
	"Groups need a shared view"
High Communication Bandwidth Enables CST	"You get better results when you can look someone in the face"
	"Teams need an environment that supports interactions"
CST Requires Technical Depth, not Width	"People are on teams because of their particular expertise"
	"Teams need more areas of technical depth"

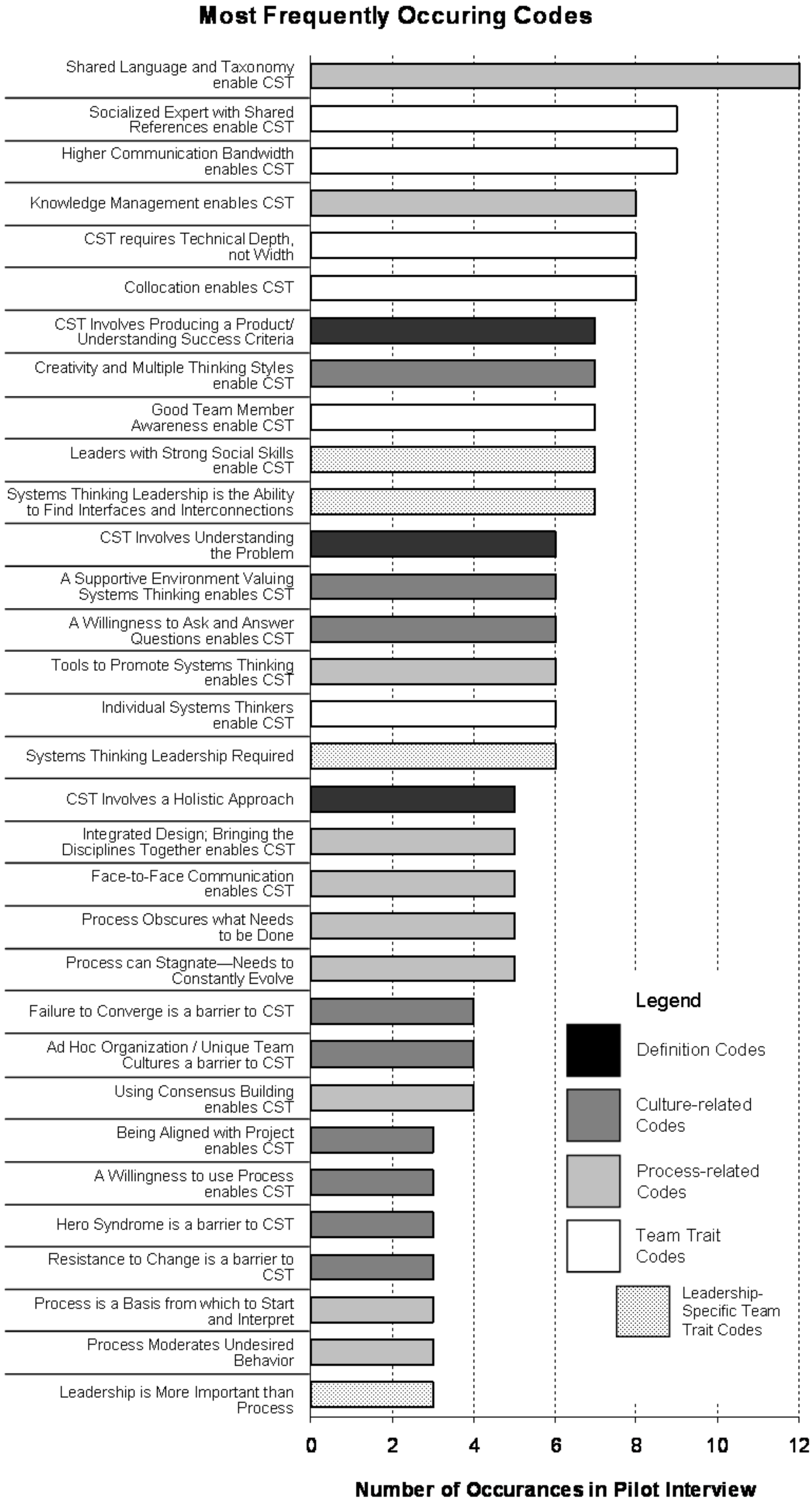


Figure 4-2: Codes that appeared most frequently within the pilot interviews.

Figure 4-3 shows those codes cited in the greatest number of interviews. Comparing and contrasting Figures 4-2 and 4-3 provides insight into which codes and constructs are most important: differentiating individual interviewee enthusiasm from commonly held opinions. The process-related codes of 'integrated design' and 'face-to-face' communication are more universally cited than frequently cited, emphasizing the importance of bringing people together during the design process in a manner that facilitates the exchange of technical information. The team trait codes of 'collocation enables CST' and 'good team member awareness enables CST' have relatively lower importance when viewed in terms of the number of interviews citing these codes– indicating these are concepts worth exploring but are not universally recognized.

Figure 4-4 shows the proximity of codes cited within the pilot interviews. Within this figure, dots indicate the number of times two codes appear one paragraph or less apart. From the figure, it can be seen that codes along the diagonal (i.e. codes within the same category) often appear in close proximity. For simplicity of presentation, the codes have been clustered according to the critical research constructs. Off diagonal clusters indicate possible relationships of interest between constructs. Off-diagonal relationships with five or more links are circled in Figure 4-4. The figure shows a link between cultural enablers and leadership enablers. This link is logical within the context of applicable literature. Leaders have the capability to influence a team's culture. Likewise, a team's culture will influence its choice of leader [126]. Another link identified is between cultural enablers and cultural barriers. This link is logically obvious and an artifact of separating enablers and barriers during axial coding. The third and strongest off-diagonal link is between process enablers and team trait enablers. Reviewing these codes indicates the relationship between process and team traits centers about links between 'composing teams of individuals with shared references' and the 'shared taxonomies provided by process' and between the team trait of 'collocation' and the types of 'interaction facilitated by process.'

The results of pilot interview analysis were used, along with results of the literature review, to inform a definition of collaborative systems thinking as discussed in Section 4.2.2.

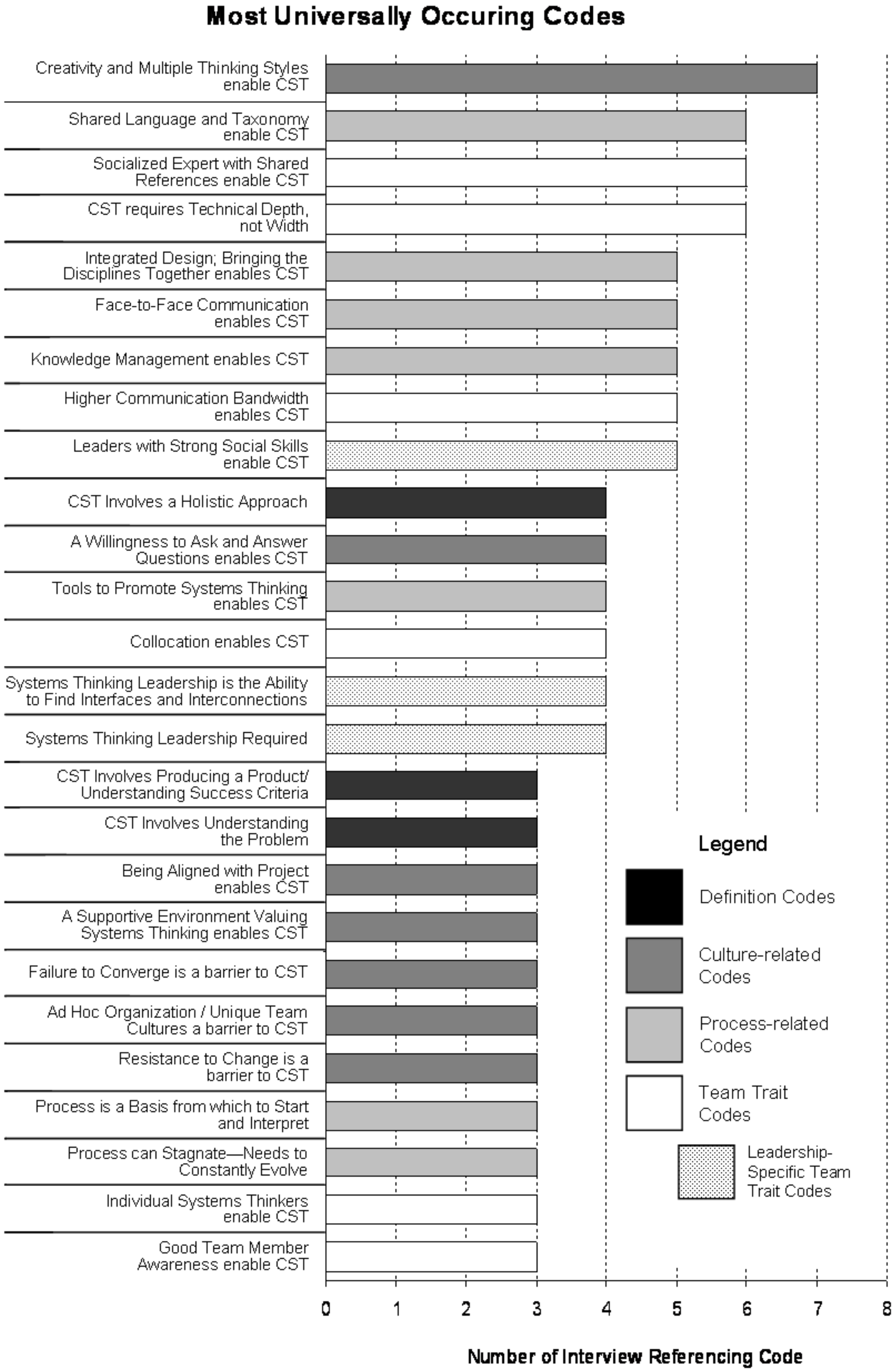


Figure 4-3: Codes that appeared in the greatest number of pilot interviews.

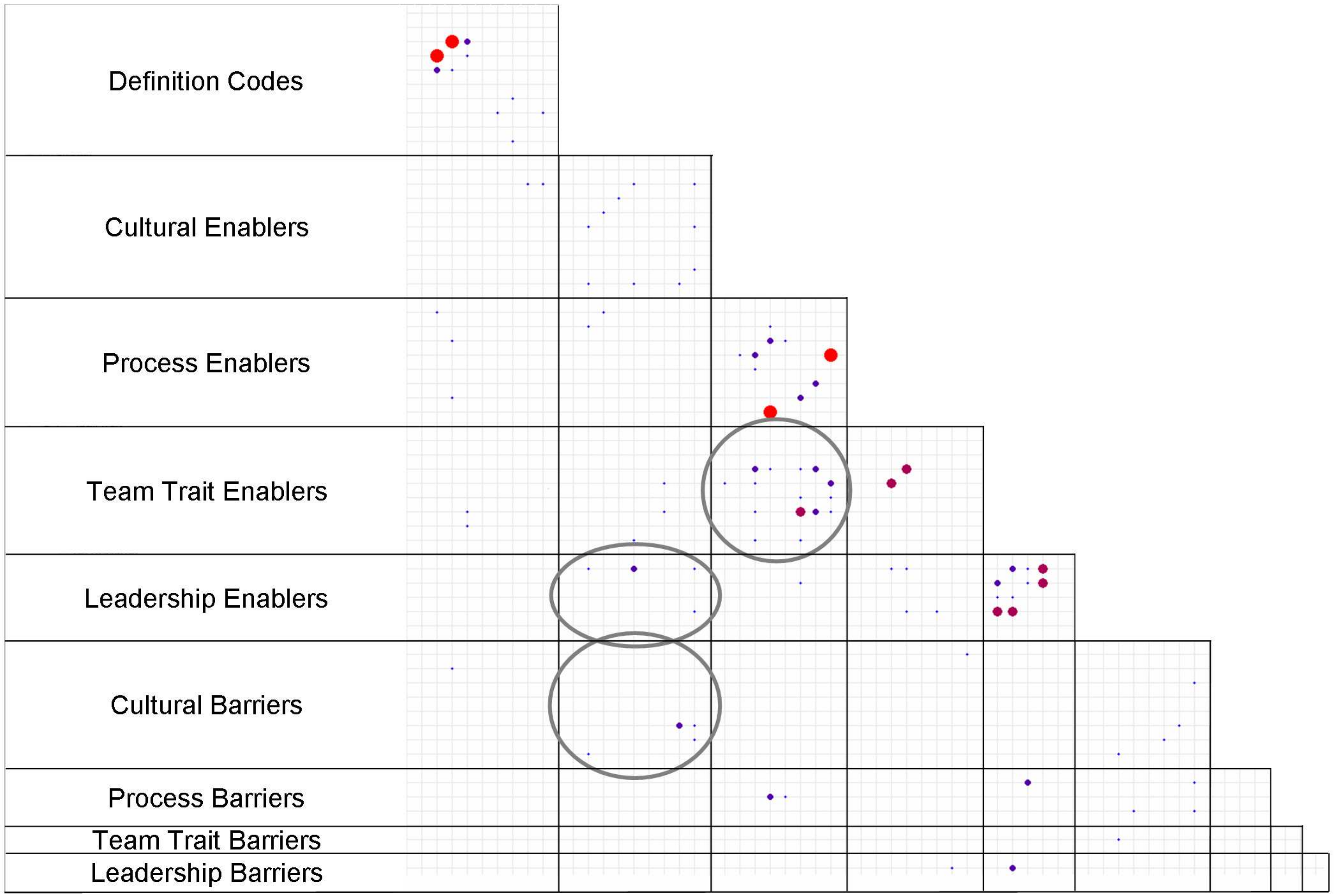


Figure 4-4: Links between off-diagonal code categories indicate possible links between constructs.

4.1.2 Case Studies

Full Case Studies

This section contains results of descriptive analysis from the full case studies. For brevity and clarity the results are graphically presented in the context of the literature frameworks introduced in Section 3.2.4.

Quantitative and qualitative data from the surveys and interviews were used to triangulate high-medium-low ratings for each team and component of the literature framework.

Figure 4-5 shows an interpretation of data collected in support of the framework linking process and culture. For comparison, each team's collaborative systems thinking assessment ranking is included at the bottom of the framework. While both positive and negative correlations were found between survey questions responses and collaborative systems thinking, the graphical data have been adjusted to all represent positive correlations with collaborative systems thinking. Bulk survey data, are reported in Appendix C. The most interesting observation from Figure 4-5 is that those cultural aspects of the framework show the best correlation to collaborative systems thinking. Those metrics in the 'espoused beliefs' and 'social networks' categories show the greatest alignment.

Figure 4-6 shows that measures of team experience and cognition are the team traits most predictive of collaborative systems thinking. It is interesting to note that some teams with low collaborative systems thinking rankings rated their environments highly. On one case study in particular, J9, interviewees spoke about efforts to reach out to younger engineers with open work spaces with sofas, wireless internet access, and coffee makers. However, these types of environmental luxuries do not appear to influence collaborative systems thinking. This raises the questions of whether industry is misplacing efforts to attract and retain younger engineers. Past research has shown shorter program lifecycles that provide a realistic expectation for seeing the systems through to completion do help with workforce attraction and retention [115].

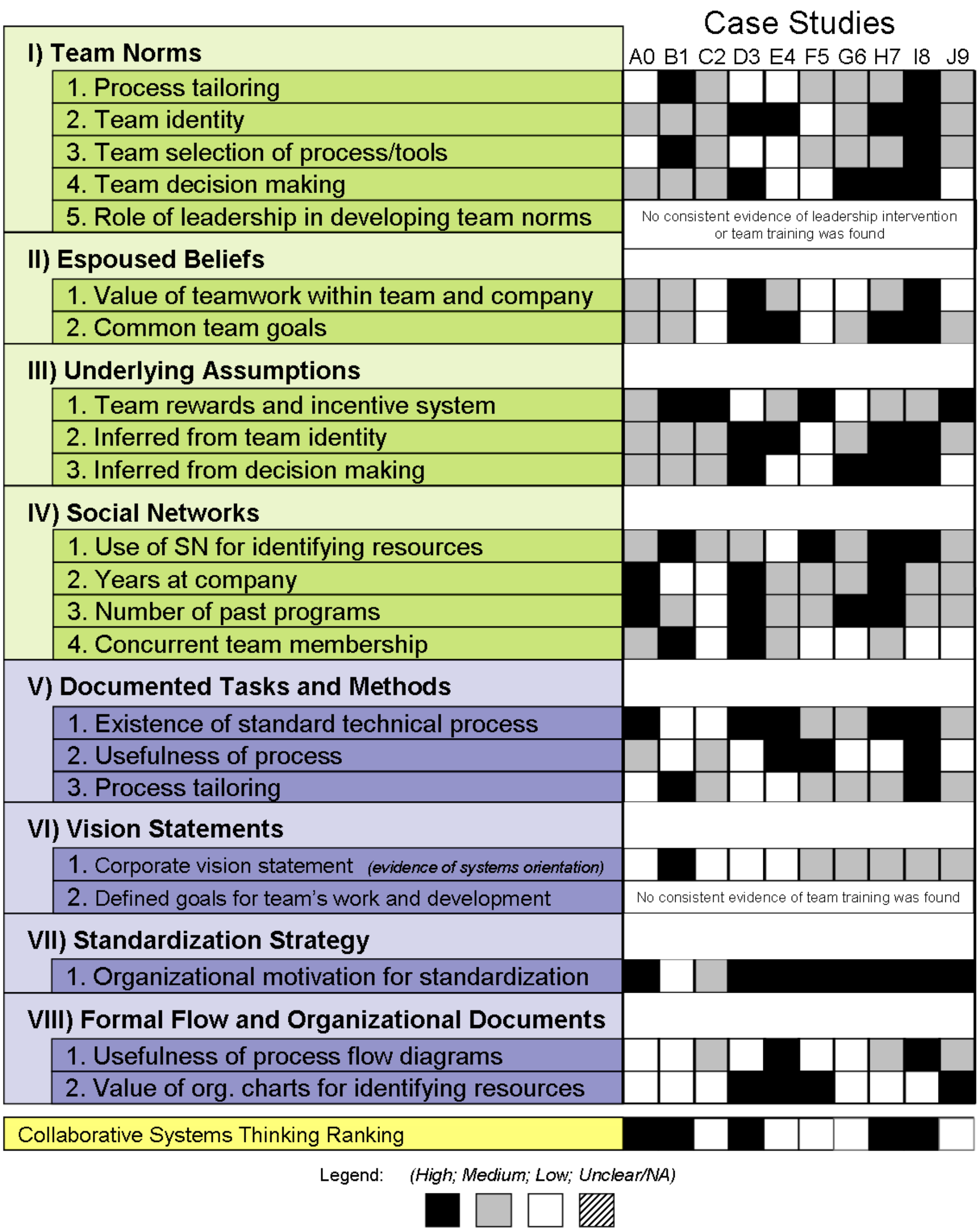


Figure 4-5: Graphical representation of data collected within the framework linking process and culture.

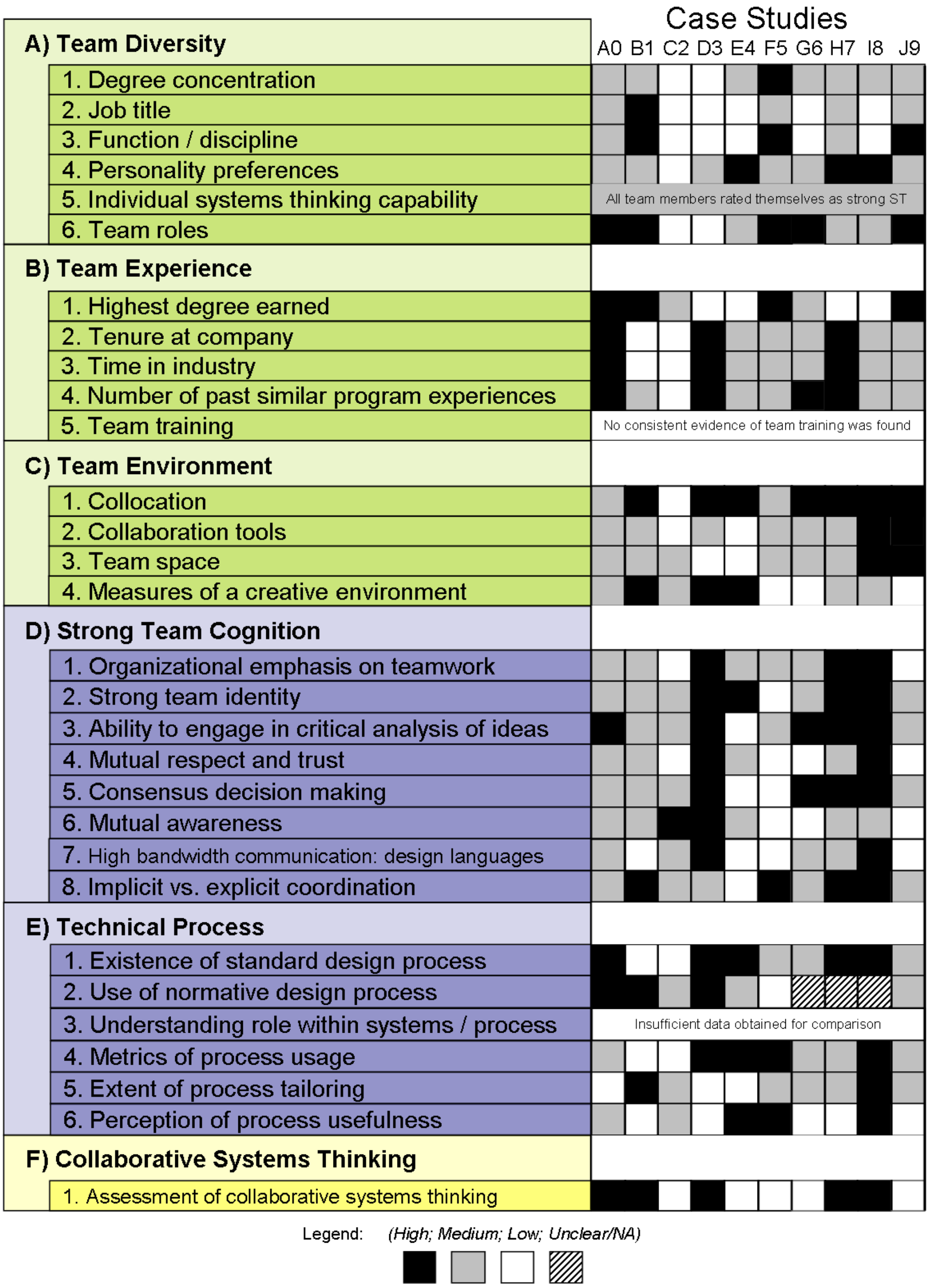


Figure 4-6: Graphical representation of data collected within the team trait exploration framework.

In addition to the metrics included in the original frameworks, two team traits emerged as important during full case studies: a three-level team structure and a social and technical leadership style. These are included, along with case selection parameters, in Figure 4-7. The existence of a three-level team structure and social and technical leadership proved highly correlated to collaborative systems thinking. Despite the strong predictive power of the emergent traits, these are subjective and difficult to measure metrics.

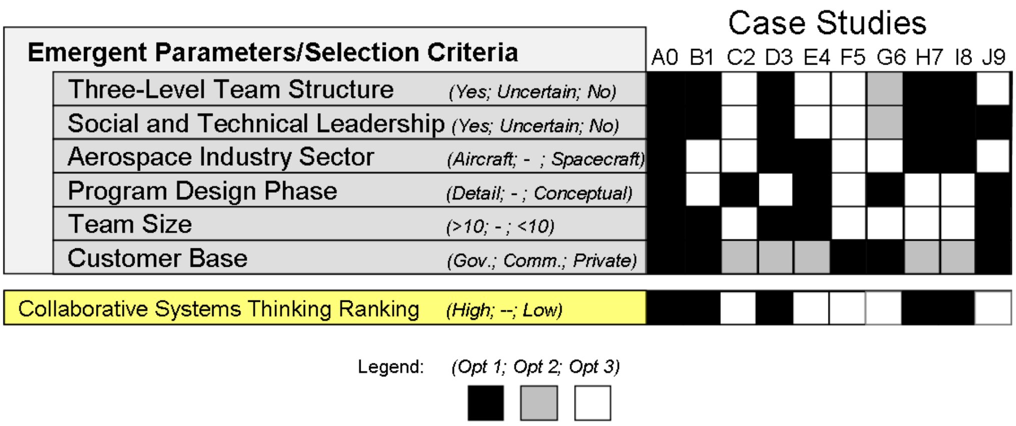


Figure 4-7: Graphical representation of emergent metrics and case study selection parameters.

Figure 4-8 shows the relative frequency of common codes from the full case studies. The case studies were placed into two groups based on collaborative systems thinking ranking. Higher collaborative systems thinking team interviews were more focused than the lower collaborative systems thinking team interviews. This is further shown by the figures in Section C.3, which show those codes comprising 60% of all comments from each set of case studies. Within Figure 4-8, the top fifteen codes from each group of case studies are shown. Codes representing concepts unique to a group are shaded blue (darker gray). Concepts that are similar to each other are shaded in yellow (lighter gray). Links between same/similar concepts in each group are shown through linking lines. Differences between commonly cited codes in the higher and lower collaborative systems thinking teams show that higher collaborative systems thinking teams spoke about ‘trusting and open cultures,’ ‘using consensus decision making,' the importance of 'past program experience,' and the use of 'design reviews to stimulate cross-discipline communication.' These codes are absent from the lower collaborative systems thinking teams interview transcripts.

Given the data collected above, clustering analysis was used to gauge which teams were most similar. A collection of average and median survey responses were used. Medians were used whenever a metric had significant outliers (e.g. number of years in industry) or the data are ordinal. In addition to the survey data, the emergent parameters were included (1=present, 0=not present / inconclusive). Each vector of metrics (with one value for each case study) was normalized to ensure no single measurement would overwhelm the distance calculations. Collaborative systems thinking rankings were not used in the clustering analysis except as a point of comparison.

Figure 4-9 shows the results of cluster analysis. Teams group, or cluster, according to higher and lower collaborative systems thinking rankings. This gives credence to the effectiveness of the measures used for differentiating collaborative systems thinking teams.

Measuring Collaborative Systems Thinking There are no universally accepted measures of team thinking, let alone collaborative systems thinking. As such, a triangulation method was used in which the opinions of multiple people were compared and combined to compile a rating of a team's collaborative systems thinking.

Because the concept of collaborative systems thinking is new to this thesis, steps were taken to ensure people across different teams were providing their evaluation of the same concept. To try and standardize responses, individuals were first asked to provide their own definition of systems thinking. This was followed by a researcher facilitated conversation highlighting any aspects of the collaborative systems thinking definition absent from the individual's definition. Usually individual definitions included the the five themes derived from common systems thinking definition identified in Section 2.2.2, but may have lacked an appreciation for the role of social interactions and effective communication–despite both these themes being prevalent in responses to other interview questions. After this discission, individuals were asked

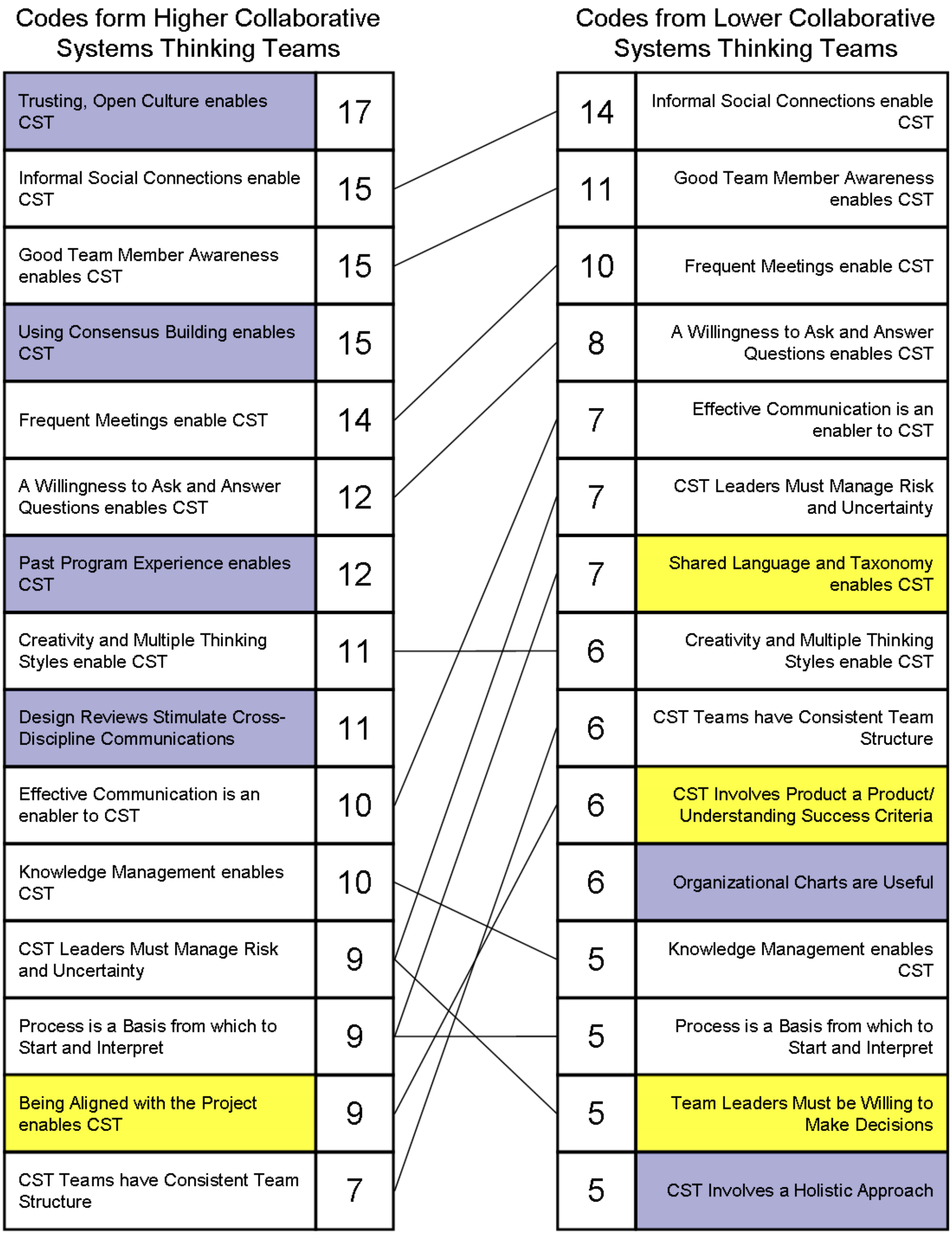


Figure 4-8: Comparison of the code frequencies from higher and lower collaborative systems thinking teams.

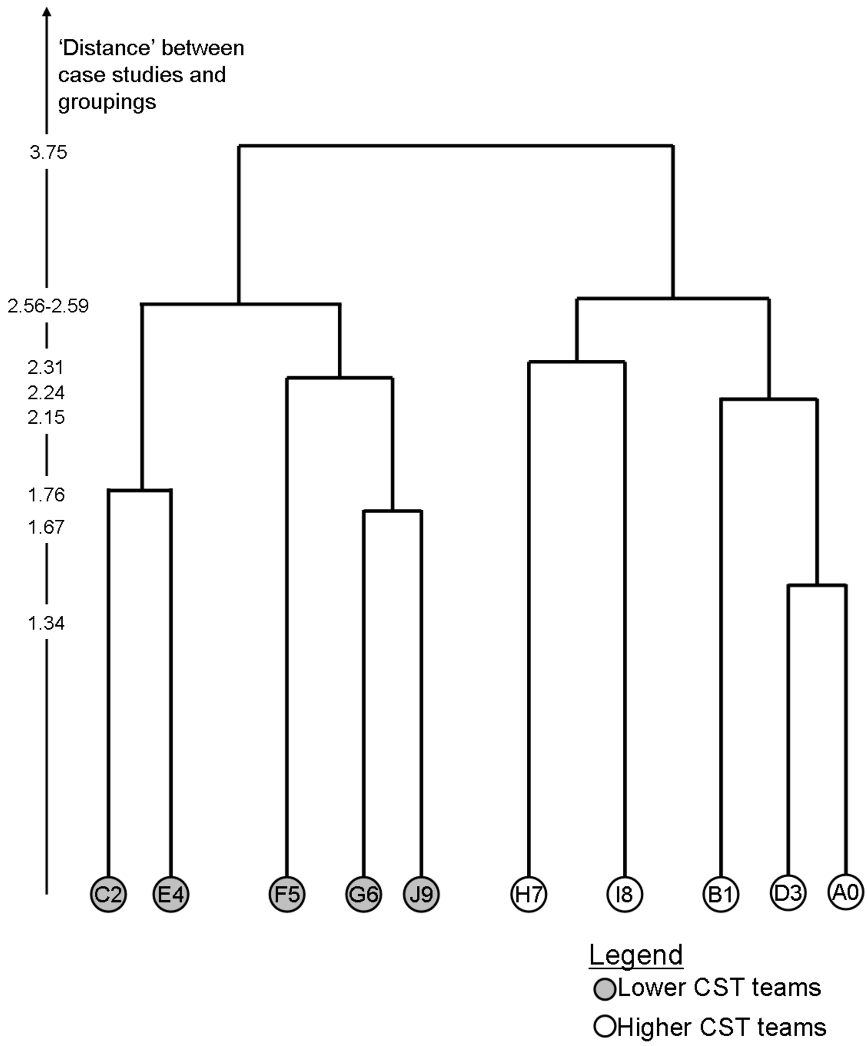


Figure 4-9: The grouping of case studies shows the measured data do effectively distinguish between higher and lower collaborative systems thinking teams.

Table 4.2: Examples Showing Consistency Within Team Collaborative Systems Thinking Ratings

Case ID	Mean Team Self-Rating	StdDev of Team Ratings
B1	7.9	0.9
C2	5.6	0.9
F5	5.5	2.3

to rate their team's collaborative systems thinking on a 1-10 scale and to provide supporting examples upon which they based their assessment. Individuals were coached that a rating of '5' would be average. An argument is made for treating these initial data as interval on the basis of allowing for triangulation to obtain a more accurate assessment of a team's collaborative systems thinking ranking.

The above process was repeated with multiple people on a single team plus one leader / supervisor with insight into the team's interactions and performance. The standard deviations for team ratings was less than the difference between the higher and lower clusters of ratings, substantiating the differences between higher and lower collaborative systems thinking teams.

Data for three case studies, those with the greatest number of individual observations, are shown in Table 4.2. Case study F5 is included because it showed the greatest observed variability in collaborative systems thinking rankings.

Abbreviated Case Studies

Sixteen abbreviated case studies were conducted to provide insight from a greater cross section of the industry than was feasible to include in the full case studies. These approximately one-hour interviews explored individuals' team experiences and their opinions on which conditions were enablers or barriers to collaborative systems thinking within those team experiences.

As was describe previously, text analysis was conducted in MaxQDA. Commonly occurring phrases and ideas were tagged and organized. Codes identified in the pilot interviews and full case study interviews were used to seed the code list, and additional codes emerged from the texts. Because of the greater number of interviews and variety of topics covered, data presentation is limited to the most common and most universal codes from these interviews.

Table 4.3 shows examples of raw text supporting eleven of the most common codes from abbreviated case study interviews. Each code was cited between 8 and 16 times across the 16 abbreviated case study interviews. Text supporting the remaining codes is included in Appendix C.

Figure 4-10 shows the codes organized by the number of times cited across all abbreviated case studies. Six of the ten most common codes are the same as those from the pilot interviews. The four new concepts, also seen in the full case study interviews, are 'effective communication,' 'using consensus building,' 'recognizing the social component of engineering,' and having an 'open and trusting culture.' These codes deal with the cultural and social components of engineering teams. As with the pilot interviews, the prevalence of 'soft skill' codes emphasizes that collaborative systems thinking is a social phenomena and is greatly influenced by the dynamics of and personalities on a given team.

Figure 4-11 shows those codes cited in the greatest number of abbreviated case studies. Comparing and contrasting Figures 4-10 and 4-11 provides insight into which codes and constructs are most important. The primary different between the most common and most universal codes is that the leadership trait of providing 'appropriate guidance' appears more universally than common. Codes prevalent in the abbreviated case studies but not in the pilot interviews include a set of codes that group into four meta-categories: product orientation, the Socratic method of questioning, leadership facilitated consensus-based decision making, and the importance of a diversity of thinking styles. These codes are listed in Table 4.4 and are addressed in greater detail in Section 4.2.3.

Table 4.3: Supporting Text for Selected Abbreviated Case Study Codes

Culture-Related Codes

Effective Communication is an Enabler to CST	"Someone can be a genius, but his intelligence is lost of it cannot be communicated to others"
	"Communication is listening to not only what is said, but what is not said. Body language is important"
Trusting, Open Cultures Enable CST	"Information has to flow freely; without hesitation"
	"Groups must have trust, must treat each person individually"

Process-Related Codes

Using Consensus Building Enables CST	"The difference between decision making on systems and non-systems is that systems require everyone to understand the points being considered through discussion and consensus building"
	"Good systems thinking leaders ask other for their input before expressing their own opinions"
	"The common denominator in achieving consensus is that all participants have an opportunity to provide input and be heard"
CST Teams Use Intelligent Questioning to Facilitate Systems Thinking	"Effective systems thinking teams ask high level questions, then drill down to the right level of detail"
	"Using the Socratic method leads to a better ends"
Frequent Meetings Enable CST	"We had weekly meetings to keep people aware of hot topics"
	"Regular meetings were instituted to improve interactions between the specialists and analysts–to get them communicating"

Team Trait Codes

CST Team Leadership Provides Appropriate Levels of Guidance	"Leadership should know when to lead, when to back off, when to allow people to make mistakes"
	"When necessary, leaders should drive teams towards central goals"
Individuals with Different Levels of Systems Thinking Facilitate CST	"Not everyone can be worrying about the entire process/program"
	"Everyone should understand some amount of the context–at least one level up in the block diagram"
Team Leaders Must be Wiling to Make Decisions	"Leaders should solicit multiple inputs, but are still responsible for the final decision "
	"A strong leader gathers information from the team in order to make a decision"

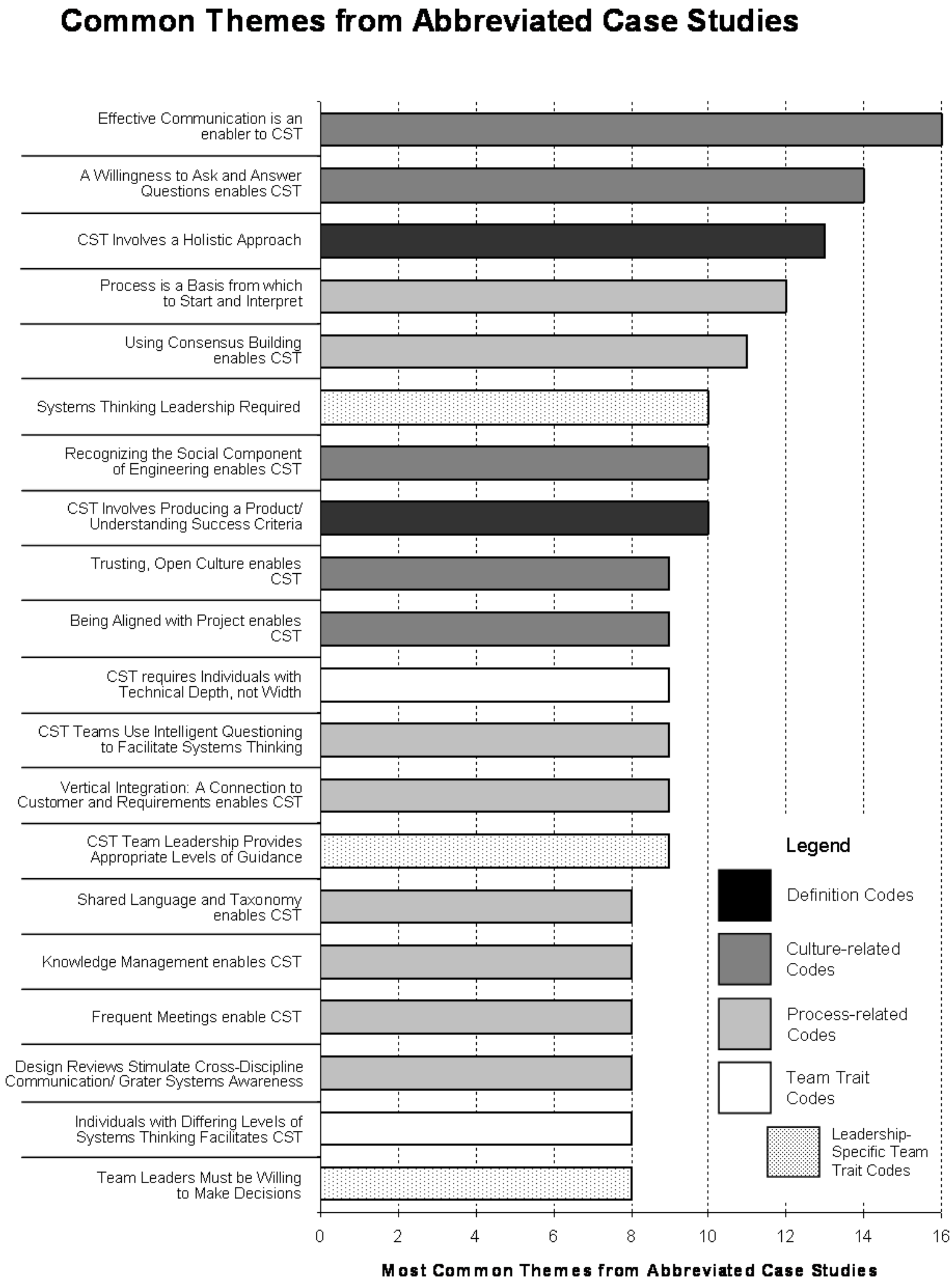


Figure 4-10: Codes that appeared most frequently within the abbreviated case studies.

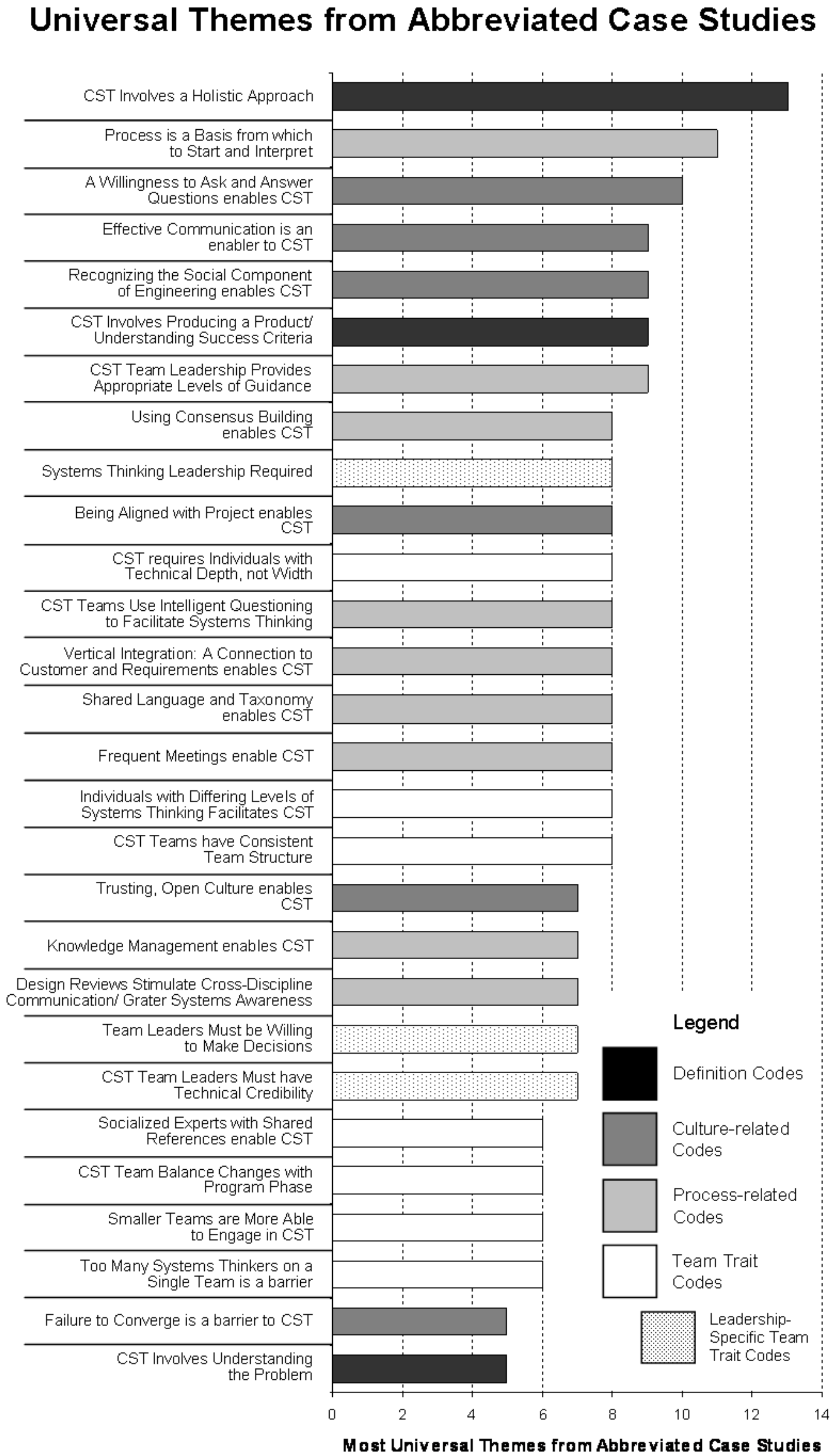


Figure 4-11: Codes that appeared in the greatest number of abbreviated case studies.

Table 4.4: Codes from the Abbreviated Case Studies not Found in the Pilot Interviews

	Abbreviated Case Study Codes
1	A connection to the customer and origin of requirements enables collaborative systems thinking
2	Collaborative systems thinking teams use intelligent lines of questioning to facilitate systems thinking
3	Design reviews stimulate cross-discipline communication and create systems awareness
4	Consensus building enables collaborative systems thinking
5	Collaborative systems thinking team leaders must be willing to make decisions
6	Individuals with differing levels of systems thinking facilitate collaborative systems thinking
7	Too many systems thinkers on a single team is a barrier to collaborative systems thinking

4.2 Results

This research began with a single question: What is the structure and behavior of systems thinking teams within the aerospace industry? From this question three objectives and three formal research questions were formulated. This section integrates the results of analysis to show how the objectives were met and questions were answered.

4.2.1 Research Objectives and Questions

This research was guided by three objectives.

1. To define collaborative systems thinking by combining insights from existing literature with observations of aerospace teams and interviews with aerospace engineers about their team experiences.

2. To identify heuristics for promoting collaborative systems thinking teams in the aerospace industry.

3. To develop a first pass theory explaining the influence of teams traits (e.g. demographics and culture) and process usage in enabling collaborative systems thinking.

The questions asked to support these objectives were as follows:

1. What is collaborative systems thinking and how does it differ from individual systems thinking?

2. What are the empirically generalized (i.e. commonly observed) traits of systems thinking teams within the context of the aerospace industry?

3. What observed mechanisms best predict collaborative systems thinking?

4.2.2 Defining Collaborative Systems Thinking

The term collaborative systems thinking was introduced in this research to differentiate individuals and teams engaging in systems thinking. Whereas systems thinking, or engineering systems thinking, is an individual skill and activity; collaborative systems thinking is a team skill and activity. As there is no universally accepted definition for systems thinking, the first research question and objective was to develop a grounded definition for collaborative systems thinking.

Common themes from literature and pilot interviews were used to construct a working definition of collaborative systems thinking. As discussed in Section 2.2.2, these themes include component complexity, interrelationships (interfaces), context, emergence, and wholes. The grounded research by Davidz developed an engineering specific definition of systems thinking that incorporates the five themes [35]. From these example definitions it was determined that a definition for collaborative systems thinking should also incorporate the five definition-related themes of systems thinking.

Table 4.5 shows how excerpts from literature and common pilot interview codes were combined to identify central concepts used in defining collaborative systems thinking (CST). The following is a discussion of each resulting concept for the collaborative systems thinking definition.

Because collaborative systems thinking is a property of teams and not individuals, it follows logically that collaborative systems thinking is itself an 'emergent behavior.' The first definition theme then comes from literature on team thinking and interactions and points to the importance of shared processing of information [124] as

Table 4.5: Integration of Concepts from Literature and the Pilot Interviews towards a Definition of Collaborative Systems Thinking

Literature Concepts	Pilot Interview Concepts	Central Concept for CST Definition
Team thinking is a valid concept based on shared processing of information [124]	'A willingness to ask and answer questions'	**Team Interaction**
Team thinking is facilitated by interactions that create pointers to knowledge held by individuals within the team [151]	'Socialized experts with shared references enable CST'	
Creative environments and multiple perspectives support systems thinking [143]	'Creativity and multiple thinking styles enable CST'	**Multiple Thinking Styles**
Normative design processes that utilize divergent and convergent thinking are superior for handing complexity [136]	'Process provides a shared language and taxonomy'	**Design Processes**
	'Process provides a starting place for executing design'	
Multiple design languages (e.g. sketching, prototypes, etc.) are required to communicate design knowledge [45]	'High communication bandwidth enables CST'	**Multiple Communication Media**
Emphasis on end product is a differentiator between successful and failed product development teams [43]	'CST involves producing a product'	**Importance of an End Product**

facilitated by team interactions that help members of a team learn what areas of expertise and experience are represented within the team [151]. The 'willingness to ask and answer questions' and to be 'aware of interactions among multiple disciplines' are complementary concepts identified through the pilot interviews as enablers for collaborative systems thinking. From these literature references and pilot interview codes, the central concept of 'Team Interaction' was identified as important to the definition of collaborative systems thinking.

From the literature a link between creativity and systems thinking was identified. Specifically, creative environments allow for multiple perspectives and good idea exchange [44, 45, 143]. This theme from literature was reinforced by the pilot interview code emphasizing the 'importance of creativity' as an enabler for collaborative systems thinking. These were combined to form a definition concept of using 'Multiple Thinking Styles.'

The processes followed during design can also influence information exchange and affect a team's ability to handle complexity [136]. Additional pilot interview codes reinforce the concept that process provides a 'framework' and 'shared language for design.' These concepts were combined to form a definition theme emphasizing 'Design Processes.'

The importance of communication was evident in both the literature and pilot interviews. The literature pointed to the importance of using multiple levels of abstraction, or design languages, to communication technical information within a team [25, 45, 63]. This was complemented by the pilot interview code of 'high communication bandwidth enables CST.' Using multiple types of media to communication enables high-bandwidth communication and therefore the theme of 'Multiple Communication Media' was added to the definition for collaborative systems thinking.

The four definition themes presented above are related to interpersonal interactions. The fifth, and final, definition theme gets at a more fundamental difference between systems thinking and collaborative systems thinking: the concept of producing a product. The literature shows that in a study of product development teams, those teams that succeeded, were more focused on the end product in contrast to being focused on the design process [32, 43, 61]. This theme also appeared in the pilot interviews as an emphasis on role of teams in producing products. Whereas individuals contribute to a team, the team must deliver a final product or component. These complementary ideas inform the final concept of the 'Importance of an End Product.'

When combining these definition-related concepts, Davidz's definition of systems thinking was used as a template. Davidz's definition for systems thinking is 'utilizing modal elements to consider the componential, relational, contextual and dynamic elements of the system of interest [35].' This definition was chosen as a starting point for composing 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 compiled, as first proposed in [80] and further discussed in [81]

> *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 systems attributes, interrelationships, context and dynamics towards executing systems design.*

This definition was used throughout the case study portion of research and was well received.

4.2.3 Generalized Traits of Collaborative Systems Thinking Teams

Based on survey and interview results, a set of generalized traits of collaborative systems thinking teams was identified. Some of these traits (e.g. engaging in consensus decision making) are based on quantified survey data reinforced by qualitative

Table 4.6: A List of Generalized Traits of Collaborative Systems Thinking Teams

	Generalized Traits of Collaborative Systems Thinking (CST) Teams
1:	CST teams engage in more consensus decision making
2:	CST teams have three categories of membership
3:	CST team communication preferences are for real-time group interactions
4:	CST team members have higher number of past and concurrent program experience
5:	CST team members rate their team environment more favorably
6:	CST teams have more creative environments
7:	CST teams require both technical and social leadership
8:	Conceptual design teams are more likely to engage in CST

interview data. Other traits (e.g. three categories of team membership) are based on qualitative interview data. Table 4.6 shows a list of generalized traits, which is followed by a discussion of each trait with a presentation of supporting data. In addition to the traits presented in Table 4.6, moderate correlation was also found between collaborative systems thinking and team industry sector. Those teams in the aircraft industry have higher collaborative systems thinking rankings than teams in the spacecraft industry. The apparent industry dependency is not seen as significant because of the relatively small sample size of this study, but may be worth exploring in future research.

In addition to learning from the generalized traits, those traits that did not differentiate collaborative systems thinking teams also provide useful information. Table 4.7 shows five traits that surprisingly do not correlate to team collaborative systems thinking ranking. The first 'non'-trait is team size. The teams surveyed varied in size from four to twenty team members. This is a relatively small range. Perhaps the effects of team size would be more pronounced with larger teams, but it is difficult to think of teams much larger than 20 people really interacting as a single team as opposed to an amalgam of smaller teams. The second 'non'-trait, customer base, was included as a dimension of interest because government customers, especially within the United States, often require minimum levels of process capability maturity. It was thought that these teams would be more process oriented and therefore more sys-

Table 4.7: A List of Team Traits that Do Not Differentiate Collaborative Systems Thinking Teams

	Team Traits not Impacting Collaborative Systems Thinking
1:	Team size
2:	Customer base (government or commercial)
3:	Measures of technical process use and/or tailoring
4:	Self-reported team member systems thinking
5:	Team collocation

tems aware. However, measures of process use and tailoring were also extremely poor predictors of collaborative systems thinking ranking (with Spearman's ρ correlations of $\approx 0.11 - 0.12$). The fourth 'non'-trait is self-reported individual systems thinking capability. Team members consistently rated themselves as better systems thinkers than did team leaders and supervisors rate the same individuals. Systems thinking is an abstract concept, and some individuals were not familiar with the term, inhibiting their ability to rank themselves. The final 'non'-trait is team collocation. Despite a strong emphasis on the importance of effective communication and real-time group interactions, the percentage of team members located at the main site was not a good predictor of collaborative systems thinking. Several of the barriers to distributed collaborative systems engineering [145] were present on the distributed teams, but these appear to be surmountable with good tools and leadership.

Team Decision Making

Indicating a preference for group decision making was the greatest single predictor of collaborative systems thinking. Figure 4-12 shows a plot of team collaborative systems thinking versus team decision making preference. Data regarding team decision making preferences come from the team survey question #24 in which individuals were asked to rate the relative frequency with which design decisions are made by groups versus individuals. Individuals were asked to indicating their response by making a mark along a continuum from 0 to 100%. The data are therefore considered interval, and a Pearson correlation coefficient of -0.82 was obtained. A lower re-

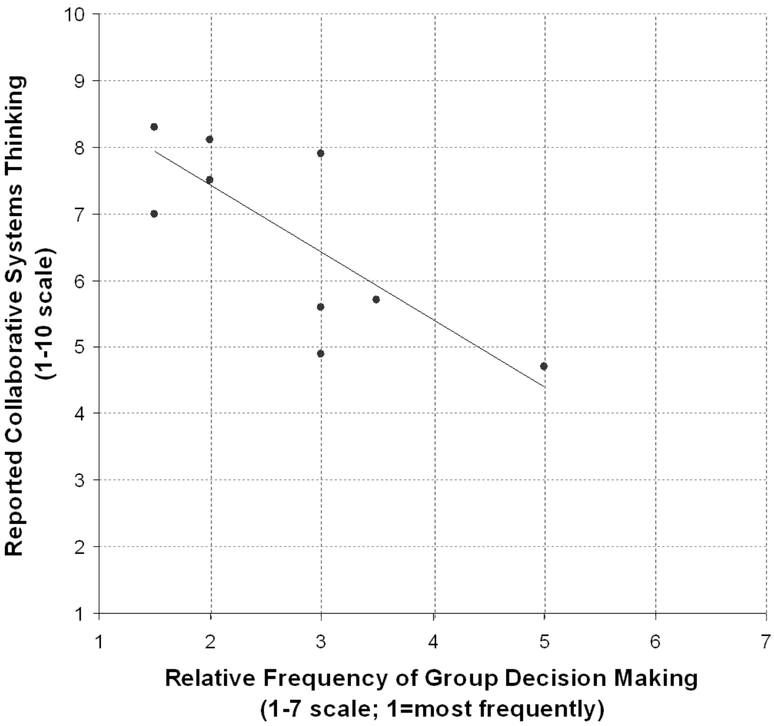


Figure 4-12: Data show that teams with higher collaborative systems thinking ratings utilize more group decision making (DM). Pearson $Corr(CST, DM) = -0.80$

sponse indicates decisions are more frequently made by groups. The data show teams engaging in more consensus decision making are rating themselves higher for collaborative systems thinking. The median of each team's responses is plotted against a team's collaborative systems thinking, calculated as described in Section 4.1.2.

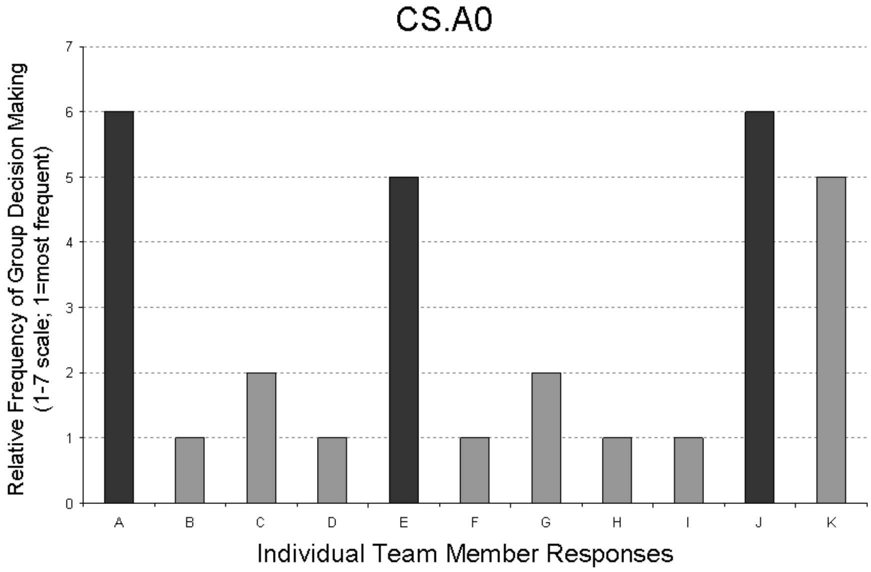
Qualitative descriptions from interviews indicate that individuals perceive the group is engaging in group decision making when they as individuals feel their ideas have been heard by the team leader, and they understand the reasoning or rationale for decisions made. It should be pointed out that the group decision making process does not appear to resemble a democratic polling process, but is indicative of teams discussing decision alternatives and coming to an agreement on how to proceed. The leaders of these groups appear to control these conversations and to determine when the team has converged on a preferred path forward. Within the abbreviated case study transcripts this concept is reinforced with the code 'Leadership must be willing to make a decision.' One participant in the abbreviated case studies described an instantiation of consensus decision making that allowed for individual team members to both approve of the team's decision and indicate that team's choice is not their first choice. This method recognizes there are often multiple valid options and encourages team members to reflect upon the validity of those options rather than focusing on their specific solution.

One unusual aspect of the team decision making data is the apparent dependency of decision making perceptions on team collocation. While the fraction of team members seated together shows little correlation to collaborative systems thinking, there is an apparent secondary effect. Shown in Figure 4-13 are two examples where those team members at the central team location had different perceptions of team decision making as compared to those team members at distributed locations.

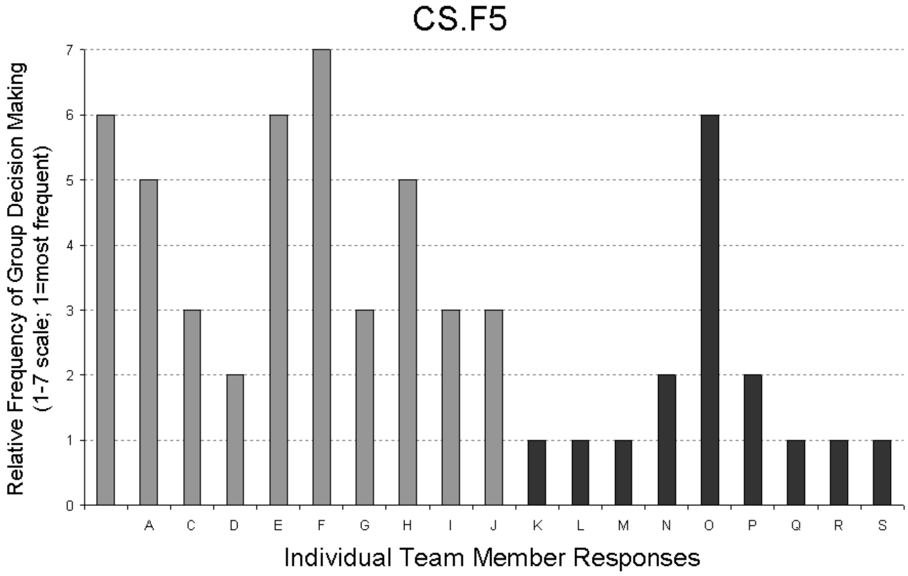
In Figure 4-13(a), team members 'A,' 'E,' and 'J' were contractors working with the team. They are full team members and were among those team members who had been with the program the longest. While they indicated that decisions were most often made by the team leader, their qualitative description of the decision making process was near identical to those collocated team members who perceived the decisions were made by the group. For context, Case A0 was among those teams with high collaborative systems thinking ratings.

In Figure 4-13(b), team members 'K'-'S' were working together as a separate location and organization. The two groups interacted regularly via teleconferences and shared file systems. In this case, Case F5, the two components of the team are of similar size and appear to have differing perceptions on team interaction influenced by their distinct organizational cultures. Team members 'A'-'J' are in a more hierarchical and process oriented organization whereas team members 'K'-'S' are in a more collegiate and research based organization. For context, Case F5 was among those teams with low collaborative systems thinking ratings.

The above two vignettes point to the added effort required to make distance team members feel a part of the 'process' and the ease with which a non-collocated team can develop subcultures that have different expectations of team interactions.



(a) Case CS.A0 team member decision making perceptions, team CST=7.9



(b) Case CS.F5 team member decision making perceptions, team CST=5.6

Figure 4-13: Examples of the impact of collocation on team member decision making perception

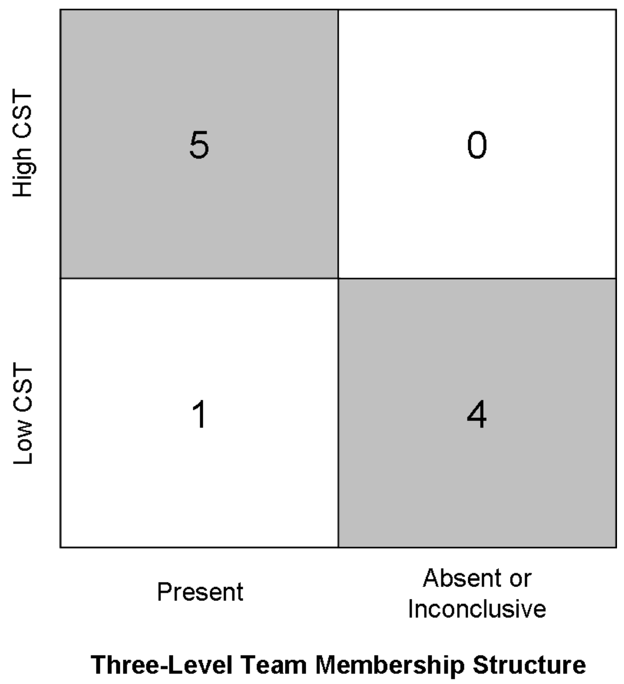


Figure 4-14: Interview and organizational chart data indicate collaborative systems thinking teams have three consistent levels of team membership. The results are statistically significant, $p = 0.004$.

Three Categories of Team Membership

A second strong indicator of collaborative systems thinking was team structure. This observation emerged from the interview data, and when available, organizational charts. This is a qualitative indicator of collaborative systems thinking. Figure 4-14 is a two-by-two diagram showing the relationships between observations of this team structure and collaborative systems thinking. In this figure, the shaded cells indicate those combinations of team-structure and collaborative systems thinking that are consistent with the team structure being an enabling characteristic of collaborative systems thinking.

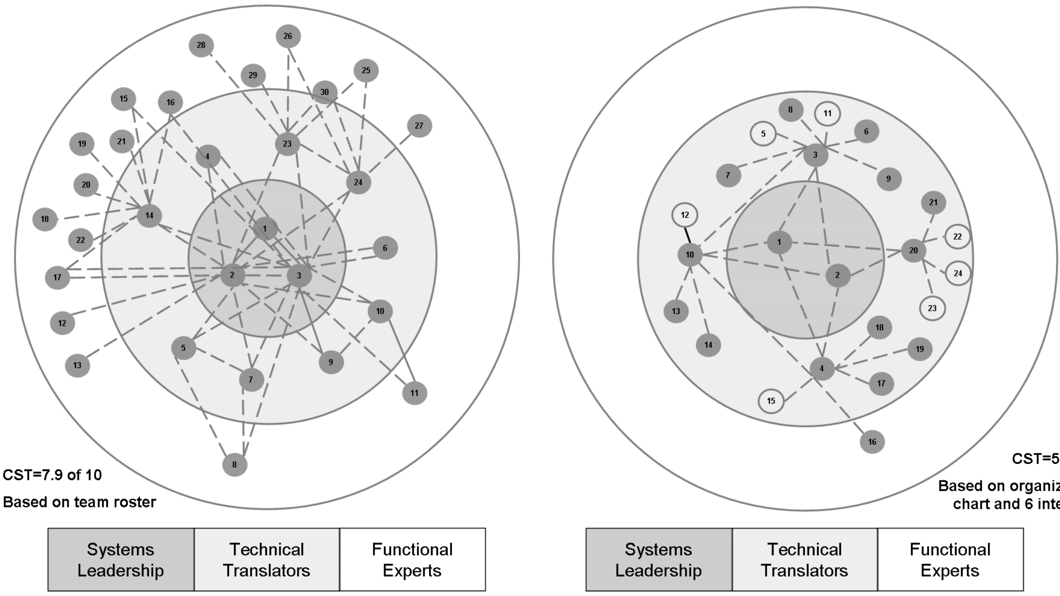
The observed structure consists of three informal categories, or levels, of team membership. Initially observed on Case B1, the three tier structure was retroactively pieced together from data for Case CA0 and was included as an interview question on subsequent full and abbreviated case studies. Interviewees were asked to comment on the structure and to present examples to reinforce or contradict the pattern.

The categories observed are systems leadership, functional experts, and an in-between category of 'technical translators.' Characteristics of each category are as follows [81]:

Systems Leadership The systems 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 the team and adjust 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 from a study of effective systems engineers at NASA and include the ability to influence others, utilize strong communication skills, engage in mentoring, critical thinking, risk management, and the ability to lead others to new insight using analogy and insightful questioning [153].

'Technical Translators' This intermediary group represents a team's developing systems professionals and consists of individuals with function responsibilities (e.g. subsystem leads or representatives of different functions) who interact closely and have an appreciation for systems issues. These individuals act as an interface between 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.

Functional Experts The functional experts bring detailed specialized 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 contribute to several teams simultaneously. As such, the functional experts are less aware of systems issues and the greater systems picture. The functional experts bring much of the past and concurrent program experience to the team.



(a) Case CS.B1 team structure

(b) Case CS.F5 team structure

Figure 4-15: Examples of three-category team membership structures

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

Figure 4-15 shows two examples of team organizational charts translated into membership levels on the basis of interview feedback. Figure 4-15(a) shows Case B1, a team with a high collaborative systems thinking rating. Lines between team members represent relationships from the organizational chart. It was this team's leader who first proposed the concept and functionality of the three categories. The systems leadership of this team consists of two individuals. Both have technical credibility within the team, but one was also seen as providing social leadership. Team members commented on the efficiency and effectiveness with which she ran meetings and described her as nurturing. Young team members spoke of her as a role model; someone to emulate. The 'technical translators' of B1 were younger engineers whose interviews reflect an awareness and curiosity for subsystem interactions, manufacturing issues, and lifecycle concerns. Finally, within Case B1 there were several functional experts contributing to the systems design. While formally part of the team these experts attended few system-level meetings and admitted that they were not always as aware as they might like of the overall system and specific design decisions. One individual cited a situation in which he made a recommendation to the team only to find out later the data he used were outdated, and therefore invalid.

Figure 4-15(b) shows the team structure of Case F5. While both teams were working on systems in the same industry and with the same customer category, their team structures were markedly different. Both teams had system-level responsibilities, but Case F5 represented a far larger and more complex system. The F5 team consists primarily of leaders and technical translators. For such a large program, the team was relatively recently formed and still in the process of identifying individuals to provide functional expertise. As with B1, F5 has two leaders, one more technical and one more social. However, the coordination between these two leaders did not appear to be as seamless as in B1. Further, the team's unique structure leaves many of the 'technical translators' without specific functional or subsystem responsibility. This led to some confusion as to individual responsibilities on the team.

As stated above, the concept of three team membership categories emerged from the case studies. It is therefore worth taking a moment to explore team and engineering literature for theories and past research supporting this observation. Two such examples are Ancona's X-Teams [8] and McMasters and Cummings's writings on the future of airplane design [98]. In the X-Teams framework, there are three expandable tiers: core, operation, and outer net. From a knowledge management and hierarchy standpoint, the expandable tiers are similar to the three categories of collaborative systems thinking teams. The core members and systems leaders are both coordinators and keepers of overall system knowledge. Operational members carry out much of the ongoing work, similar to the central role of 'technical translators.' Finally, outer net members within the X-Team framework are specialized and part-time. They therefore fulfill the same role as functional experts on collaborative systems thinking teams.

The second framework of comparison comes from McMasters and Cummings [98]. Their framework shows architects, general contractors, and specialist craftsmen as the three kinds of people required to build airplanes. The architects, or synthesizers and systems thinkers, correlate to the above systems leadership. The specialist craftsmen, or technical specialists, correlate to the above functional experts. The third kind of person, general contractors, doesn't translate well to the collaborative systems thinking team categories. General contractors are responsible for budget and schedule–traditional management responsibilities [98]. Within the collaborative systems thinking team framework, budget and schedule responsibilities lie with the systems leadership. McMasters and Cummings identify a group of individuals called analysts as precursors to either the specialist craftsmen or architects. This category of analysts most closely reflects the 'technical translators' on collaborative systems thinking teams.

Based on these comparisons to literature, the three-level collaborative systems thinking team structure provides new and complementary insights into engineering team structure.

Team Communication Preferences

Question #14 on the team survey explored the conditions under which teams interacted. Specifically, team members were asked to identify common interactions along three axes: 1-on-1 vs. groups; in-person vs. virtual; and real-time vs. delayed. Responses were marked along a continuum indicating the relative percent of interactions along each dipole of interaction types from 0 to 100%. These data are interval, and the Pearson correlation coefficient for each trait is displayed in the following three figures.

Given the above discussed preference for group decision making, it comes as no surprise that collaborative systems thinking teams are more likely to interact in groups rather than pairs. The trend is illustrated in Figure 4-16. This relatively strong correlation is reinforced by abbreviated case study emphasis on the importance of frequent team meetings and design reviews.

The second dimension of team interaction is in-person versus virtual interactions. Examples of virtual interactions include teleconferences, web-based meetings, and email or other electronic communication. While nearly every team mentioned some

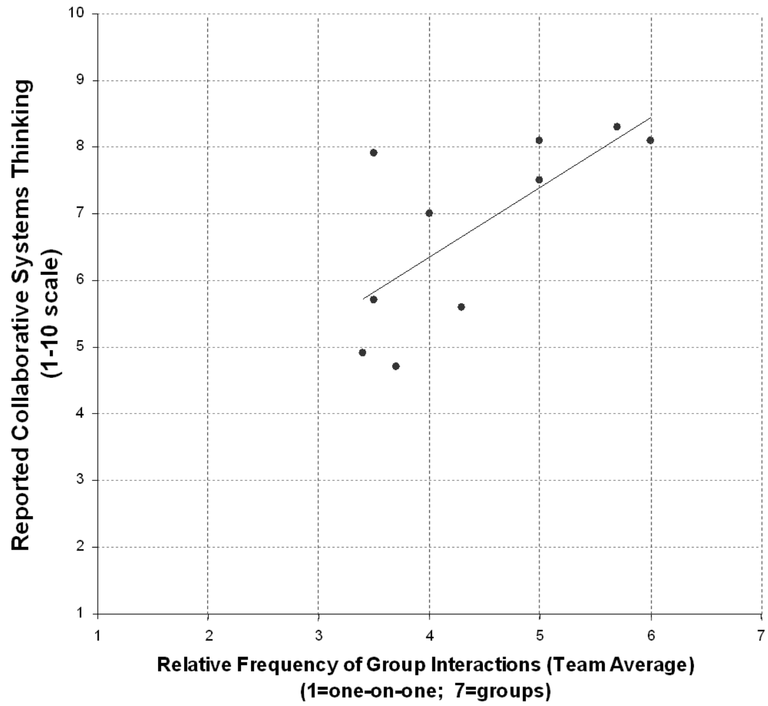


Figure 4-16: Collaborative systems thinking teams express a preference to meet in groups (G) versus one-on-one. Pearson $Corr(CST, G) = 0.71$

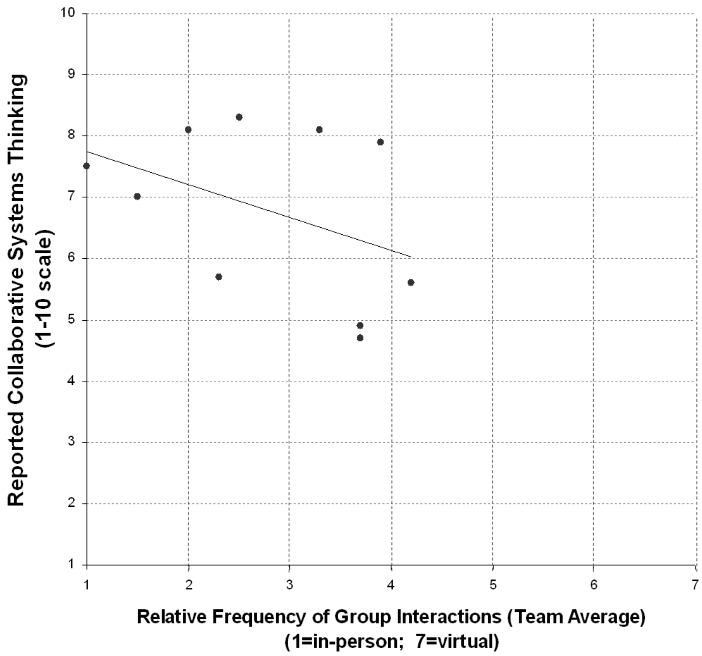


Figure 4-17: Collaborative systems thinking teams have a weak preference for interacting in-person (IP) versus virtually. Pearson $Corr(CST, IP) = -0.42$

type of online collaboration, collaborative systems thinking teams indicated a weak preference for in-person interactions as shown in Figure 4-17. As with the group interaction preference, this is consistent with the emphasis on frequent meetings and design reviews. Comments from all case study interviews showed that email has a important role in documenting decisions and action items resulting from more casual interactions, but face-to-face interactions are invaluable for improving communication and establishing trust within a team. As one individual from Case J9 stated, it is 'hard to delete a walk-in.' Face-to-face communication facilitates the use of sketching, gesturing, and interacting with prototypes and physical models: all shown to improve technical communication [45].

The third dimension of team interaction is real-time versus delayed interactions. Examples of delayed interactions include email, editing documents on a shared server, and phone messages. When teams are geographically distributed and span multiple time zones, delayed (or asynchronous) interactions are near unavoidable. Given the

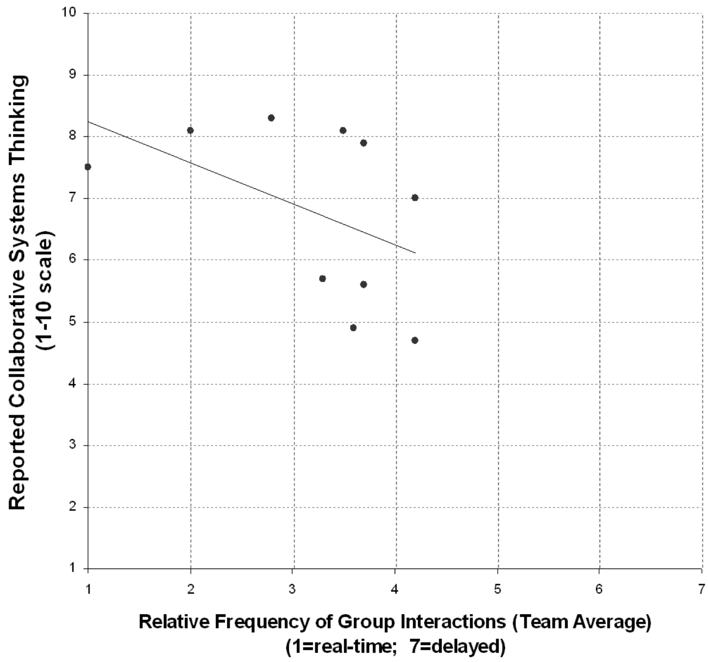


Figure 4-18: Collaborative systems thinking teams have a preference for interacting in real-time (RT). Pearson $Corr(CST, RT) = -0.48$

prior two preferences for in-person and group interactions, it is consistent that collaborative systems thinking teams prefer in-person interactions, shown in Figure 4-18.

Importance of Past and Concurrent Program Experience

Past research indicates that experiential learning is an enabler for engineers developing individual systems thinking [35]. It is logical that teams with a greater number of past program experiences would therefore be more likely to express collaborative systems thinking. This relationship is shown in Figure 4-19. There is a moderate correlation between collaborative systems thinking and both past program experience and concurrent program participation, shown in Figure 4-20. These correlations are both stronger than that between collaborative systems thinking and the number of *years* of industry experience ($Corr = 0.42$). This underlies the importance of going through the system design process as a critical enabler of systems thinking at both the individual and team levels, as has been suggested by past research into engineering systems thinking development [35].

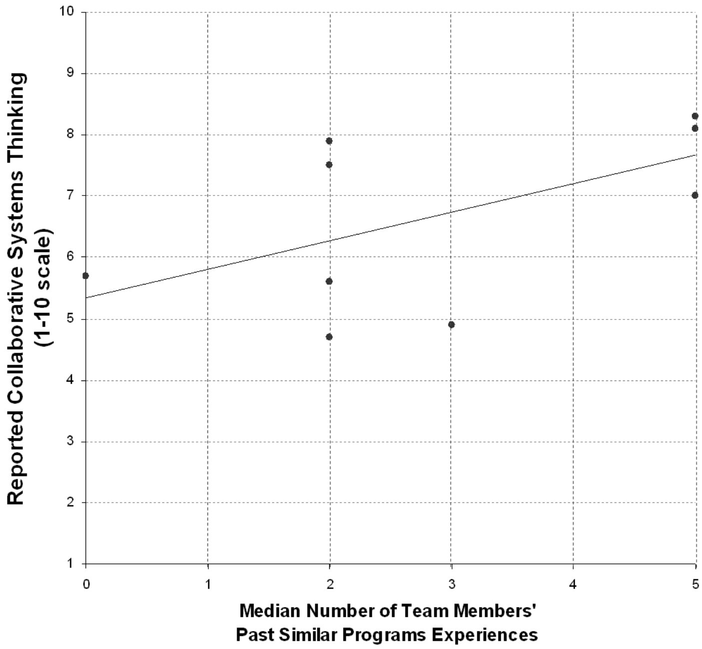


Figure 4-19: Data show that teams whose members have more past program experience (PPE) have higher collaborative systems thinking ratings. Pearson $Corr(CST, PPE) = 0.59$

Both graphics represent a limited range of past and concurrent program experience. It is expected that the positive correlation between collaborative systems thinking and past program experience will hold when extrapolated to larger numbers of past program experience. The same is not likely true for concurrent program participation. A common rule of thumb is that most people cannot remember lists longer than seven items long, and recent research in multiple fields has shown that multitasking reduces performance on even simple tasks. As such, a team median of three concurrent programs is probably an upper limit past which further concurrent program participation would results in distractions and time demands that would detract from individuals' abilities to actively contribute on any given team.

There is much support for the benefits of past and concurrent program experience. Many organizations have some type of job rotation program for new hires. These programs seek to rapidly introduce individuals to several programs, design phases, and functions. Some programs go one step further and use smaller programs or

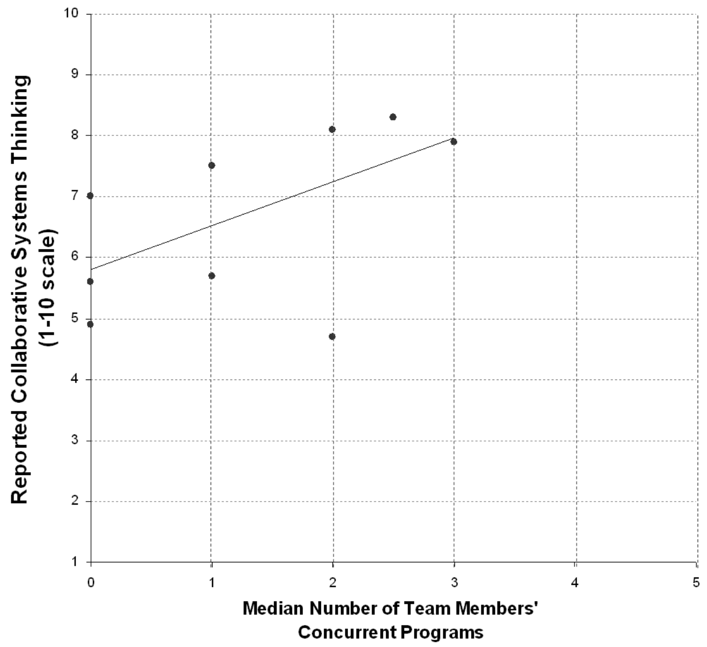


Figure 4-20: Data show that teams whose members work on more concurrent programs (CP) have higher collaborative systems thinking ratings. Pearson $Corr(CST, CP) = 0.57$

research initiatives to expose new career hires to multiple program lifecycles [48]. The purpose of these programs is both to expose young engineers to entire systems and to the process by which those systems are designed.

Concurrent program participation likely improves collaborative systems thinking both by exposing individuals to more systems and systems experiences and by increasing the number of weak links into other programs. These weak links provide shortcuts to information outside the purview of the core team members [13]. These links provide insight into new knowledge, methods, and resources. Within the X-Team framework, these weak links help programs gain greater visibility within an organization and result in a social network that can be leveraged for knowledge and resources [8].

Supportive Team Environment

Team members were asked to rate their agreement with a set of statements about team environment. These statements were influenced by a variety of sources within the literature (e.g. [124, 126]) and focus on aspects of shared team identity, team awareness, and mutual respect and trust among team members. The majority of these statements showed weak correlation with collaborative system thinking. Three statements regarding team environment stood out as moderate predictors of collaborative systems thinking. Each statement regarding team environment was measured through a Likert scale response. The median response of each team was chosen as representative of the team. These data are ordinal, and their correlation with collaborative systems thinking was calculated using the Spearman's ρ correlation coefficient.

The first enabling aspect of team environment is trust among team members in their mutual ability to meet deadlines. Competence-based trust is an important component of information exchanges [32]. Schedule pressure adversely affects a team's creativity and environment [143]. It is therefore logical that trust in others' abilities to meet deadlines works to reduce schedule uncertainty and improve the team environment. Trust in general reduces the need to inspect or replicate other team members' work, thus improving team efficiency. Survey data suggesting a moderate to strong correlation between trust and collaborative systems thinking are shown in Figure 4-21. Interview data reinforce this pattern through codes emphasizing that collaborative systems thinking team members are aware of each other's activities and perceive each other as technically credible. Interviews from teams with lower collaborative systems thinking rankings showed confusion over individual team member contributions and technical backgrounds. Explanations for this difference could be the relative length of time a team has been to together or the quality of their interactions. However, the data collected are insufficient to make this generalization as system size and complexity are potential confounding variables.

The second enabling team environment trait is a shared understanding of team purpose. The purpose of teams is to work towards an end: a common goal. Com-

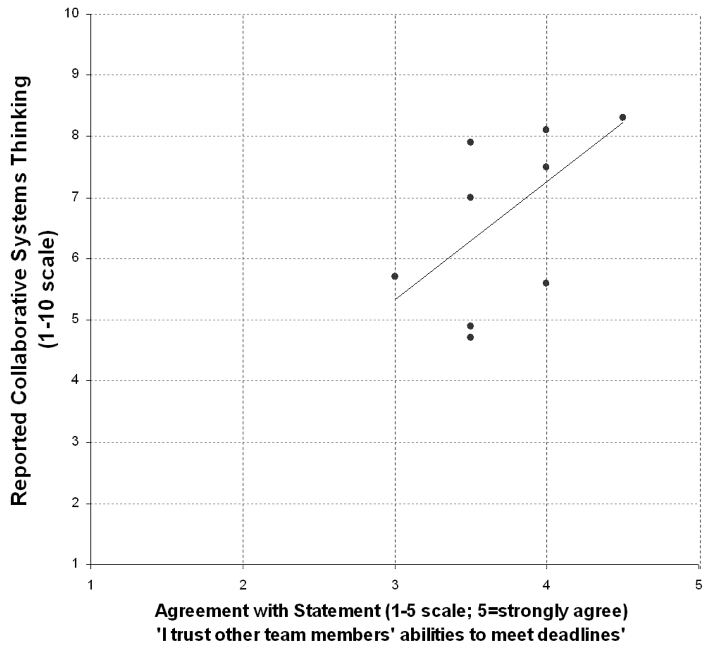


Figure 4-21: Data show that teams who trust (T) each other's abilities to meet deadlines have higher collaborative systems thinking ratings. Spearman's ρ $Corr(CST, T) = 0.63$

pelling vision and a belief in the end goal are two parameters that energize teams [32]. Figure 4-22 shows a moderate correlation between higher collaborative systems thinking teams and team agreement with the statement that 'the team understands its purpose within the overall system design.' The team survey included a question about team identity. Of those indicating a unique team identity, the most common response was that team identity is centered about the product. This theme was present in both the pilot interviews and abbreviated case studies.

The third enabling team environment trait is engaging in team discussions that stimulate good ideas. This team environment trait is rooted in the concept that good design processes utilize brainstorming, trade studies, and other aids to fully explore the problem space before downselecting a design for evaluation [136]. These methods better handle complexity and are therefore thought to enable systems thinking. The survey data show a weak to moderate correlation between collaborative system thinking and engaging in stimulating team discussion, shown in Figure 4-23. There is some

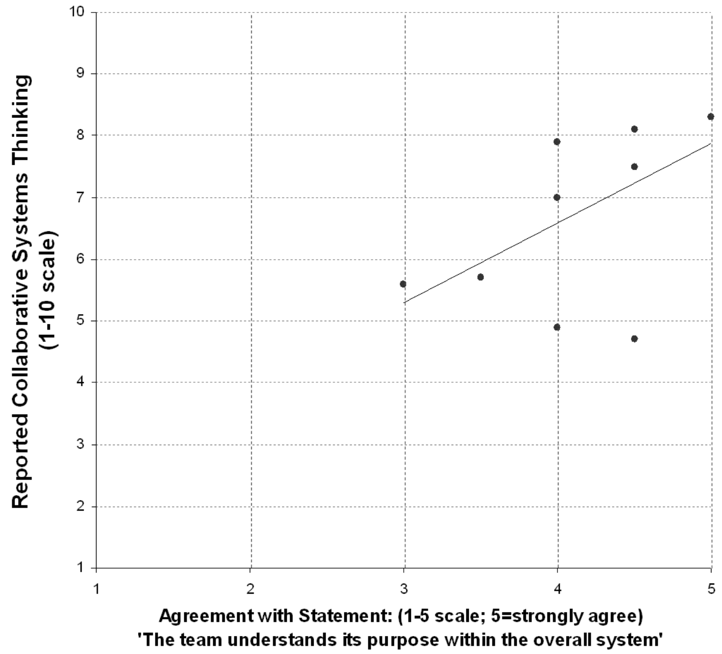


Figure 4-22: Data show that teams who understand their purpose (P) have higher collaborative systems thinking ratings. Spearman's ρ $Corr(CST, P) = 0.57$

evidence in the case study interviews to reinforce the survey data. The frequently cited codes of 'willingness to ask and answer questions,' is related to the concept of stimulating discussion. The importance of a creative team environment, discussed below, is also linked to stimulating team discussion.

Creative Team Environment

The team survey included a series of questions based on a creativity framework described in [143]. The following nine parameters of team creativity were queried:

1 Project Management
2 Access to Resources
3 Decision Freedom
4 Realistic Schedule
5 Individual Incentives and Recognition
6 Team Incentive / Recognition
7 Interesting and Challenging Work
8 Collaborative Environment
9 Organizational Interest in Mission of Team

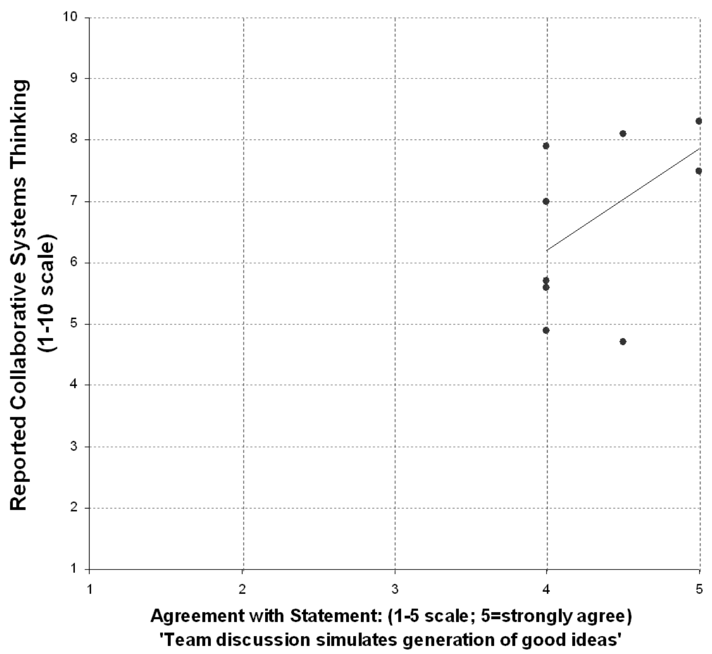


Figure 4-23: Data show that teams whose discussion (D) stimulate good ideas have higher collaborative systems thinking ratings. Spearman's ρ $Corr(CST, D) = 0.51$

Of these nine parameters, three showed a moderate correlation to collaborative systems thinking. Other parameters (e.g. interesting and challenging work) proved poor indicators because every team indicated their work was challenging and interesting. Questions gauging the creativity of a team's environment were measured through a Likert scale response. The median response of each team was chosen as representative of the team. These data are ordinal, and their correlation with collaborative systems thinking was calculated using the Spearman's ρ correlation coefficient.

Teams that rated their decision freedom highly were also more likely to have high collaborative systems thinking rankings. Having the latitude to make important decisions as a team provides both a sense of contribution and progress: both are shown to energize teams [32]. Figure 4-24 shows the moderate to strong correlation between collaborative systems thinking and decision freedom.

A correlation between collaborative systems thinking and collaborative team environment seems quite obvious. The moderate to strong correlation shown in Figure 4-25 is likely a result of the greater team and organizational emphasis on teamwork.

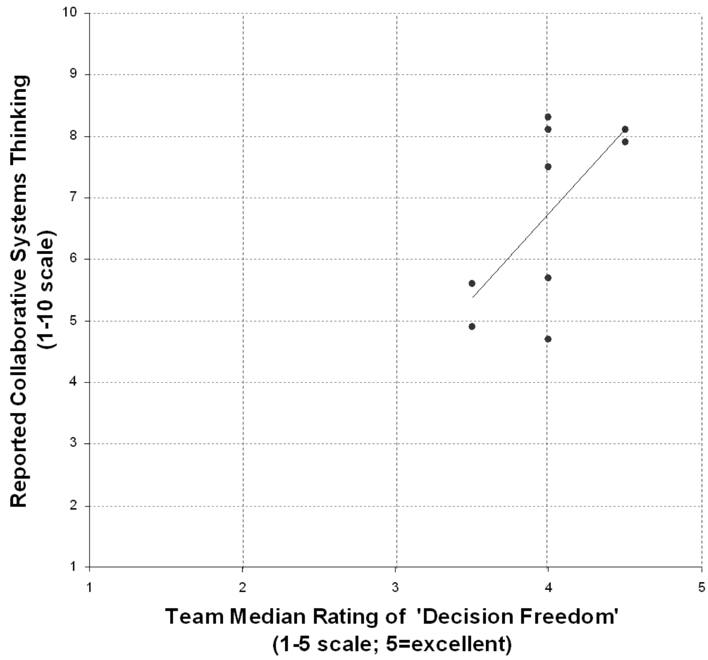


Figure 4-24: Data show that teams who perceive they have greater decision freedom (DF) have higher collaborative systems thinking ratings. Spearman's ρ $Corr(CST, DF) = 0.57$

Team responses to survey questions on the value placed on teamwork did show weak to moderate correlation with collaborative systems thinking. More basically, though, a collaborative environment implies more team interaction, and therefore more opportunities to share experience and knowledge within the team. These interactions and basic team member awareness form the basis for team thinking [124, 151]

Figure 4-26 shows a weak to moderate correlation between collaborative systems thinking and a team's perception that their schedule is realistic. The importance of a realistic schedule also appeared in interviews with members of seven of the full case study teams. Individuals commented that schedule pressures inhibited collaborative systems thinking. In a separate case study, schedules were looked at as enablers that counterbalanced the engineering tendency to wait until the last minute to complete work. In this case, a realistic schedule contained sufficient milestones to drive progress on tasks that might otherwise languish. These two viewpoints provide two reasons

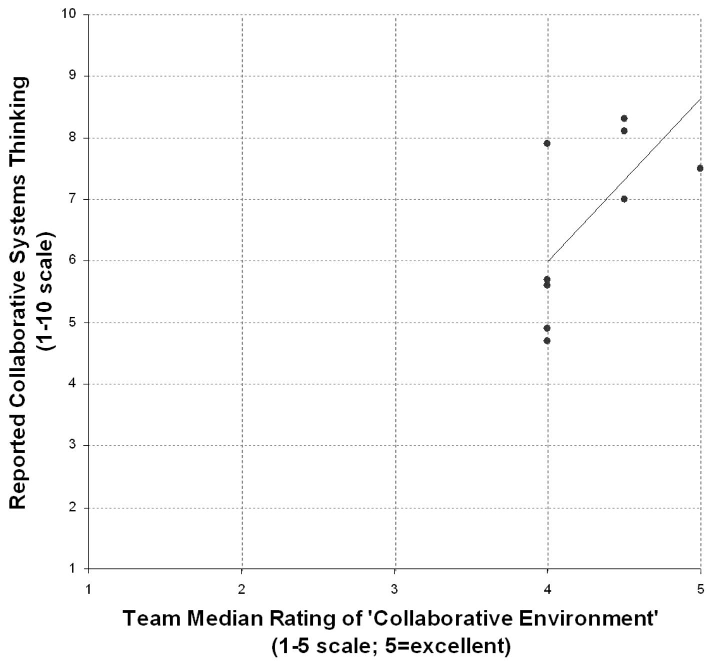


Figure 4-25: Data show that teams that rate their environments as more collaborative (CE) have higher collaborative systems thinking ratings. Spearman's ρ $Corr(CST, CE) = 0.65$

that realistic schedules can help by providing structure and ensuring that sufficient time and resources are allocated to each engineering task.

Social and Technical Leadership are Required

Another outcome of the case study interviews is the concept that leadership is an important enabler of collaborative systems thinking and that this leadership must provide both technical and social structure and guidance. An expansion of the systems leadership level of collaborative systems thinking team membership, the importance of both technical and social leadership is supported by several codes from the case study interviews. These codes include 'recognizing the social component of engineering,' 'leaders with strong social skills enable collaborative systems thinking,' 'nurturing leaders are an enabler,' 'technical credible leadership is required,' and 'leadership must provide appropriate levels of guidance to a team.' Each of these codes appeared with similar frequency in both the full and abbreviated case study interviews. Figure 4-27

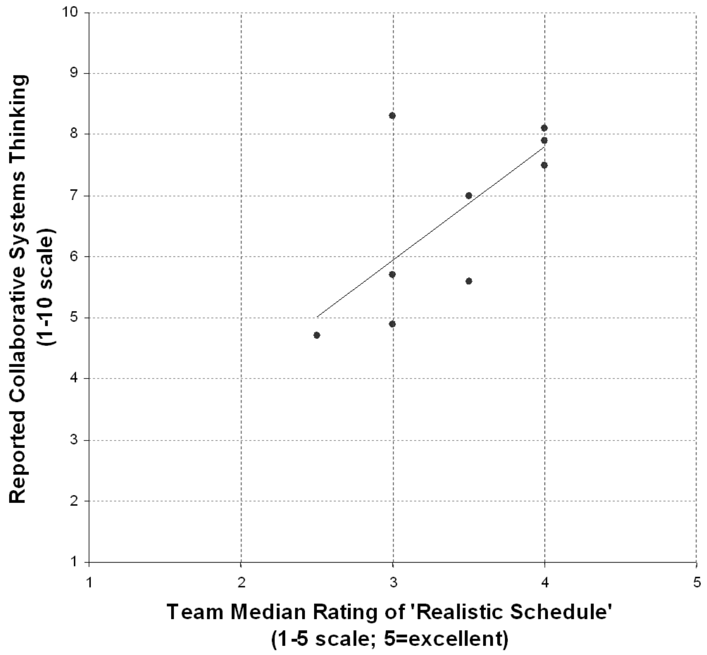


Figure 4-26: Data show that teams that perceive their schedules as more realistic (RS) have higher collaborative systems thinking ratings. Spearman's ρ $Corr(CST, RS) = 0.58$

shows how the presence of both social and technical leadership relates to collaborative systems thinking. The shaded boxes indicate which pairings support the proposed pattern of social and technical leadership enabling collaborative systems thinking teams. Future research should look more closely at team leadership traits and compare observations with the vast literature on team management and leadership.

Collaborative Systems Thinking Teams have People-Oriented Members The emphasis on social leadership is in contrast to stereotypical views that engineers are overly technically oriented. While a full battery of personality preference questions was infeasible because of time and privacy concerns, a small set of questions loosely based on the Myers-Briggs personality types was asked in the surveys. When asked to choose between two statements indicating a preference to interact and discuss new ideas with others or to form new ideas through abstraction and personal reflection, participants in the team survey overwhelmingly indicated a preference to discuss new ideas with others. Because this observation was consistent across all

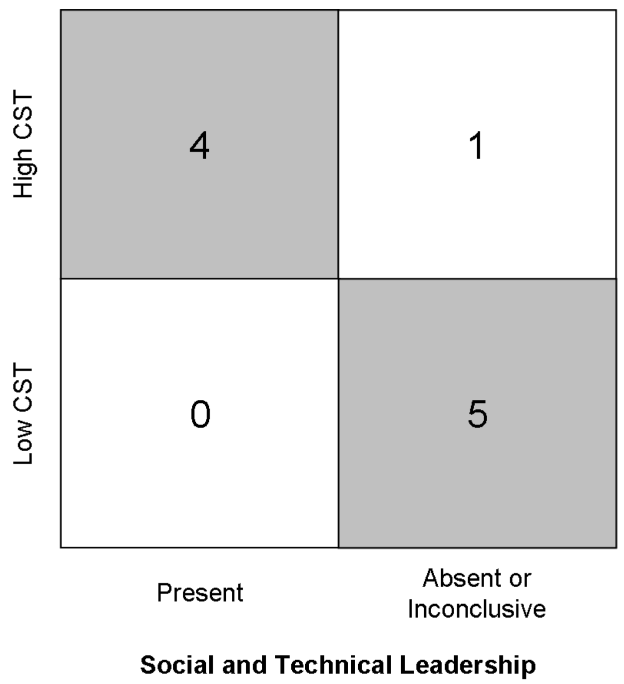


Figure 4-27: Interview data suggest that leaders of collaborative systems thinking teams provide both strong social and technical leadership to team members. The results are statistically significant, $p = 0.004$.

teams, regardless of collaborative systems thinking ranking, this does not provide information valuable to predicting collaborative systems thinking teams. However, this expressed preference to interact with people goes against the typical engineering personality preference for introversion [29]. Interviewing and interacting with these team members reinforced that these were articulate individuals, comfortable in communicating with others. This data provides hope that the reforms in engineering education (e.g. CDIO initiative [24]) are helping to reverse the typical isolated stereotype often associated with engineers as discussed in Section 2.2.1.

Conceptual Design Teams Engage in More Collaborative Systems Thinking

Figure 4-28 shows a two-by-two comparison of design phase and collaborative systems thinking ability. It appears that conceptual design teams are more likely to engage in collaborative systems thinking, with those pairings supporting the pattern shaded in grey. Teams in conceptual design have greater latitude to affect the design, and may

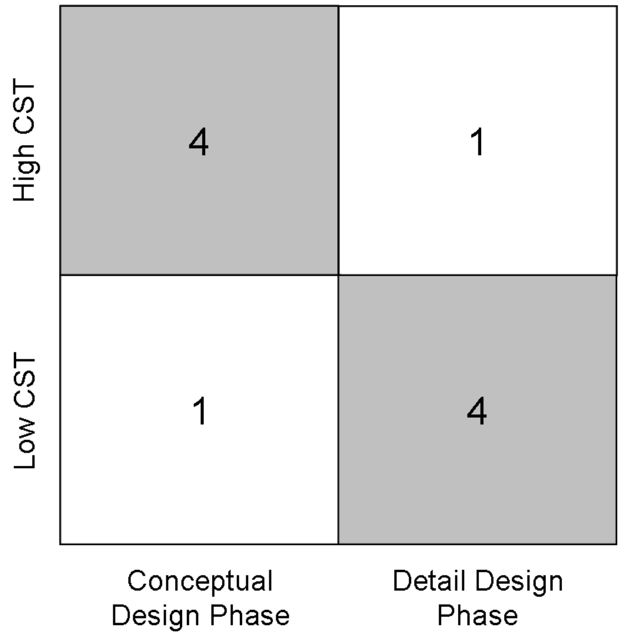


Figure 4-28: Conceptual design teams appear more likely than detail design teams to express collaborative systems thinking. The results are intriguing, but not statistically significant, $p = 0.067$.

therefore be more aware of what trades are available and the impact of those trades. Comments from some case study interviews support the idea that the emphasis of systems thinking shifts with program phase. The theoretical memo shown in Figure 3-4 captures these comments.

The proposed differences between design phases were identified through case study interviews. The patterns suggested are reinforced by research into engineering design process, specifically the relative roles of divergent and convergent thinking [136]. Comments from the case study interviews suggest the emphasis of systems thinking changes from the conceptual design to detail design to testing and integration. Comments suggest that conceptual design is dominated by divergent, creative thinking. During conceptual design, leadership is more important than process in terms of keeping a team focused and productive. 'Technical translators,' or generalists, dominate the team membership during conceptual design because having a systems perspective is more important than specific technical detail. Systems thinking during conceptual design is best described as out-of-the-box and architecture oriented. When the program shifts to detail design, convergent thinking and decision making become more important. At this phase, systems thinking becomes detail and execution oriented. More functional experts participate in detail design. Also, process becomes more important for coordinating trade studies, information flow, and decision making. The final phase of systems development mentioned during case study interviews is the integration and test phase. Because the purpose of integration and test is to verify system requirements are met, process is very important. Yet, the types of issues encountered during integration and test require creative thinking and problem solving skills. Integration and test are characterized by constrained divergent thinking, and the teams appear to have members who are generalists and confer with functional experts as required.

While this progression of collaborative systems thinking and team composition make logical sense, the theory emerged later in the interview progression and therefore only a handful of interviews explicitly asked about this concept. Yet, a code indicating 'team balance changes with program phase' was among the most universally cited in the abbreviated case studies. This is an area worthy of further research.

4.2.4 Heuristics for Collaborative Systems Thinking

Heuristics are metaphors; abstractions of experience into rules-of-thumb [90]. These snapshots of codified knowledge with broad applicability are qualitative phenomenological theories that provide insight into complex phenomena for which there is no rigorous theory [148]. Cognitive psychologist Gerd Gigerenzer describes heuristics as a method through which complexity is reduced, enabling for quicker action based on fuzzy (and inexact) information [55].

Within engineering practice, heuristics provide insights into common patterns of action. Heuristics fall squarely into the camp of engineering art. These are sayings, sometimes witty, based on anecdotes and stories that provide some self-evident truths [90] about context and problems encountered during engineering.

Heuristics that prove useful across multiple systems and contexts provide insights that inform new theories and help integrate the art and science of engineering. Within the context of collaborative systems thinking, heuristics provide insight into the types of team environments and practices that enable teams to leverage systems thinking.

The following is a discussion of heuristics that emerged from the interview transcripts. Those tidbits of knowledge chosen as heuristics either appeared in multiple interviews or are comments from one interview that expand upon an insight from literature. Each heuristic is presented and followed by a short discussion linking the heuristic to the generalized traits of collaborative systems thinking, other supporting data, and relevant literature. Some of the insights provided in these heuristics provide the qualitative 'glue' that ties together the propose theory of collaborative systems thinking as presented in Section 4.2.5.

Heuristic 1: Concentrate on the System

The following two heuristics are closely related and concentrate on product orientation as enabling collaborative systems thinking.

> *Collaborative systems thinking teams concentrate on the system, on finding an elegant solution. Requirements are secondary to that design.*
>
> *Teams engage in systems thinking when the individuals are genuinely interested and engaged in the task. Fundamentally, the solution comes not when we are concentrating on the constraints, but when we become engrossed with the problems at hand.*

These heuristics show that successful design is more than putting requirements into a black box and turning the crank. Teams whose members relate to their systems and become engaged in its success do a better job of systems thinking. The literature backs these assertions. The meaningfulness of any teams is improved by having a task identity [61]. Being actively engaged in and contributing to that goal and ways in which team members are energized [32]. Curiosity into customer needs and wants has

Table 4.8: Heuristics Identified During Research

	Heuristics for Enabling Collaborative Systems Thinking
1	A product orientation is important to team success.
	1.A Collaborative systems thinking teams concentrate on the system, on finding an elegant solution. Requirements are secondary to that design.
	1.B Teams engage in systems thinking when the individuals are genuinely interested and engaged in the task. Fundamentally, the solution comes not when we are concentrating on the constraints, but when we become engrossed with the problems at hand.
2	Clear communication is critical to collaborative systems thinking. Teams tend to over-use email and other IT tools. Sometimes you just need to walk around and speak with others. After all, you can't delete a walk-in.
3	The asking and answering of questions brings both parties to new realizations. It helps teams and individuals identify built-in assumptions and move away from "what we've always done." A team needs the leader to ask the right questions; an individual who is curious, imaginative, knowledgable, and can help others look at the problem from outside of the box.
4	Many people are comfortable following guidelines and rules, but process can become brittle. Teams require a balance of individuals that follow the letter of the law and individuals who follow the 'spirit' of rules; who reframe problems to get around rules. This is how we innovate and improve.
5	In a team setting there must be a balance between experience and analysis. Experience feeds the team's intuition and frames how each new problem is faced. However, in innovative situations intuition can be a liability, and teams must use tools to find new knowledge and overcome the inertia of past experience.
6	Engineering mistakes repeat every 7-10 years. This is the time it takes for critical people to rotate off a program and for important knowledge to be lost and rediscovered through failure. Successful programs have a line of succession: a continuity of knowledge through awareness of the past, present, and future. When this continuity is broken is when teams are doomed to repeat failures of the past.
7	Team members, especially the smart and innovative, come with 'warts.' Team leaders cannot tolerate disruptive behavior, but need to treat each person individually to get their best work and to help them become better engineers and team members.

been proposed an an indicator of team thinking on product development teams [6], supporting the heuristics assertion that teams must before engrossed in their design problems.

Comments on the definition of collaborative systems thinking show the importance of a product orientation both for its benefits on a team's ability to see the entire system, but also on their motivation. Having a product orientation provides a sense of accomplishment and feedback at the end of a program. The product orientation was further emphasized by several comments that suggest concentrating on the system's operation, end user, and maintainer help a team maintain a system lifecycle perspective that can be obscured by written requirements.

Heuristic 2: Communicate Effectively for the Context

The literature and case study data support the importance of communication within teams. This heuristic gets the heart of facilitating that communication.

> *Clear communication is critical to collaborative systems thinking. Teams tend to over-use email and other IT tools. Sometimes you just need to walk around and speak with others. After all, you can't delete a walk-in.*

Electronic communication provides teams multiple ways to communicate technical information: CAD models, email, and shared document stores. This technology facilitates communication in many of the languages of design (e.g. text and dynamic models)[45]. However, teams too often put an overemphasis on communicating via email. This delayed, virtual interaction goes against the empirically-based characteristics of collaborative systems thinking teams, which prefer to interact in real-time groups.

Research has shown that communication is improved with good coaching and close proximity [26] and when individuals can hear each other clearly and jointly manipulate sketches and notes [63]. These characteristics are all met by face-to-face interactions; by engineers walking down the hall to speak with co-workers instead of sending broadcast emails.

Within the case study interviews, the code of effective communication represents the single most frequently touched-upon concept. The interviews transcripts highlight not only the obvious importance of communication as necessary for transmitting knowledge and ideas, but also on the importance of subtleties such as body language, passing sketches, and the creative energy that comes from having several people together in one room. Other comments from the interviews spoke to the complexity of IT tools used within teams. Shared digital storage spaces have such vast capacity that data can quickly become disorganized and near useless. Email allows people to share their thoughts with several people for marginal additional effort, failing to tailor their message to what each receiver value or requires. As one individual stated, 'We are mired in process and IT overload..but as we learn to better use these tools we will see an improvement in productivity.'

Heuristic 3: Ask Lots of Questions

Questions can spark curiosity. Guided questions can help team members come to new realizations and avoid 'not invented here' syndrome.

> *The asking and answering of questions brings both parties to new realizations. It helps teams and individuals identify built-in assumptions and move away from "what we've always done." A team needs the leader to ak the right questions; an individual who is curious, imaginative, knowledgable, and can help others look at the problem from outside of the box.*

The willing of teams to ask and answer questions was a powerful theme across every phase of this research. Pilot interview results indicate teams can quickly quell this openness by 'shooting the messenger' and creating a cultural expectation that it is better not to ask questions. Likewise, an overly hierarchical environment can result in a power structure that makes it difficult for concerns at the bottom to be heard at the top.

Case study themes supporting this heuristic include identifying the 'benefits of bringing disciplines together early in the design process,' using 'design reviews to encourage cross-discipline interactions,' and using 'intelligent lines of questioning to facilitate systems thinking.' The benefits of these patterns of behavior are reinforced by NASA research characterizing 'highly regarded' systems engineers. This study showed that these systems engineers used questions to seek information and guide the team; they often asked series of questions to bring the team to an end realization; and that by asking these questions they were more effective at communicating technical information [153].

Heuristic 4: Good Process Execution Needs Both Standardization and Innovation

This heuristic addresses the delicate balance process must find between enabling and stifling collaborative systems thinking. Interestingly, the balance has less to do with the specific process and more to do with the people interpreting the process.

> *Many people are comfortable following guidelines and rules, but process can become brittle. Teams require a balance of individuals that follow the letter of the law and individuals who follow the 'spirit' of rules; who reframe problems to get around rules. This is how we innovate and improve.*

To quote Charles Darwin: "It is not the strongest of the species that survive, nor the most intelligent, but the one most responsive to change." Darwin's observations on the evolution of species apply equally well to engineering teams. Teams are a part of a dynamic ecosystem in which they must constantly adapt and innovate. Having a small number of team members reframing problems and working around rules tests the process and helps the team operate more efficiently when faced with a problem for which the existing process is inappropriate of inadequate [60].

One abbreviated case study interviewee expressed this concept in terms of the kinds of people needed for a balanced team. His experience showed that some number of intelligent, curious and motivated individuals are required to drive progress and push boundaries. While every human resources representative will say they want teams full of these winning individuals, the interviewee insisted this would not result in a balanced team. Rather teams need intelligent individuals with average motivation to work on the hard problems identified by those leading the team and people of average intelligence and motivation who are content to carry out more routine tasks.

Heuristic 5: Both Experience and Analysis are Important

Experience is an important indicator of collaborative systems thinking, but even experience has drawbacks. This heuristic speaks to the situation under which experience can be a liability for a team.

> *In a team setting there must be a balance between experience and analysis. Experience feeds the team's intuition and frames how each new problem is faced. However, in innovative situations intuition can be a liability, and teams must use tools to find new knowledge and overcome the inertia of past experience.*

This heuristic speaks to the organizational inertia that can sweep up a team. In contrast to some opinions that standard process is best suited for routine tasks and that greater creativity and leeway should be allowed for non-routine tasks, this heuristic suggests that more rigor and analysis is required during non-routine tasks to avoid relying on potentially misleading or inapplicable past experiences. Specifically, utilizing analysis will help identify and quantify those aspects of a team's intuition that need adjusting.

While there are specific examples in the literature upon which to ground this heuristic, the process of engaging in thorough analysis before making important design decisions is grounded in normative deign practices [136].

Heuristic 6: History Tends to Repeat Itself

Given the impending 'silver tsunami' within the aerospace industry, experience is an important commodity. This heuristic addresses cycle of engineering mistakes and knowledge.

> *Engineering mistakes repeat every 7-10 years. This is the time it takes for critical people to rotate off a program and for important knowledge to be lost and rediscovered through failure. Successful programs have a line of succession: a continuity of knowledge through awareness of the past, present, and future. When this continuity is broken is when teams are doomed to repeat failures of the past.*

This heuristic emphasizes the importance of knowledge management within a team or program. If knowledge resides within individuals and is not shared and kept alive through experience, then that knowledge is easily lost and often rediscovered only after a mistake is repeated. Such knowledge was referred to in the case study interviews as 'tribal knowledge' and was associated with experienced team members, often called 'gray beards.'

The literature shows that teams are more likely to reuse knowledge to innovative ends when 1) the team and organizational encourages reuse and exchange of knowledge, 2) team members were open to asking questions and examining the applicability of past knowledge to solve current problems, and 3) there was an imperative (e.g. performance gap or need to reduce risk) that motivated people to seek out past knowledge [108]. These observations get to what is meant by 'continuity of knowledge.' It is not sufficient to have the large knowledge stores available, but there must be a motivation to access and reuse that knowledge in order for continuity to be maintained. On one case study, such a mechanism for continuity was suggested. This individual suggested the use of small intermediary programs, placed between larger programs, and designed to keep important individuals and knowledge in place. While such programs come with costs, they seem complementary to the goal of exposing team members to several system design cycles, and thus increasing the workforce average number of past program experiences, a powerful predictor of collaborative systems thinking.

Heuristic 7: Engineers are Unique Individuals

Process seeks to reduce variability in engineering execution: to capture the best practices and avoid relearning and reinventing that which is known and perfected. Engineers are the most variable component of the design process [96]. While process reduces the downside of variability through standardization, this heuristic addresses an opportunity to maximize the upside by working individually with engineers.

> *Team members, especially the smart and innovative, come with 'warts.' Team leaders cannot tolerate disruptive behavior, but need to treat each person individually to get their best work and to help them become better engineers and team members.*

This heuristic gets to the central reasons some engineers resist using standard process. One of the primary purposes of standard process is to control variability in executing design and to create standard expectations of how engineers work and interact during design [96]. This philosophy recognizes the engineers as highly variable components within the design process, components whose expected performance can be improved through standardization. Detractors from process say that simply mimicking past successful behaviors does not in itself guarantee success. This mindset confuses the process and the execution of said process [113].

This heuristic suggests that what really makes great systems teams is the individual coaching and mentoring that helps each individual engineer find his or her own way to best contribute to the team.

4.2.5 A Proposed Theory of Collaborative Systems Thinking

No fact is really respectable until there's a theory to account for it. The theory may turn out to be wrong–it usually is, in some details at least–but it must provide a working hypothesis.

–Dr. van der Berg, in Arthur C. Clarke's 2061: Odyssey Three

The primary purposes of compiling a theory of collaborative systems thinking is to test the generalizability of the theory and formulate hypotheses for future testing. In this section, data are combined into a numerical model that provides a more objective vehicle for validation and a basis upon which to develop a set of hypotheses for future research.

From the complete set of team metrics, five parameters were chosen from which to compile a multi-variate regression model. These parameters were chosen based on ability to explain the observed variability in collaborative systems thinking rankings. The five traits shown in Table 4.9 account for 85% of the variability observed in the team collaborative systems thinking rankings. Equation 4.1 shows the equation derived to explain the observed variability.

The model incorporates interval data (e.g. Concurrent program experience, Relative Frequency of Delayed Interactions, and Relative Frequency of Non-Consensus Decision Making) and ordinal data (e.g. Measures of Creativity and Perception of a Realistic Schedule). Both types of data are treated as interval data following a precedent set by Labovitz [78, 79]. By treating the ordinal data as interval, it is possible to gain insights that would be otherwise difficult to identify. While there are errors introduced by treating ordinal data as interval, there is evidence to suggest these errors are small and acceptable for an exploratory model [18, 67, 75, 159]. Detractors from using ordinal data in regression models refute these claims, saying that ordinal data may only be used to make weak claims of inference in theoretical frameworks [154]. Because this research is exploratory, and the model is not proposed as an accurate tool but rather as a tool to identify those areas most fruitful for future research, the errors associated with treating ordinal data as interval are acceptable.

Components of Equation 4.1

Variable	Survey Question	Unit	Scale
CP: Concurrent Program Experience	#7	Number of Programs	Integer ≥ 0
DI: Relative Frequency Delayed Interactions	#14C	Percent of Interactions that are Asynchronous	(0,1)
CY: Measure of Creativity	#17	Likert Scale Response	1,5
RS: Perception of a Realistic Schedule	#17D	Likert Scale Response	(1,5)
DM: Relative Frequency of Non-Consensus Decision Making	#24	Percent of Decisions that are Non-Consensus	(0,1)

$$CST = 0.50(CP) - 1.87(DI) + 1.38(CY) + 1.11(RS) - 4.31(DM) \tag{4.1}$$

Figure 4-29 shows a plot of predicted ($\hat{y}_i$) versus observed (y_i) collaborative systems thinking ranking. Also shown on the figure is the approximate range of values corresponding to the 90% confidence interval as calculated using the lower and upper estimates of each trait slope as shown in Table 4.9.

Using the regression equations discussed in Section 3.1.3, the standard error ($s\hat{e}_k$), 90% confidence bounds, and weighted slope (b_k^*) for each trait slope (b_k) were calculated and are shown in Table 4.9. The model has five degrees of freedom (10 case

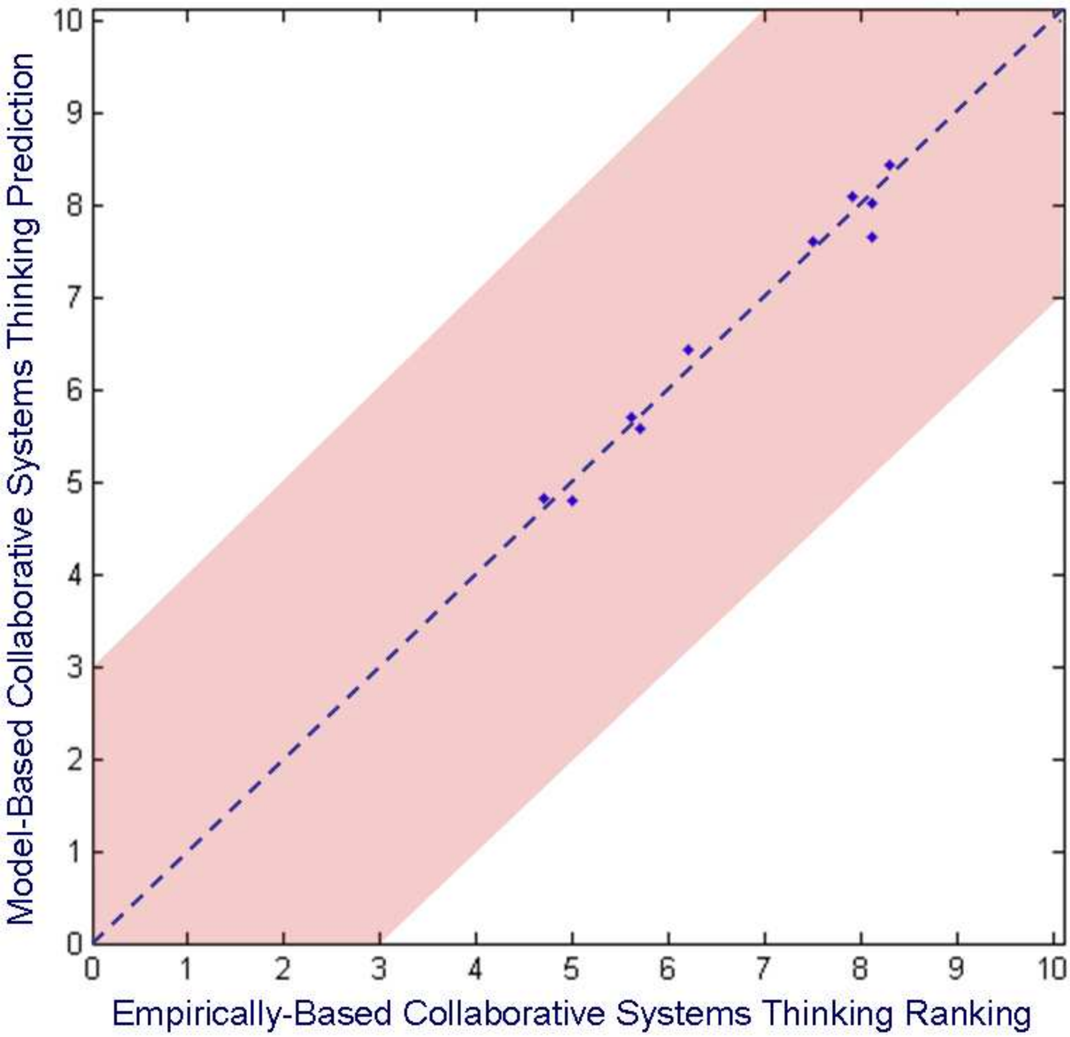


Figure 4-29: Plot of model-predicted collaborative systems thinking vs. team-generated ranking.

Table 4.9: Properties of the Five Traits that Best Predict Collaborative Systems Thinking

Trait	b_k	$\hat{se}_k$	90% Confidence Bounds	Beta-Weights
CP: Concurrent Program Experience	0.50	0.09	(0.37) – (0.62)	0.55
DI: Relative Frequency Delayed Interactions	−1.87	0.66	(−2.85) – (−0.90)	−0.27
CY: Measure of Creativity	1.38	0.36	(0.84) – (1.92)	0.36
RS: Perception of a Realistic Schedule	1.11	0.26	(0.73) – (1.49)	0.41
DM: Relative Frequency of Non-Consensus Decision Making	−4.31	0.62	(−5.22) – (−3.40)	−0.66

studies, minus five predictor variables and no intercept). This corresponds to a Student's T-distribution value of 1.476 for a 90% confidence bound [155]. From these calculations, it can be said with 90% confidence that there is a relationships between collaborative systems thinking and each of the five traits. This can be said because the confidence bounds do not include a slope of 0, which would correspond to no relationship between the variables.

From the weighted slopes shown in Table 4.9, it can be seen that Consensus Decision Making and Concurrent Program experience are the two largest predictors of variability in collaborative systems thinking ranking. While the weighted slopes provide some insight, it must be remembered that correlations among the variables result in correlations between the weighted slopes. Correlations among the five top traits are shown in Table 4.10. Specifically, multiple program participation and measures of a creative environment are highly correlated, indicating they are likely of near-equal importance despite differences in their relative weighted slopes.

Table 4.10: Correlation Among the Five Traits that Best Predict Collaborative Systems Thinking

Trait	CP	DI	CY	RS	DM
CP: Concurrent Program Experience	1.00	−0.14	0.92	0.01	0.04
DI: Relative Frequency Delayed Interactions	−0.14	1.00	−0.11	−0.17	0.43
CY: Measure of Creativity	0.92	−0.11	1.00	−0.12	−0.04
RS: Perception of a Realistic Schedule	0.01	−0.17	−0.12	1.00	−0.52
DM: Relative Frequency of Non-Consensus Decision Making	0.04	0.43	−0.04	−0.52	1.00

The combination of the five traits explains 85% of the observed variability and the resulting model has a regression coefficient of $adjR^2 = 0.99$.

From the model, five hypotheses were generated and form the basis for a initial theory of collaborative systems thinking. These hypotheses are shown in Table 4.11. In each hypothesis, one team trait from the model is linked to a specific component of the definition for collaborative systems thinking. The ways in which these hypotheses may be used to direct future research are discussed in Section 6.3.

Table 4.11: Hypotheses Derived from the Model Explaining Collaborative Systems Thinking

	Hypothesis About Collaborative Systems Thinking
1	Teams that engage in consensus decision making will have teams members with a greater awareness of systems attributes, interrelationships, and the design motivation and purpose.
2	Teams whose members concurrently participate on multiple programs will be more aware of of available deign processes, tools, and resources than teams whose members do not contribute to other programs. This relationship holds only to approximately three concurrent programs, past which point team member attention will be too divided to support collaborative systems thinking.
3	Programs with more realistic schedules (neither too optimistic or pessimistic), will be better able to properly utilize the design process to consider the entire systems and its context when making decisions.
4	Teams with more creative environments, who engage in more collaboration and have greater decision freedom, will interact more, utilize both divergent and convergent thinking styles, and subsequently engage in more collaborative systems thinking.
5	Teams whose interactions are primarily in real-time will communicate technical information more effectively and using a greater number of design abstractions (e.g. sketches, prototypes, gesticulation) as compared to teams who primarily communicate asynchronously.

Chapter 5

Validation

5.1 Validation Case Studies

Validation is difficult with grounded theory research. Within the grounded theory methodology, one method to prove external validity is to take the results from a set of case studies and test those explanations on a new set of case studies [140]. If the results hold true and have explanatory power over the phenomena observed within the new case studies, then generalizability is established and the ground is set for future causal research.

A subset of the full case study survey questions were asked during the validation case studies. This abbreviated survey focused on those measures found most important during regression analysis. A copy of this survey is shown in Appendix B. A follow up conversation was used to assign each team a collaborative systems thinking ranking. Eight validation, or 'predictive,' case studies were conducted, and the results were combined using the regression weights determined by the multi-variate regression mode discussion in Section 4.2.5.

In this chapter, the selection criteria for validation case studies are put forth, and the results and insights gained from the validation activity are discussed.

5.1.1 Validation Case Study Selection

Validation case studies were selected to push the theoretical limitations of observations made from the full case studies. Case studies were selected so as to expand the original selection criteria (by including software teams and integration and test teams).

The validation case studies used on one individual to provide team data. As such, additional selection criteria were enforced. The validation case studies utilized individuals who are themselves individual systems thinkers, have been with their current team for several years, and are in a position to have insight into their team (i.e. several of these individuals were team leaders). An additional criterium for selection was that individuals chosen to participate in the validation case studies not be familiar with the research results so as to avoid bias in their answers. These individuals were asked to provide estimates of average team member past experience and concurrent program participation. They were also asked to answer survey questions on team interaction preferences, decision making preferences, and aspects of team environment including those traits from the creativity framework discussed in [143].

As shown in Figure 5-1, the eight validation case studies were selected along similar criteria as the full and abbreviated case studies. These teams included advanced concepts teams, an aerospace component supplier, integration and test teams working in both industry and academia, and a team working in general aviation design. Additionally, two of the teams included worked primarily on software products for the aerospace industry. These teams provide a contrast to the original case study set which was heavily concentrated on hardware-oriented teams.

The literature emphasized communicating technical information using multiple level of abstraction (or design languages). Because hardware and software teams work on products that exist at different levels of abstractions (i.e. hardware is tangible and software is not), only hardware teams were included in the initial case study sample set. The concept arose during abbreviated case study interviews that the conclusions and concepts of this research were applicable to software teams, and therefore two software teams were included in the validation case study sample. Finally, by choosing teams with a different industry sector and program phase, it is possible to explore the apparent dependencies on industry sector and design phase [1].

5.2 Results of Validation Activity

Outputs from the validation case study survey were compared to those from the original case studies using the regression model put forth in Section 4.2.5. These results are shown in Figure 5-2. The regression model developed using the original case study data accounts for 60% of the variability in collaborative systems thinking ratings observed in the validation case studies, as compared to 85% of the variability in the original case study set. The predicted values for collaborative systems thinking fall well within the 90% confidence bounds of the regression model, thus validating the predictive capability of the these five team traits.

5.2.1 Predictive Results of the Regression Model

While the traits do prove effective predictors for collaborative systems thinking, there are differences in the strength of correlation between the predictive traits and collaborative systems thinking, as shown in Table 5.1. The traits are listed in order of weighted contribution to the regression relationships, from high to low.

As can be seen in Table 5.1, the observed correlations for the first two traits, Consensus Decision Making and Concurrent Program Experience, are about equivalent to those observed int he original case study set. The next two traits, Realistic Schedule and Overall Creativity, have stronger correlations with collaborative systems thinking than were observed in the original case study set. Because both the original case study set and validation case study set represent small samples, the important

[1]Initial case study data suggest that conceptual design teams are more likely to engage in collaborative systems thinking than detail design teams. Additionally, teams working in the aviation hardware sector were more likely to engage in collaborative systems thinking than teams working in the space hardware industry sector

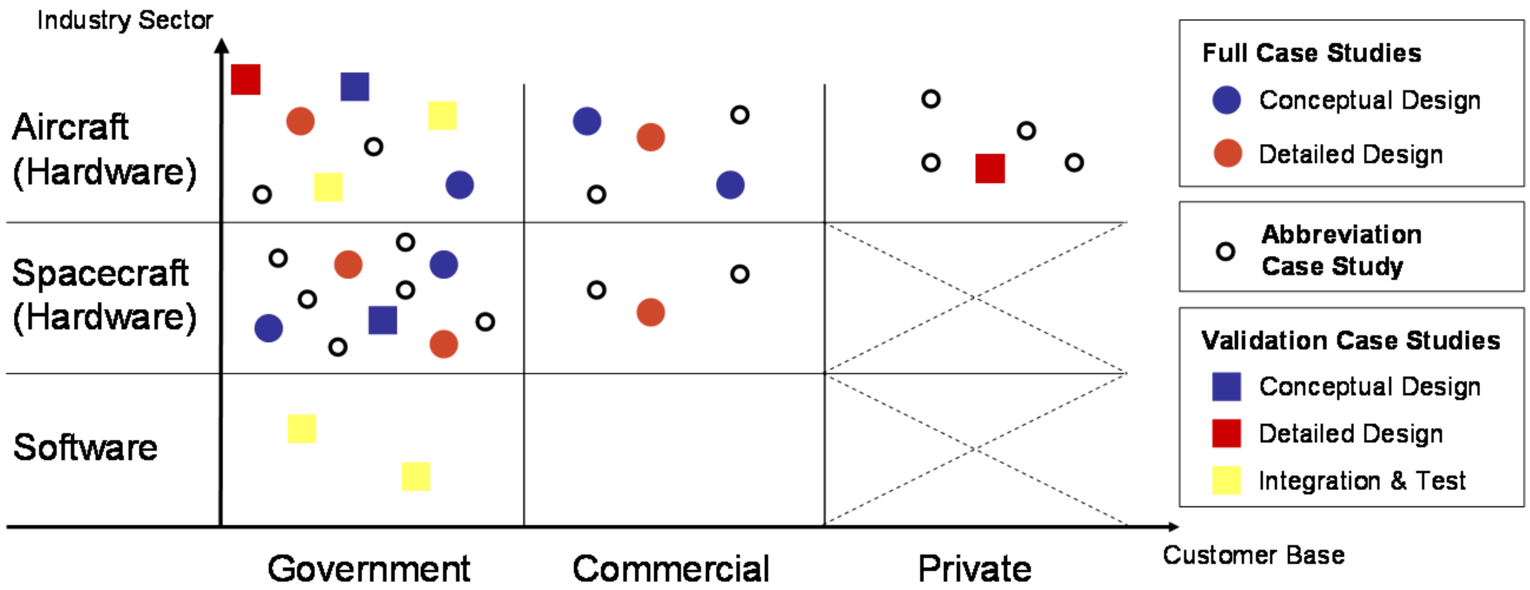


Figure 5-1: The sample set of eight validation case studies compared to the full and abbreviated case study sample sets.

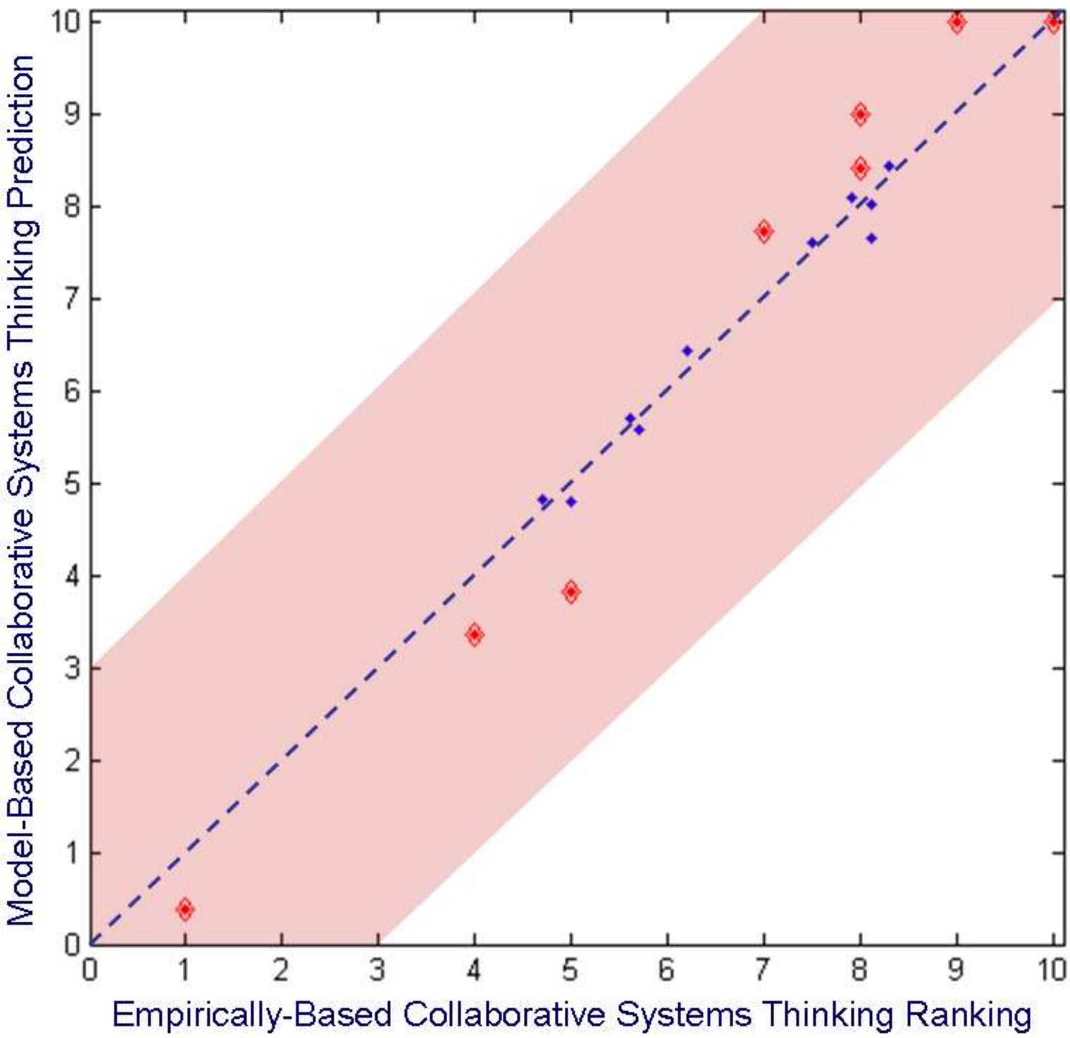


Figure 5-2: Plot of model-predicted collaborative systems thinking vs. team rating. Diamonds mark the validation case study data in comparison to the full case study data, marked by blue dots.

Table 5.1: Correlation of Case Study Results with 'Predictor' Traits

Team Trait	Full Case Study Correlation	Validation Case Study Correlation
Relative Frequency of Non-Consensus Decision Making	-0.80	-0.88
Concurrent Program Experience	0.57	0.56
Perception of a Realistic Schedule	0.58	0.92
Measure of Creativity	0.59	0.83
Relative Frequency Delayed Interactions	-0.48	0.65

observation is that the sign of the correlation is the same. The final trait, concerning team interactions, has a different correlation in the validation case studies than was observed in the initial case study set. When all three interaction questions are considered, the validation case study teams appear to have different interaction preferences than the full case study teams. Table 5.2 shows the three dimensions of interactions preferences in the full and validation case studies. Whereas the original case study set teams show a preference for real-time and in-person group interactions, the validation case study teams show a preference for asynchronous and virtual team interactions. These differences may be due to the inclusion of software teams (which by nature of their work utilize more virtual and asynchronous communication) and the inclusion of teams in the integration and test phase (which engage in more problem solving than design).

When the interaction trait is removed from the regression model, then the regression model based on the original accounts for 67% of the variation observed in collaborative systems thinking rankings. This value was calculated by comparing the root mean square (RMS) of the differences between the team's self rating and the mean of those ratings and the predicted ratings.

Table 5.2: Comparison of Team Interaction Preferences Between Full and Validation Case Studies

Interaction Trait	Full Case Study Correlation	Validation Case Study Correlation
Individual vs. Group	0.71	0.46
In-Person vs. Virtual	-0.42	0.37
Real-Time vs. Asynchronous	-0.48	0.65

As a matter of curiosity, the validation survey also included a question about the average number of past similar programs worked. The responses to this question have a correlation of -0.16 with collaborative systems thinking (as compared to 0.59 in the full case studies). This significant deviation from the original data appears to be the result of one outlying validation case study data point. One team reported an average of 10-20 previous program experiences per team member. All of the full case study data and remaining validation case study data suggest that 1-5 previous program experiences is the norm. When this data point is removed, the correlation between collaborative systems thinking and previous program experience is 0.28: less than the correlation with concurrent program experience, but more reflective of the importance of systems experience as an enabler for collaborative systems thinking.

Team size did not appear as an important indicator of collaborative systems thinking within the full case studies ($Corr = -0.17$). However, the validation case studies do show some dependency on team size. The correlation between collaborative systems thinking and team size observed in the validation case studies is $Corr = -0.66$. This contrast to the original data suggest that additional research is required to determine the effect of team size on collaborative systems thinking.

5.2.2 Qualitative Results of Validation

In addition to the numerical data shown above, qualitative data were also collected as part of the validation case studies. A followup question was included in the validation case studies: to describe and provide examples supporting the team's collaborative systems thinking ranking. These responses provide qualitative data that can be compared to the codes and concepts identified within the full case studies.

The initial case study set suggested a that aircraft teams were more likely to engage in collaborative systems thinking than are spacecraft teams. This pattern was not continued in the validation case studies. Of the three validation teams with low collaborative systems thinking ratings, all were aircraft hardware teams. The teams with higher collaborative systems thinking ratings included missile teams, software teams, and spacecraft hardware teams. These data, taken in concert with the original case study data, suggest there is no relationship between team industry sector and collaborative systems thinking rating.

The inclusion of integration and test teams allowed for comparison between the conceptual design and test program phases. The original set of case studies suggested conceptual design teams were more able than detail design teams to engage in collaborative systems thinking. The validation case studies suggest that conceptual design teams are also more able than integration and test teams.

As with the full case studies, the system customer did not influence a team's likelihood of engaging in collaborative systems thinking.

Comments from the higher collaborative systems thinking teams support the original case study findings that frequent meetings, open communication, and effective leadership are important enablers of collaborative systems thinking. These teams also refer the the use of domain experts and well-documented knowledge. One team with a high rating is distributed across the entire country, reinforcing the concept that non-collocation is not a barrier to collaborative systems thinking. One team with a higher collaborative systems thinking rating described an organizational environment where all individuals were encouraged to think about interactions, thus emphasizing the role culture plays in enabling collaborative systems thinking.

Comments from the lower collaborative systems thinking teams suggest that functional silos, an absence of leadership, and a failure to ask question are barriers to collaborative systems thinking. These data reinforce qualitative results from the original case study sample population. One individual commented on the specific need to have more than just the project manager engaging in systems thinking. This individual identified the systems exchange between different components as critical to breaking down program silos. Two of the three validation case studies specifically mentioning the importance of culture were the lower rated teams. This suggests that a collaborative culture is an necessary enabler of collaborative systems thinking.

Finally, one individual provided a concise description of the 'fine line his team walks between collaborative systems thinking and individual systems thinking.' He described a context in which individuals leading different subsystems engage in individual systems thinking relative to their own realms and then 'marry' their individual thoughts together in the act of group discussion and compromise. This discussion provides insight into the multi-level systems thinking interactions. The comment also further supports the three-categories team membership model wherein the individuals leading different subsystems represent the 'technical translator' category. These individuals are responsible for much of the individual systems thinking at the component or subsystem level. They then enable collaborative systems thinking in system-level meetings by 'marrying' their individual thoughts into group discussion.

In conclusion, the validation case studies support both the quantitative and qualitative findings from the original case study set. This suggests the results are applicable to all program lifecycle phases, to large and small programs, and may be extensible to software programs as well.

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Chapter 6

Conclusions

The demand for systems engineering practitioners has increased at the same time the engineering workforce is declining in the US and other countries [20, 137]. Several studies cite an acute erosion of engineering competency within the government and aerospace/defense industry. The development of systems competencies is critical given the challenges faced; yet the communities affected lack the empirical basis for developing a well-informed, data driven strategy to develop new systems expertise [119]. The increasing demand for systems leaders coupled with the growing need to address socio-technical challenges motivates research in engineering systems thinking and practice [120].

Within the aerospace industry, the need for systems skill development is particularly urgent given that more than 25% of aerospace industry professionals will be eligible for retirement before 2013 [20]. This predicted 'silver tsunami' is in addition to the large post-coldwar reductions in workforce the aerospace industy has already seen. The result is an aerospace industry that is being asked to produce more advanced systems with fewer resources, fewer experienced engineers, and fewer programs from which to learn. It is therefore important to understand how systems skills develop and to explore new ways in which to leverage systems skills and to thus avoid having even more artifacts in museums for which we no longer possess the requisite systems knowledge [121].

This dissertation addresses the systems skill shortage within the aerospace industry by looking to engineering teams as a unit of systems thinking. Team level systems thinking has been termed "collaborative systems thinking" because of the collaborative team member interactions required to facilitate systems thinking at the team level. Little is known about how engineers or teams of engineers develop systems thinking. What literature does exist is based on empirical studies of individual engineers [35] or teams of engineering students [88]. This thesis focuses on teams of practicing engineers working on complex real-world aerospace systems. As aerospace systems have increased in complexity and lifecycles grown longer, individual engineers are no longer with a program for its duration, and the team has become the stable unit of knowledge within programs. It is therefore important to understand how these real-world *teams* engage in systems thinking.

This area of research requires empirical studies and case-based research for the purpose of understanding how to enable more effective systems thinking development within aerospace teams. Through surveying these teams, interviewing team members, and making field observations when possible, a diverse set of qualitative and quantitative data were used to identify those traits most closely linked to collaborative systems thinking. The exploratory nature of this research resulted in a set of initial generalizations about collaborative systems thinking teams and a set of hypotheses for future directed research.

By its nature, this research does not fit neatly into traditional academic engineering departments. Empirical research into engineering teams requires both an in-depth understanding of engineering practice and the use of social science methods for empirical observations. Grounded theory methods informed the research framework because the methods are well suited for exploratory, empirically-based research [140]. Interviews and case studies were used for data collection, as case studies are flexible and effective ways to gather many types of information and are helpful in establishing external validity of the data collected. Case studies are also valuable in increasing the domain over which results may be generalized [158].

From the data presented in Chapter 4, a few conclusions may be drawn. First, collaborative systems thinking is a team property distinct from individual systems thinking. Second, collaborative systems thinking teams have differentiating characteristics, grounded in data, that may help to explain why some teams are better at handling systems issues. These characteristics include easily quantifiable traits (e.g. past program experience) and fuzzier structural and cultural traits (e.g. the presence of social and technical leadership). Finally, these characteristics proved generalizable to teams outside of the initial full case study set as shown through the abbreviated case studies and validation case studies.

The following sections outline the contributions of this thesis to practice, the implications for academia, industry and government, and suggestions for future research into collaborative systems thinking.

6.1 Contributions to Practice

This research has produced four distinct contributions to the practice: a definition of collaborative systems thinking, a set of generalized collaborative systems thinking team traits, a set of heuristics for enabling collaborative systems thinking, and hypotheses for directing future research.

6.1.1 A Definition of 'Collaborative Systems Thinking'

The first contribution is a working definition for collaborative systems thinking:

> *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 systems attributes, interrelationships, context and dynamics towards executing systems design.*

This definition is grounded in past definitions of systems thinking, research on engineering systems thinking, literature on engineering design teams, and concepts from pilot interviews.

6.1.2 Generalized Traits of Collaborative Systems Thinking Teams

The second contribution is a list of empirically generalized traits of systems thinking teams, shown in Table 6.1. These traits were identified through surveys and interviews from ten case studies. Some of these traits (e.g. engaging in consensus decision making) are based on quantified survey data reinforced by qualitative interview data. Other traits (e.g. three categories of team membership) are based on qualitative interview data. Those teams in the aircraft industry have higher collaborative systems thinking rankings than teams in the spacecraft industry. The apparent industry dependency is not significant because of the relatively small sample size of this study, but may be worth exploring in future research.

The generalized traits reinforce patterns from the literature and past empirical research on engineering systems thinking development. Experiential learning (past and concurrent program experience) is an important indicator of collaborative systems thinking just as experiential learning is one of the three main enablers of engineering systems thinking development [35]. Effective team leadership in combination with team norms facilitating interaction and team member buy-in are also important enablers of collaborative systems thinking. These effective team norms are part of the enabling framework for superior team performance [60]. Finally, creative team environments appear to better foster collaborative systems thinking. This in reinforced by literature on both systems thinking and engineering design teams [44, 45].

Equally important is the list of traits that appear not to affect collaborative systems thinking, shown in Table 6.2. In particular, non-collocation does not appear to be a major barrier to collaborative systems thinking despite initial pilot interview comments to the contrary. Immediate team size, program customer base, measures of technical process use, and self-reported individual systems thinking are all poor predictors of team collaborative systems thinking. Further research is needed to determine if these traits are in fact independent of collaborative systems thinking. The emphasis on real-time group interactions points as an enabler suggests that collocation

Table 6.1: Empirically Generalized Traits of Collaborative Systems Thinking Teams

	Generalized Traits of Collaborative Systems Thinking Teams
1	Collaborative systems thinking teams engage in more consensus decision making
2	Collaborative systems thinking teams have three categories of membership
3	Collaborative systems thinking team communication preferences are for real-time group interactions
4	Collaborative systems thinking team members have higher number of past and concurrent program experience
5	Collaborative systems thinking team members rate their team environment more favorably
6	Collaborative systems thinking teams have more creative environments
7	Collaborative systems thinking teams require both technical and social leadership
8	Conceptual design teams are more likely to engage in collaborative systems thinking

Table 6.2: Empirically Identified 'Non-Traits' of Collaborative Systems Thinking Teams

	Team Traits not Impacting Collaborative Systems Thinking
1	Team size
2	Customer base (government or commercial)
3	Measures of technical process use and/or tailoring
4	Self-reported team member systems thinking
5	Team collocation

should be a barrier. Do these teams simply have better procedures for communicating with their non-collocated team members? Or is there an additional variable at work? Similarly, research has shown that larger teams incur communication losses as more time must be spent coordinating dependent tasks [60]. Perhaps there was insufficient variation in team size within the sample to view this phenomena. Finally, the customer base was chosen as a variable of interest because of varying customer requirements on process use and maturity. It is therefore not surprising to find both the metrics of customer based and technical process usage on the same list. However, effectively designed and used processes have been shown in other research to dramatically improve the design process [136, 26]. Perhaps having greater access to the processes used by each team would provide insights into differences between their processes that act as enablers or barriers to collaborative systems thinking.

6.1.3 Heuristics for Collaborative Systems Thinking

The third contribution is the set of heuristics gathered from the interview transcripts. The heuristics listed in Table 6.3 emerged from the full and abbreviated case study interviews and represent snapshots of wisdom for composing, leading, and working in engineering teams. Each heuristic represents an insight from multiple interviews (both from the full and abbreviated case studies). These insights were chosen because of their ability to either highlight a generalized trait of collaborative systems thinking teams or complement existing literature.

Table 6.3: Heuristics Identified During Research

	Heuristics for Enabling Collaborative Systems Thinking
1	A product orientation is important to team success.
1.A	Collaborative systems thinking teams concentrate on the system, on finding an elegant solution. Requirements are secondary to that design.
1.B	Teams engage in systems thinking when the individuals are genuinely interested and engaged in the task. Fundamentally, the solution comes not when we are concentrating on the constraints, but when we become engrossed with the problems at hand.
2	Clear communication is critical to collaborative systems thinking. Teams tend to over-use email and other IT tools. Sometimes you just need to walk around and speak with others. After all, you can't delete a walk-in.
3	The asking and answering of questions brings both parties to new realizations. It helps teams and individuals identify built-in assumptions and move away from "what we've always done." A team needs the leader to ask the right questions; an individual who is curious, imaginative, knowledgable, and can help others look at the problem from outside of the box.
4	Many people are comfortable following guidelines and rules, but process can become brittle. Teams require a balance of individuals that follow the letter of the law and individuals who follow the 'spirit' of rules; who reframe problems to get around rules. This is how we innovate and improve.
5	In a team setting there must be a balance between experience and analysis. Experience feeds the team's intuition and frames how each new problem is faced. However, in innovative situations intuition can be a liability, and teams must use tools to find new knowledge and overcome the inertia of past experience.
6	Engineering mistakes repeat every 7-10 years. This is the time it takes for critical people to rotate off a program and for important knowledge to be lost and rediscovered through failure. Successful programs have a line of succession: a continuity of knowledge through awareness of the past, present, and future. When this continuity is broken is when teams are doomed to repeat failures of the past.
7	Team members, especially the smart and innovative, come with 'warts.' Team leaders cannot tolerate disruptive behavior, but need to treat each person individually to get their best work and to help them become better engineers and team members.

Table 6.4: Hypotheses for Future Research

	Hypothesis About Collaborative Systems Thinking
1	Teams that engage in consensus decision making will have teams members with a greater awareness of systems attributes, interrelationships, and the design motivation and purpose.
2	Teams whose members concurrently participate on multiple programs will be more aware of available deign processes, tools, and resources than teams whose members do not contribute to other programs. This relationship hold only to approximately three concurrent programs, past which point team member attention will be too divided to support collaborative systems thinking.
3	Programs with more realistic schedules (neither too optimistic or pessimistic), will be better able to properly utilize the design process to consider the entire systems and its context when making decisions.
4	Teams with more creative environments, who engage in more collaboration and have greater decision freedom, will interact more, utilize both divergent and convergent thinking styles, and subsequently engage in more collaborative systems thinking.
5	Teams whose interactions are primarily in real-time will communicate technical information more effectively and using a greater number of design abstractions (e.g. sketches, prototypes, gesticulation) as compared to teams who primarily communicate asynchronously.

6.1.4 Hypotheses for Future Research

The fourth and final contribution is a first-attempt model and theory for predicting collaborative systems thinking from a subset of team traits. The model was used to demonstrate, through the validation case studies, that the observations may be generalized beyond the initial set of case studies. From this model, five hypotheses are proposed as theory to spur future research. These hypotheses are centered on the role of team environment, team decision making process, team member experience and links to outside programs, and team communication preferences.

6.2 Implications for Practice

From this research three sets of recommendations are put forth: for the aerospace industry, academia, and government policy.

6.2.1 Recommendations for Industry

Data from this research support past research emphasizing the role of systems experience as an enabler for engineering systems thinking [35]. Industry should use internal research and development (IR&D) funding to establish smaller, higher-risk programs to provide systems experience to the workforce. As a secondary benefit, such shorter-term, cutting edge programs have been shown to improve workforce retention, especially among women within the aerospace industry [115]. Anecdotal evidence suggests these program experiences are also pivotal in learning how to manage risk and uncertainty and provide the confidence necessary for decision making. The wide number of industry-sponsored rotation programs are a good first step toward providing systems experience to younger engineers, but more small systems design-based programs (e.g. JPL's Phaeton [48]) should be pursued to provide system experience crossing multiple disciplines and lifecycle phases. Such programs pair younger engineers with experienced engineers in a setting that provides both practical training and mentoring: a type of 'whole' training experience. If such programs are looked at from both research and development and training perspectives, the cost is more easily justified.

This research provided no conclusive results on the role of traditional training activities as an enabler or barrier to collaborative systems thinking. Teams did speak to a disconnect in process as currently implemented within large companies. Better feedback channels are needed to improve existing processes based on program experience. Other teams expressed a desire for more latitude in process tailoring. They indicated that process tailoring used to be more informal but has now become more bureaucratic, limiting the decision freedom of the team and team leader. These individuals spoke to an indifference that was developing towards documented process because 'no program can actually afford to complete all the recommended processes.' This indifference to process undermines its effectiveness and the feedback mechanism for improvements. Training individuals to modify the process and providing them the authority to do so should help improve several of the metrics of creativity that were effective predictors of collaborative systems thinking.

Finally, industry needs to do more to develop strong team leaders. Interviews indicate that most believe leaders are chosen solely on technical ability, but that more needs to be done to either identify leaders with both social and technical ability or to provide training to develop such future leaders. By contrast, one individual expressed frustration with non-technical leaders. These comments emphasize the importance of leaders having both technical credibility and good people skills, a pattern reinforced by past leaders within the industry who have been charismatic individuals with a compelling technical story.

Recommendations for Industry

1	Use IR&D funds for small development programs that provide employees with pertinent systems experience
2	Encourage informal mentoring relationships, in combination with real program experience, as a way to train the future workforce
3	Emphasize both technical and social skills when selecting team leadership

6.2.2 Recommendations for Academia

Academia provides future engineers with their first exposure to engineering practice. Aerospace engineering programs across the country have already embraced this role through partnerships with industry that aim to update coursework and ensure its relevance to contemporary industry needs. One prominent example of this new curriculum method is CDIO [24, 65]. Central to these new curricula are hands-on design projects. Such projects provide a connection between engineering science and design.

Placing students, especially teams of students, in a non-deterministic design environment helps develop communication and decision making skills. Exposure to real-world design decisions also help teach students to deal with uncertainty. Examples of such real-world design projects include senior capstone projects [65] and sponsored design programs (e.g. the AIAA Design-Build-Fly competition). Participation in systems projects such as the FIRST Robotics Competition have been shown to triple the likelihood of a student pursuing an engineering degree and a career in engineering [99]. These data apply to high-school age students, and no similar longitudinal data is currently available for college age engineering students. However, the improvement in retention is likely to be similar. Currently, nearly 50% of aerospace engineering degree holder work outside of the industry [106]. Retaining those individuals, especially young professionals, trained in aerospace engineering will help address the industry's 'silver-tsunami' and help assure a sufficient number of individuals are in the pipeline and developing systems skills.

Capstone projects and design competitions provide an opportunity to introduce students to accepted design practices (e.g. gate reviews and requirements management). While employers utilize specifically tailored processes, educating engineering students in good design procedures is as important as teaching science students the scientific method. Teaching the design process will encourage creativity and the out-of-the-box thinking central to past advancements within the aerospace industry.

Technical communication skills (e.g. sketching and modeling) are also reinforced through capstone projects and design competitions. Writing and speech course requirements at schools such as MIT show that academia already understand the importance of communication. However, classes on drawing, drafting, and modeling would help to round out a student's technical communication toolbox. Such drawing and drafting classes were traditionally taught at the high school level, but anecdotal evidence suggests that high schools are both eliminating these programs due to budget cuts and dissuading college-bound students from enrolling in such 'vocational' education courses. Such moves only work to solidify the gap between the art and science of good engineering.

	Recommendations for Academia
1	Universities should provides systems experiences for students
2	Schools should encourage team activities and provide guidance on how to work effectively in teams
3	Engineering students need engineering courses that integrate technical writing and speaking, emphasizing the importance of both technical and social skills
4	Engineering coursework should introduce students to drawing, drafting and model making as a way to encourage communication using multiple design languages and more creative team environments

6.2.3 Recommendations for Government

This research extends the recommendation of the American Institute of Aeronautics and Astronautics Workforce and Education subcommittee that more spending is needed in research and development to counter the decline in industry R&D spending since 1998 [3].[1] This funding is critical to providing systems experience to the current and future workforce. Especially now, during an economic downturn, these investments in the future workforce are extremely important. While R&D funding may appear an easy place to cut overhead expenses, the benefits of R&D are long-term, and the government should establish policies that encourage such positive and long-sighted behavior. Speakers in the "Rebuilding the Nation's Image of Aerospace Contributions to Society" session at the 2009 AIAA Inside Aerospace conference spoke to the need to not only hire more people into the industry, but to train these individuals. Reinforcing the need to hire and train young workers, Dr. Charles Vest, president of the National Academy of Engineering, spoke at the same conference and opened his presentation with the statistic that the average age of an Apollo program engineer

[1] The author is a member of the AIAA Public Policy Subcommittee on Workforce and Education

was 27. The average NASA employee is now over 49 years old [83]. This dramatic aging of the workforce speaks to a need to revitalize the workforce and to provide opportunities for younger engineers to contribute meaningfully to programs. Two mechanisms enabling this change are policies that provide incentives for corporate IR&D funding and increased funding of graduate engineering education.

Two comments (from a pilot interview and abbreviated case study interview) specifically mentioned black programs as vehicles that allowed for greater risk taking, and therefore greater systems learning. By classifying small high-risk programs, the government could use a 'portfolio' approach to both develop new technologies and provide formative systems experience to younger engineers.

Further, government should support the use of small business grants to foster small, agile, and creative organizations with the capabilities and flexibility to address new problems facing the industry. Most aerospace organizations have large 'marching armies' and lack the agility to respond quickly to new challenges. Smaller organizations can support tight-knit communities, based on interpersonal trust, that are more readily able to handle new and innovative problems.

Recommendations for Government

1	Support policies that incentivize corporate IR&D funding to provide systems experience to the industry workforce
2	Support research funding within academia to ensure a sufficient number of students are in the systems skills development pipeline
3	Use black program environments, or similar, to allow teams the opportunity to take greater risks and work in environments with greater uncertainty and more latitude to make decisions
4	Promote entrepreneurship through small business grants to encourage creativity, innovation, and reasonable risk taking

6.3 Future Work

There are significant challenges to conducting research on engineering systems thinking and collaborative systems thinking. These challenges lie both in the relative immaturity of the area of study and in gaining access to the necessary data [121]. Because research into engineering systems thinking and collaborative systems thinking is relatively new, research to this date has been largely exploratory in nature. These studies have focused on niches of interest (e.g. the aerospace industry), but encompass phenomena that are likely applicable to much larger realms. The second issue, access to data, is a product of the many types and depth of data required to investigate a social and technical phenomena such as collaborative systems thinking. To truly understand the impact of culture (unarticulated and unobservable traits of culture) an ethnography must be completed. Such a study would require unfettered access to a team and more time than is feasible in the course of a single dissertation. Being imbedded within a team would also provide higher fidelity data on process use and process design. These steps are necessary to move future work from the descriptive realm to the prescriptive realm and to build upon the foundational research that will lead to more scientific and rigorous studies [121].

Table 6.5 shows suggested paths for future research into collaborative systems thinking

Establishing a Link Between Collaborative Systems Thinking and Performance Aerospace industry leaders have identified a need for more systems skills. Research has identified systems thinking as a necessary skill for senior systems engineers [35]. However, the concept of systems thinking teams is new, and no data exist to support the assertion that systems thinking teams perform better. If organizations must invest in promoting collaborative systems thinking, there must be a demonstrated payback on that investment. A cross-sectional study, such as the one described in this dissertation, cannot draw conclusions about the impact of collaborative systems thinking on team performance for two reasons: 1) many of the systems under design cannot yet be labeled as successes or failures and 2) companies closely

Table 6.5: Areas Proposed for Future Collaborative Systems Thinking Research

	Suggested Future Work
1	Use a larger sample size and longitudinal study to identify what relationship exists, if any, between collaborative systems thinking and team performance on program measurables (e.g. schedule, budget, requirements met)
2	Use hypothesis-based research to test the five hypotheses developed based on those five team traits that best predict collaborative systems thinking
3	Conduct more in-depth exploratory research to better understand the three-level team structure identified through case study interviews and the role of both technical and social leadership as enabling collaborative systems thinking
4	Develop simulations or games to more accurately assess (and promote) collaborative systems thinking
5	Use longitudinal studies to determine the effects of interventions (e.g. training or team building activities) on collaborative systems thinking development

guard data on performance metrics such as cost and schedule. In order to identify a link between collaborative systems thinking and team performance, these obstacles must be overcome. The first obstacle can be overcome by a longitudinal study that follows several teams over a period of years. The time period is required to determine the success or failure of the systems. The large sample size is required to exclude other extraneous variables (e.g. politics, program cancelation, etc.) that will also impact program success.

Hypothesis-Based Prescriptive Research Exploratory research attempts to explain observations. It cannot establish cause and effect relationships. Hypothesis-based research tests a link between a perceived cause and effect. By varying the input variable (e.g. average number of past program experiences) and controlling for other variables through careful case selection, cause and effect relationships can be inferred between the generalized traits and collaborative systems thinking. Without such testing, it is difficult to say if creative teams are more likely to engage in collaborative systems thinking or if collaborative systems thinking teams are more creative. Research to better understand these cause and effect relationships will result in more precise recommendations to organizations seeking to promote collaborative systems thinking.

Additional Research to Explore Team Structure and Leadership The traits of three-level team structure and social and technical leadership emerged from the case study interviews. As such, the understanding of these traits is less developed. Both traits have precedence in existing literature, but it is unclear how specifically each support a team's collaborative systems thinking. Additional interviews and greater access to organizational charts and team rosters is required to validate the importance of these traits and to better explain why these appear to enable collaborative systems thinking. Such an understanding will help organizations develop strategies and interventions to promote these culture and leadership-based traits within teams.

Develop Simulations to Assess and Promote Collaborative Systems Thinking Similar to the Lean Enterprise Value Simulation [82], an interactive simulation or game could be developed and used to demonstrate the need for collaborative systems thinking, assess a team's ability to engage in collaborative systems thinking, and/or as a tool to enable its development. If such a simulation could be developed, it would be invaluable for hypothesis-based research. Much like flight simulators have proven an effective means for teaming research, a simulation designed around collaborative systems thinking would facilitate controlled experiments to identify the relationships between collaborative systems thinking and the generalized traits identified within this research. For instance, the rules of the simulation could be varied to create more or less creative environments. Likewise, teams with individuals who have played the game multiple times could be compared to teams with no prior simulation experience. The difficulty with this path is in developing and testing a simulation that actually tests collaborative systems thinking. Guidance on this task could come from systems thinking interventions (e.g. [142]) and development on the Lean Enterprise Value Simulation [82].

Impacts of Interventions on Collaborative Systems Thinking Presuming collaborative systems thinking improves team performance and organizations value this performance improvement, the question is then how to actively promote collaborative systems thinking. The results of hypothesis-based research combined with a simulation would provide a way to intervene in a team collaborative systems thinking development. To establish the effectiveness of such an intervention, a longitudinal study would be required to prove a cause and effect link between the team's intervention and any subsequent improvement in collaborative systems thinking. This path of future research is listed last because of its dependence on the other paths for future research.

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Appendix A

MIT COUHES Approval

CONSENT TO PARTICIPATE IN INTERVIEW

Collaborative Systems Thinking

You have been asked to participate in a research study conducted by Caroline Lamb from the Lean Advancement Initiative (LAI) at the Massachusetts Institute of Technology (MIT). The purpose of the study is to gather information about the role of organizational culture and standard technical process in promoting team-level systems thinking: collaborative systems thinking. The results of this study will be included in Caroline Lamb's doctoral thesis. You were selected as a possible participant in this study because you are involved/ have been involved in a large aerospace or defense project. You should read the information below and ask questions about anything you do not understand before deciding whether or not to participate.

- This interview is voluntary. You have the right not to answer any question and to stop the interview at any time. This interview is expected to take about 1 hour.
- You will not be compensated for this interview.
- Unless you give permission for the use of your name, title, and / or to quote you in any publications that may result from this research, the information you provide will be confidential.
- Notes will be taken during this interview. All notes taken will be stored in a secure work space until the completed of this research project (12/2009). At that time, all notes taken during this interview will be destroyed.

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

I give permission for the following information to be included in publications resulting from this study: (Please check all that apply)
[] my name [] my title [] direct quotes from this interview

Name of Subject

Signature of Subject ______________________________ Date ________________

Signature of Investigator __________________________ Date ________________

Please contact Caroline Lamb, by email at cmtwomey@mit.edu, or by phone at 617-308-0954 with any questions or concerns.

If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E32-335, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253 6787.

Appendix B

Research Instruments

B.1 Pilot Interview Protocol

The following 12 questions comprise the pilot interview protocol.

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1. Given the following definition of systems thinking, how would you change or modify this definition for systems thinking when perceived as a property of a group or organization?

   "The ability to understand technical interdependencies in a system,
   the ability to understand social interdependencies in a system.
   the ability to think about feedback dynamics in a systems, and
   the ability to understand multi-level enterprise dynamics."

2. Have you participated in a group you would describe as possessing systems thinking characteristics? What steps were taken within this group to promote team systems thinking? [Referred to as collaborative systems thinking (CST)]

3. What enablers, barriers, and/or precursors exist to the development of CST?

4. What is the role of culture in CST?

5. What is the role of standardized process (standard work) in CST?
6. What is the role of a group's physical environment in CST?
7. Do you have a high-performing group you would describe as thinking and acting systematically?
8. How did the group develop these traits?
9. Do the individual members of this team embody systems thinking characteristics? Is individual systems thinking a necessary condition for CST?
10. How does CST develop within a team over time?
11. Can you recommend any relevant references or sources?
12. May I contact you later with questions related to this conversation?

B.2 Case Study Protocol

B.2.1 Full Case Study Protocol

The full case study protocol consists of a survey administered to all team members, an engineering interview administered to a subset of team members, and an interview administered to an individual not on the team, but familiar with the team's work. Additional forms were generated to guide field notes.

Team Survey

Collaborative Systems Thinking Questionnaire

Background: This survey is in support of research exploring the role of organizational culture and standard technical process usage in the existence and development of team-level systems thinking.

Your Rights: Your participation in this survey is voluntary; you many decline to answer any or all questions; you may decline further participation in this survey at any time without adverse consequences; and your confidentiality and/or anonymity are assured.

1. What is your job title?

   ____

2. What function or discipline do you represent on this team? (e.g. aero, structures, etc.)

   ____

3. What is your highest level of education? (Check one)

   ______ High School
   ______ Associates Degree
   ______ Bachelor of Art or Science
   ______ Master of Art or Science
   ______ Doctorate
   ______ Other ______________

4. In what field is your degree?
   (e.g. mechanical eng., math, physics, aerospace eng., etc.)

   ____

5. How long have you been with
   this team? ______________________________
   this company? ______________________________
   the aerospace industry? ______________________________

6. On how many similar projects have you worked in the past?

   ____

7. On how many different teams (projects) do you currently contribute as a member?

   ____

8. With what fraction of your current team members have you previously worked?

   No one (0%) ______|______|______|______ Everyone (100%)

9. With which **THREE (3)** of the following team roles do you personally identify on this team?

    ________ Creative, unorthodox problem solver
    ________ Good communicator, finds team new opportunities, well-connected
    ________ Coordinator, clarifies team goals, facilitates decision making
    ________ Performs well under pressure, tenacity to overcome obstacles, dynamic
    ________ Strategic individual, carefully weighs options, good judgement
    ________ Team player, diplomatic, builds consensus, avoids team friction
    ________ Reliable, disciplined, gets things done, conservative, practical
    ________ Detail oriented, focused on completion, time/schedule conscious
    ________ Specialist, narrow focus, technical focus

10. In each of the following four statement pairs, please circle the statement with which you most identify.

1.a) I form new ideas through discussion with others and relate well to people and things.	1.b) I form new ideas through internal monologue and relate well to concepts and abstract ideas
2.a) I am interested in concrete ideas and prefer to interact with my surroundings	2.b) I am imaginative and enjoy exploring future possibilities and gaining new insights
3.a) I make decisions based on objective analysis and logic	3.b) I make decisions based on my values, what feels right
4.a) I plan far into the future, preferring to have life planned and orderly	4.b) I am spontaneous, flexible with my plans and don't want to miss anything

11. Has your team received training as a team? (Circle one) Yes No

    If YES, which of the following topics did team training include?

    Was the training effective?

Training Topic	**Included?**	**Effectiveness**						
Process Usage		Low	1	2	3	4	5	High
Technical Knowledge		Low	1	2	3	4	5	High
Team Development		Low	1	2	3	4	5	High
Human Resources Training		Low	1	2	3	4	5	High
Other ________________		Low	1	2	3	4	5	High

12. Is your team collocated (same office space, building, campus)?

    (Circle one) Yes No

    If NO, please rate the impact on team's ability to communicate technical information.

    Negative _______|_______| No Impact |_______|_______ Positive

13. What tools and space (real or virtual) does the team use to communicate and interact?

    ____

14. How do you most commonly interact with other team members?

    Place an 'X' one the line between the two options to indicate the relative frequency of the two interaction styles. E.g. an 'X' placed in the middle would indicate both type of interactions occur with equal frequency.

    A) Do you interact one-on-one (face-to-face, telephone calls, IM) or in groups (team meeting, conference calls, WebX)?

       1-on-1 _______|_______|_______|_______ Groups

    B) Do you interact in person or virtually (telephone calls, email, WebX)?

       In person _______|_______|_______|_______ Virtual

    C) Are your interactions real-time or delayed response (e.g. email)?

       Synchronous _______|_______|_______|_______ Asynchronous

15. Which of the following are most commonly used to communicate technical information within the team? (Circle three)

A Verbal (written or spoken)	**E** Sketches
B Mathematical equations	**F** Part drawings
C Computer models (static)	**G** Scale models
D Computer models (dynamic)	**H** Prototyping

16. Does your team have an established identity or culture that distinguishes your team from other teams? (Circle one) Yes No

    If YES, is the team identity focused more on product, process, or people?

    ____ Product ____ Process

    ____ People ____ Other __________________

    Please describe briefly.

    ____

17. Please rate each of the following aspects of team environment (1-Poor to 5-Excellent)

Project management	Poor	1	2	3	4	5	Excellent
Access to resources	Poor	1	2	3	4	5	Excellent
Decision freedom	Poor	1	2	3	4	5	Excellent
Realistic schedule for deliverables	Poor	1	2	3	4	5	Excellent
Individual incentives and recognition	Poor	1	2	3	4	5	Excellent
Team incentives and recognition	Poor	1	2	3	4	5	Excellent
Interesting/challenging work	Poor	1	2	3	4	5	Excellent
Collaborative environment	Poor	1	2	3	4	5	Excellent
Organizational interest in mission of team	Poor	1	2	3	4	5	Excellent

18. Is teamwork valued within your team?

    Not Valued 1 2 3 4 5 Highly Valued

19. Is teamwork valued within your organization?

    Not Valued 1 2 3 4 5 Highly Valued

20. Do rewards and incentives promote individual or team-level accomplishment?

    Individual _______|_______|_______|_______ Team

21. Does your organization have a standardized technical design process? (Circle one) Yes No

    If YES, to what extent do you, as an individual, comply with the standard process?

    Non-Compliance 1 2 3 4 5 Full Compliance

If YES, to what extent does the team as a whole comply with the standard process?

Non-Compliance 1 2 3 4 5 Full Compliance

22. How relevant and easy to use is the standard process?

    The standard process is relevant and useful on this program.

    Disagree 1 2 3 4 5 Agree

    The standard process is easy to use and understand.

    Disagree 1 2 3 4 5 Agree

23. Did your team have the opportunity to tailor or modify the organization's standard process to help better complete your tasks?

    (Circle one) Yes No

    If YES, to what extent was the standard process modified?

    Minor Modifications ________|________|________|________ Major Modifications

24. Are design decisions within the team more often made by an individual or team consensus?

    Team consensus ________|________|________|________ Individual

If INDIVIDUAL decision making is more common, are most decisions made by..	If CONSENSUS decision making is more common, are decisions made...
A) the same individual	A) when the supporting information is presented and with little or no time for discussion or reflection
B) the team leader	B) after a period of reflection and discussion.
C) one of a rotating set of individuals	

25. How aware are you of other team members' design tasks?

    Not Aware ________|________|________|________ Fully Aware

26. How aware are you of other team members' relevant expertise and knowledge?

    Not Aware ________|________|________|________ Fully Aware

27. Please rate your agreement with each of the following statements.

    (1-Strongly Disagree to 5-Strongly Agree)

	Strongly Disagree |			Strongly Agree	
I respect other team members' technical knowledge and expertise	1	2	3	4	5
I trust other team members' abilities to meet deadlines	1	2	3	4	5
I trust other team members to deliver high quality work products	1	2	3	4	5
Team discussion stimulates the generation of good ideas	1	2	3	4	5
The team environment is fair and egalitarian	1	2	3	4	5
The team encourage critical questioning and analysis	1	2	3	4	5
The team is accepting of new ideas	1	2	3	4	5
The team has a clear and mutual goal	1	2	3	4	5
The team understands its purpose within the overall systems design	1	2	3	4	5
The team has a shared vision for meeting milestones and requirements	1	2	3	4	5

28. Systems thinking is one of many recognized engineering skills. Given the following definition of *engineering systems thinking...*

    Systems thinking is utilizing tools, models, processes and different thinking styles to consider the componential, relational, contextual, and dynamic elements of the system of interest.

    How do you rate your systems thinking ability? (On a scale of 1-7 with 7 representing strong systems thinking)

End of Survey.

Thank you for your time and participation in my research.

Engineering Interview

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1. What is your teams role within the organization? within the standard process? within the overall system under design?

2. How useful are artifacts like process maps and organizational charts in helping you determine what needs to be done and who to involve?

3. What is your perception of the standard process? What benefits and drawbacks are inherent in its use? Why does your organization have a standard technical process in place?

4. To what extent does the team alter or tailor the organization-level standard process? Up to what level may the team choose its own processes, tools, and methods for design

5. Engaging in analysis of the problem space and critical discussion are recognized ways of managing complexity and improving system design. How does your team discuss new ideas? Does your team analyze the design problem before proposing specific designs for evaluation?

6. What do your teammates contribute to the overall design? What are they currently working on? What past experience do team members have that is relevant to the current design project?

7. In what ways do your informal social connections help you complete tasks? Please compare and contrast the role of social connections with the usefulness of organizational titles and formal channels of communication.

8. Does the team rely more on formal or informal coordination? Please give an illustrative example?

    - Formal coordination is top-down, articulated, documented management.
    - Informal coordination is more spontaneous, bottom-up coordination. It utilizes team member knowledge about where expertise and resources are within the company, team member awareness of each others tasks to anticipate and meet team members needs.

9. How far ahead is the team is planning? What is the average delivery date for open action items? This is not addressing long-range planning documents, but gaging how far into the future the teams is actively thinking on a daily basis.

10. How do you define systems thinking?

11. In what ways does your team engage in systems thinking? Would you consider your team a strong systems thinking team? Please rate your team's CST on a 1-10 scale.

Third Party Interview

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1. How technologically complicated is the teams task? (1-5 scale)
2. How logistically complicated is the teams task? (1-5 scale)
3. What fraction of the team members would you describe as individual systems thinkers?
4. What considerations are made when forming teams? Functional contribution? Personality? Team roles? Past team interaction? Past experience on similar projects? Establishing mentoring relationships?
5. Does the organization use standardized technical processes? If yes, why?
6. What are the goals of team training? Technical enrichment? Team development? Addressing human resource concerns?
7. How process compliant is the team under consideration?
8. To what extent may and has the team under consideration tailored the standard process for current usage?
9. Where in the organization does this team fit? Where within the system under design?
10. How good is team at meeting deadlines, working within budget, and producing defect-free work?
11. How would you rate the teams collaborative systems thinking capability? (1-10 scale) What examples or properties do you use to make this evaluation?

Field Note Guides

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1. How long has the team been working together? How stable is the team's membership (how frequently are members added/removed)?
2. At what level of the system (system, subsystem, component, R&D) is the team operating?
3. How does the team fit within the organizational structure?
4. Is the team co-located?
5. Are members in offices, cubicles, shared spaces?
6. Are special teams rooms or spaces visibly utilized?
7. Observations of design artifacts within design space: posters, bulletin boards for sharing ideas.
8. Does the organization or team have a formal measure of process or capability maturity? (Externally or internally measured) If yes, how mature is the process?
9. Why does the organization have a standard process?
10. If possible, find a copy of the organization's process documentation or flow chart to review in advance of the case study?
11. Observe whether individuals are familiar with org-chart and process-flow diagram.
12. What is the corporate vision statement?
13. What programs or initiatives are in place to promote team work?
14. What type of leadership style is in use?
15. How are questions phrased, do others support lines of questioning, interrupt each other, etc?

B.2.2 Abbreviated Case Study Protocol

The abbreviated case study utilized an open ended interview protocol. The following questions were used to start the conversation.

1. Please tell me about your education and work background.

2. How do you define systems thinking? How does you definition change if applied to a team of engineers?

3. Please describe your experiences with high and low systems thinking teams. What traits and conditions differentiated these teams?

Additional questions were asked as appropriate. Here are examples of two common lines of followup questioning.

4. How would you describe your team's organization? Does your team have three levels of membership (leadership, go-between, and functional experts)? If yes, what fraction of the team is in each level?

5. Does the type of systems thinking change with program phase? If yes, can the same leaders lead during conceptual and detail design?

B.3 Validation Protocol

Collaborative Systems Thinking Validation Survey

Background: This survey is in support of research exploring the role of organizational culture and standard technical process usage in the existence and development of team-level systems thinking.

Your Rights: Your participation in this survey is voluntary; you many decline to answer any or all questions; you may decline further participation in this survey at any time without adverse consequences; and your confidentiality and/or anonymity are assured.

1. What industry sector(s) best describe your current program?

Space	Aviation
Hardware	Software

2. How many individuals contribute on your program team?

---

3. What lifecycle phase best describes our program?

   Conceptual Design

   Detail Design

   Integration and Test

   Operational Support

4. Which category best describes the customer for your program?

   Government   Commercial   Private

5. On how many similar projects has the average team member worked in the past?

   ____

6. On how many different teams (projects) does the average team member currently contribute?

   ____

7. How do team members most commonly interact with each other?

   Place an 'X' one the line between the two options to indicate the relative frequency of the two interaction styles. E.g. an 'X' placed in the middle would indicate both type of interactions occur with equal frequency.

   A) Do you interact one-on-one (face-to-face, telephone calls, IM) or in groups (team meeting, conference calls, WebX)?

      1-on-1 ________|________|________|________ Groups

   B) Do you interact in person or virtually (telephone calls, email, WebX)?

      In person ________|________|________|________ Virtual

   C) Are your interactions real-time or delayed response (e.g. email)?

      Synchronous ________|________|________|________ Asynchronous

8. Please rate each of the following aspects of team environment (1-Poor to 5-Excellent)

Project management	Poor	1	2	3	4	5	Excellent
Access to resources	Poor	1	2	3	4	5	Excellent
Decision freedom	Poor	1	2	3	4	5	Excellent
Realistic schedule for deliverables	Poor	1	2	3	4	5	Excellent
Individual incentives and recognition	Poor	1	2	3	4	5	Excellent
Team incentives and recognition	Poor	1	2	3	4	5	Excellent
Interesting/challenging work	Poor	1	2	3	4	5	Excellent
Collaborative environment	Poor	1	2	3	4	5	Excellent
Organizational interest in mission of team	Poor	1	2	3	4	5	Excellent

9. Are design decisions within the team more often made by an individual or team consensus?

   Team consensus ________|________|________|________ Individual

End of Survey.

Thank you for your time and participation in my research.

Appendix C

Supplemental Analysis

C.1 Pilot Interview Analysis

The following three tables shows examples of supporting text for each code cited multiple times during the pilot interviews.

C.2 Full Case Study Analysis

The following is a report of the numerical data supporting the summary graphics in Section 4.1.2, the correlation relationships in Section 4.2.3, and the regression model in Section 4.2.5.

To protect the anonymity of participating companies, excerpts from the full case study interviews are not included in the reported data.

Note: Case studies H7 and I8 were based entirely on interviews and extensive observation. Interviewees were asked as many survey questions as possible during the interviews. Interview data was used to fill in responses to as many survey questions as possible. When insufficient data were available, 'NA' is indicated.

Table C.1: Supporting Text for All Pilot Interview Codes: Part 1

Definition Codes

CST Involves Producing a Product	'Teams must realize successful products'
	'The idea of producing a product is absent from the systems thinking definition'
CST Involves Understanding the Problem	'In a group it is important to understand the problem at hand'
	'Program teams focus on understanding problems'
CST Involves a Holistic Approach	'Must constantly have the systems view in mind'
	'It is important to have peripheral vision, to see what lies out of focus'

Culture-Related Codes

Creativity and Multiple Thinking Styles Enable CST	'Metaphorical thinking allows for exploring and making connections'
	Teams need 'innovative individual thinking'
Alignment with Project Enables CST	'A shared identity forms in alignment with the project'
A Supportive Environment Valuing Systems Thinking Enables CST	'Teams require constant reminders to stay in a systems thinking mode'
	'Individual team members must listen, understand, and make value-add comments to the team'
A Willingness to Use Process Enables CST	'The desired culture is one where people are willing to use standard process'
A Willingness to Ask and Answer Questions Enables CST	'Teams must be constantly questioning'
	'A managerial culture where people can raise their hands and ask for help when in trouble'
	'Teams must be willing to answer questions'
'Problem Families' that Fail to Converge are a Barrier to CST	'Long standing teams can become insular'
	'They burrow into one problem at the detriment of others'
Ad Hoc Organization is a Barrier to CST	'Ad how teams are error prone'
	'Each site develops different culture; this is an issue with collaboration across the organization'
Hero Syndrome is a Barrier to CST	'Current culture rewards he outcome when everything turns out well, irregardless of path taken'
	'We are still dealing with the myth of the lone designer'
Resistance to Change is a Barrier to CST	'There is often a cultural resistance to change'

Table C.2: Supporting Text for All Pilot Interview Codes: Part 2

Process-Related Codes	
Integrated Design: Bringing the Disciplines Together Enables CST	'Get important people and disciplines involved early in design'
Process Provides a Starting Point from which To Start and Interpret	'Teams need to interpret process'
	'Process enforces a program lifecycle through clear gates'
Shared Language and Taxonomy Enable CST	'Process enables communication'
	'Process provides a mutually agreed upon taxonomy'
	'Shared reference frame,' 'Shared framework'
Tools to Promote Systems Thinking Enable CST	'Standard process provides a tool to promote systems thinking'
	Process is a 'reminder' and 'companion' for systems thinking
Process Moderates Undesired Behavior, Enabling CST	'Process provides guidance for group behavior'
Face-to-Face Communication Enables CST	'The maturity of teams depends on the type and frequency of communication'
	'When you want to get something done, go and meet face-to-face'
Using Consensus Building Enables CST	'Decisions should be made in teams'
A Knowledge Management Enables CST	'Need to share experiences on a diverse set of missions'
	'Tools should support frictionless data flow'
Process can Stagnate, Act as a Barrier to CST	'Process can become too rigid'
	'Rigid process squelches innovation'

Table C.3: Supporting Text for All Pilot Interview Codes: Part 3

Team Trait Codes

Individual Systems Thinkers Enable CST	‘Having a great number of people with systems thinking is a success factor’
	‘Everyone on the team needs some minimal level of systems thinking’
Socialized Experts/ Shared References Enable CST	‘Teams need many experts–well socialized’
	‘Mature teams have socialized members’
	‘Groups need a shared view’
CST Requires Technical Depth, not Width	‘People are on teams because of their particular expertise’
	‘Teams need more areas of technical depth’
Collocation Enables CST	‘Collocated teams are more efficient’
	‘Distributed teams must spend more effort to overcome disadvantage of being apart’
High Communication Bandwidth Enable CST	‘You get better results when you can look someone in the face’
	‘Teams need an environment that supports interactions’

Leadership Codes

Leaders with Strong Social Skills Enable CST	‘Leaders must know how to influence people’
	’Good team leaders and technically competent individuals who know how to lead’
Systems Thinking Leadership is Required for CST	‘Collaborative systems thinking is facilitated by strong systems thinking leadership’
	‘Non-systems thinking leaders need to work closely with a systems thinker’
	‘Teams need an influential systems thinking member’
Systems Thinking Leadership is the Ability to Find Interfaces and Interconnections	‘Systems thinking leaders must tease out interconnectedness of disciplines and decisions’
	‘Systems thinking leaders must be influential and able to pull people into the problem’

Table C.4: Full Case Study Supporting Data, Part 1

Metric (and how Calculated)	Supporting Survey Question #'s	Summary Case Study Data									
		A0	B1	C2	D3	E4	F5	G6	H7	I8	J9
Job Titles (Number of different job titles)	#1	7	9	4	4	5	6	5	7	4	6
Function / Discipline (Number represented on team)	#2	7	9	4	4	4	11	5	7	6	9
Highest Degree Earned (Median: B.S.=3; M.S.=4)	#3	4	4	4	3.5	3.5	4	3.5	3.5	3.5	3.5
Degree Concentration (Number of different degrees earned)	#4	5	4	2	3	4	7	4	4	4	5
Years at Company (Team average)	#5B	26	7	3	28	13	18	18	20	NA	18
Time in Industry (Median range in years)	#5C	25-30	5-10	0-5	30-35	15-20	20-25	20-25	25-30	15-20	20-25
Past Program Experience (Mode of team)	#6	5	2	0	5	2	2	5	5	2	3
Concurrent Team Membership (Median of team)	#7	2	3	1	2.5	2	0	0	2	1	0
Team Roles (RMS deviation from uniform distribution across Belbin team roles)	#9	3.4	4.1	1.0	1.7	2.6	3.7	4.2	3.0	NA	3.2

Table C.5: Full Case Study Supporting Data, Part 2

Metric (and how Calculated)	Supporting Survey Question #'s	Summary Case Study Data									
		A0	B1	C2	D3	E4	F5	G6	H7	I8	J9
Personality Preference (Percent Identifying with People vs. Abstractions)	#10	72%	67%	50%	74%	89%	67%	67%	86%	NA	73%
Team Training	#11	Responses to the question on team training were too varied, indicating the responses are invalid									
Leadership Influence on Team Norm Development	#11, Interview	The data for this parameter are inconclusive									
Stated Goals for Team Development	#11, Documentation	The data for this parameter are inconclusive									
Collocation (Percent of team collocated)	#12, Observation	70%	90%	50%	100%	100%	60%	100%	100%	80%	100%
Collaboration Tools (Number tools cited)	#13	8	8	7	9	6	8	9	8	14	12
Team Space (Number of spaces, real or virtual, cited or observed)	#13, Observations	6	6	5	3	4	6	6	6	8	9
Effective Communication / Design Languages (Weighted sum of team averages)	#14A (1-7 scale) #14B (1-7 scale) #14C (1-7 scale) #15 (RMS)	5.0 3.3 3.5 10	3.5 3.9 3.7 14	3.5 2.3 3.3 5	5.7 2.5 2.8 4	3.7 3.7 4.2 9	4.3 4.2 3.7 17	4.0 1.5 4.2 7	6.0 2.0 2.0 NA	5.0 1.0 1.0 NA	3.4 3.7 3.6 10
Strong Team Identity (Weighted sum of team averages)	#16 (Percentage) #27H (1-5 scale) #27I (1-5 scale) #27J (1-5 scale)	63% 4.2 4.3 3.6	40% 4.3 4.1 3.6	100% 4.3 3.3 2.8	100% 4.8 4.8 3.8	60% 4.5 4.3 4.0	7% 3.1 2.9 2.8	0% 4.0 4.2 3.2	80% 4.3 4.5 4.0	100% 5.0 5.0 5.0	50% 3.8 4.0 3.4

Table C.6: Full Case Study Supporting Data, Part 3

Metric (and how Calculated)	Supporting Survey Question #'s	Summary Case Study Data									
		A0	B1	C2	D3	E4	F5	G6	H7	I8	J9
Measures of a Creative Environment (Average of team responses)	#17 (1-5 scale)	3.6	3.9	3.5	4.0	3.7	3.2	3.4	3.5	3.6	3.2
Ability to Engage in Critical Analysis (Median)	#17H (1-5 scale)	4.5	4.0	4.0	4.5	4.0	4.0	4.5	4.5	5.0	4.0
	#24 (1-7 scale)	2.0	3.0	3.5	1.5	5.0	3.0	1.5	2.0	2.0	3.0
	#27D (1-5 scale)	4.5	4.0	3.5	5.0	4.5	4.0	4.0	4.5	5.0	4.0
Value of Teamwork within Team and Organization (Median)	#18 (1-5 scale)	5.0	5.0	4.0	5.0	5.0	4.0	4.5	4.5	5.0	5.0
	#19 (1-5 scale)	4.0	4.0	3.5	5.0	4.0	4.0	3.5	4.5	5.0	3.0
	#20 (1-5 scale)	4.0	5.0	5.0	3.5	4.0	5.0	3.0	NA	NA	6.0
Organizational Emphasis on Teamwork (Median)	#19 (1-5 scale)	4.0	4.0	3.5	5.0	4.0	4.0	3.5	4.5	5.0	3.0
Rewards and Incentives (Median)	#20 (1-5 scale)	4.0	5.0	5.0	3.5	4.0	5.0	3.0	NA	NA	5.0
Existence of Standard Design Process (Percent Indicator Process In Place)	#21	100%	60%	50%	100%	100%	80%	80%	100%	100%	80%
Metrics of Process Use (Median)	#21A (1-5 scale)	4.0	4.0	3.5	4.5	4.0	4.5	4.0	4.0	4.0	4.0
	#21B (1-5 scale)	4.0	3.0	2.5	5.0	4.5	4.5	4.0	4.0	5.0	4.0
Perception of Process Usefulness (Median)	#22A (1-5 scale)	3.0	3.0	4.0	4.0	4.0	4.0	3.0	3.0	4.0	3.5
	#22B (1-5 scale)	4.0	3.0	3.0	4.0	3.5	4.0	3.0	3.0	4.0	3.0
Extent of Process Tailoring (Median)	#23B (1-7 scale)	3.0	5.5	4.0	3.0	3.5	3.5	4.0	4.0	5.0	4.0

Table C.7: Full Case Study Supporting Data, Part 4

Metric (and how Calculated)	Supporting Survey Question #'s	Summary Case Study Data									
		A0	B1	C2	D3	E4	F5	G6	H7	I8	J9
Consensus Decision Making (Median)	#24 (1-7 scale)	2.0	3.0	3.5	1.5	5.0	3.0	1.5	2.0	2.0	3.0
Mutual Awareness (Median)	#25 (1-7 scale)	5.0	4.5	6.0	6.0	4.5	5.0	5.0	NA	NA	4.0
	#26 (1-7 scale)	6.0	5.5	6.0	6.5	5.0	5.0	4.5	NA	NA	4.0
Mutual Respect and Trust (Median)	#27A (1-5 scale)	4.5	4.5	4.5	5.0	5.0	4.0	4.5	4.5	5.0	4.0
	#27B (1-5 scale)	4.0	3.5	3.0	4.5	3.5	4.0	3.5	4.0	4.0	3.5
	#27C (1-5 scale)	4.0	4.5	3.0	4.5	4.5	4.0	3.5	4.0	4.0	4.0
Common Team Goals (Median)	#27H (1-5 scale)	4.0	4.5	4.5	5.0	4.5	3.0	4.0	4.5	5.0	4.0
	#27I (1-5 scale)	4.5	4.0	3.5	5.0	4.5	3.0	4.0	4.5	5.0	4.0
	#27J (1-5 scale)	3.5	3.5	3.0	4.0	4.0	3.0	3.0	4.0	5.0	3.5
Individual Systems Thinking Ability (Team median)	#28 (1-7 scale)	6	5	5	6	5	6	5	6	4	5

Table C.8: Full Case Study Supporting Data, Part 5

Metric (and how Calculated)	Data Source(s)	Summary Case Study Data									
		A0	B1	C2	D3	E4	F5	G6	H7	I8	J9
Use of Informal Connections for Identifying Resources	Interview Transcripts (Number of Code Citations)	4	5	2	2	0	7	NA	3	1	5
Use of Normative Design Process	Interview Transcripts / Documentation	Yes	Yes	Yes	Yes	Yes	No	NA	NA	NA	Yes
Understanding Role within System	Interview Transcripts	Insufficient data obtained for comparison									
Collaborative Systems Thinking	Interview Transcripts (Average)	8.1	7.9	5.7	8.3	4.7	5.6	7.0	8.1	7.5	4.9
Systems Emphasis in Corporate Vision Statement	Documentation / Website (looking for wording with social and technical systems emphasis)		Strong Systems Wording				Weak Systems Wording				
Organizational Emphasis on Process Standardization	Interview Transcripts / Documentation	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Usefulness of Process Flow Diagrams	Interview Transcripts Observation (Low–Medium–High)	M	L	M	L	H	L	NA	M	H	M
Value of Organizational Charts	Interview Transcripts (Number of Code Citations	0	0	0	2	2	1	0	0	0	3

C.3 Abbreviated Case Study Analysis

The following two figures shows the most commonly cited codes arranged by high and low collaborative systems thinking teams. Figures C-1 and C-2 show the most common themes from full case studies interviews, sorted by higher and lower collaborative systems thinking teams. Between the two graphics it can be seen that 'product alignment,' and 'past program experience' are important in the higher collaborative systems thinking case studies, but do not appear among the most common codes in the lower collaborative systems thinking case studies. Similarly, the codes for a 'trusting and open culture' and 'consensus building' appear significantly less frequently in the lower collaborative systems thinking case studies as compared to the higher collaborative systems thinking case studies. The final notable difference is that frequent meetings were seen as both an enabler and barrier to collaborative systems thinking on the lower collaborative systems thinking teams. This concept was absent from higher collaborative systems thinking team interview transcripts.

The following tables (C.9, C.10, and C.11) show examples of supporting text for each code cited more than four times during the abbreviated case studies (excluding those already characterized in the Pilot Interview Analysis).

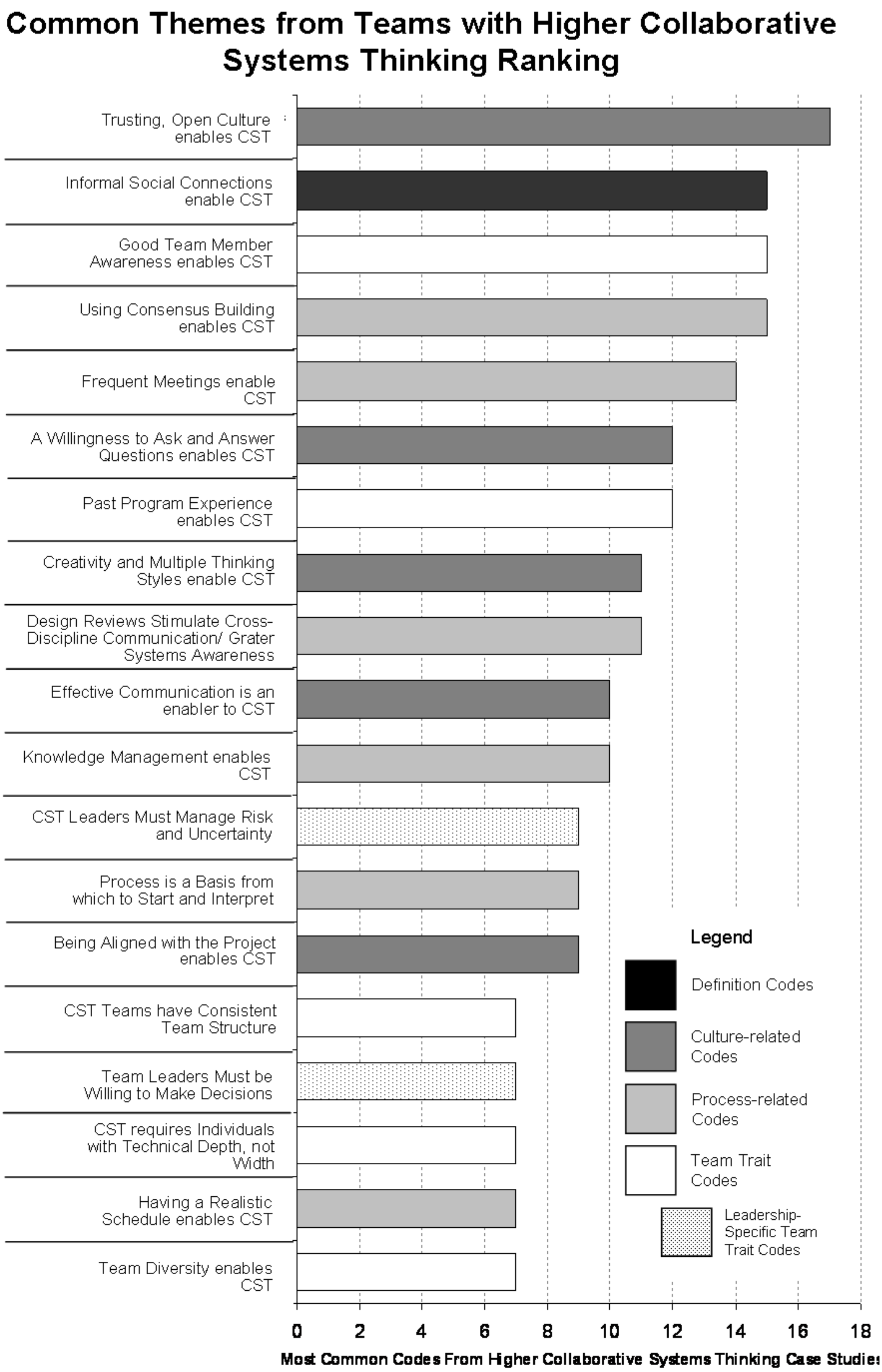

Figure C-1: Codes that appear most frequently in the higher collaborative systems thinking case studies

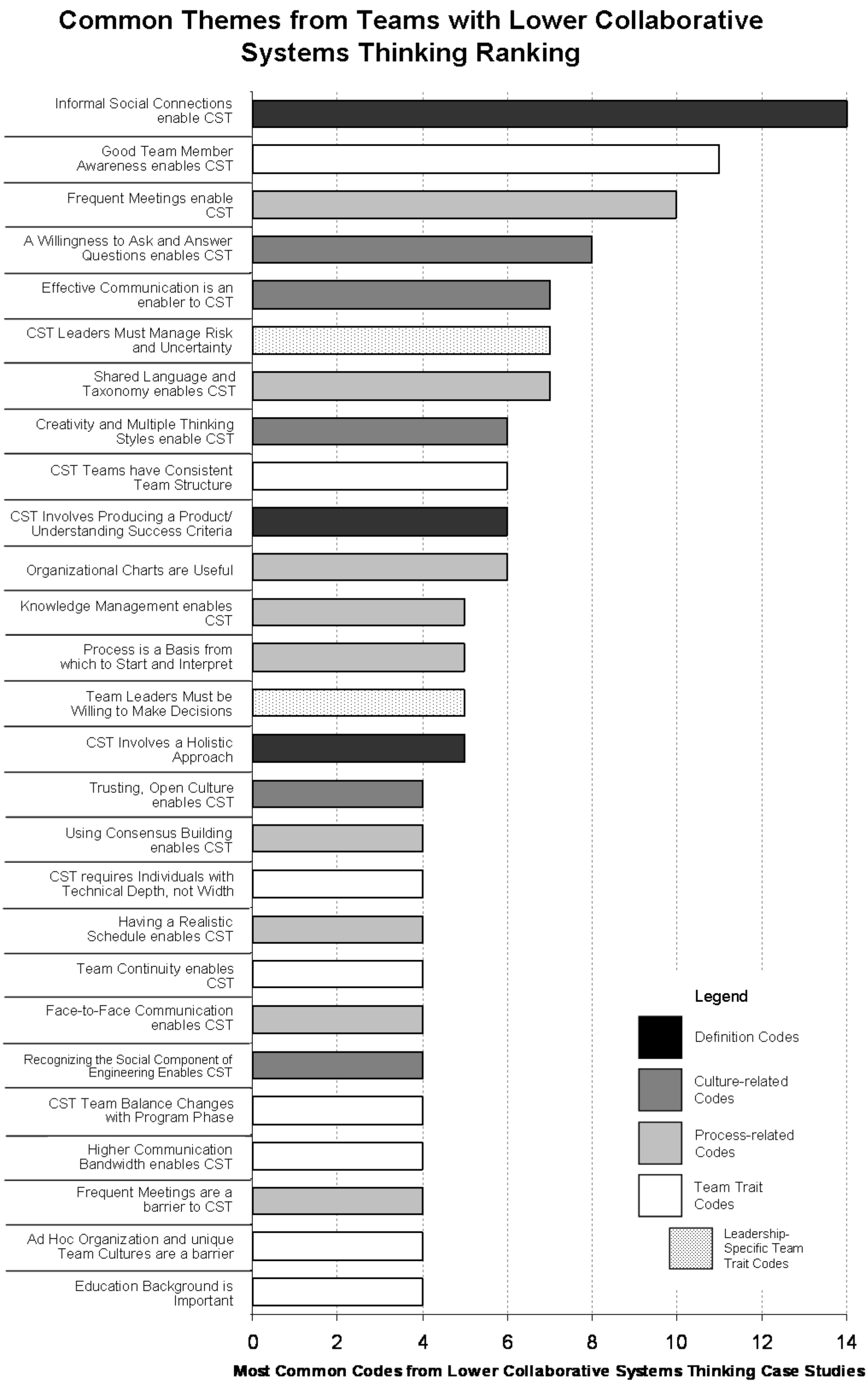

Figure C-2: Codes that appear most frequently in the lower collaborative systems thinking case studies

Table C.9: Supporting Text for All Abbreviated Case Study Codes: Part 1

Culture-Related Codes	
Effective Communication is an Enabler to CST	"Someone can be a genius, but his intelligence is lost of it cannot be communicated to others"
	"Communication is listening to not only what is said, but what is not said. Body language is important"
Recognizing the Social Component of Engineering Enables CST	"My journey has switched over to social side in contrast to what was taught in engineering school "
	"Engineering is taking the social aspect and marrying it to the technical. The result is a better informed team. "
Trusting, Open Cultures Enable CST	"Information has to flow freely; without hesitation"
	"Groups must have trust, must treat each person individually"
Failing to Converge on a Solution is a Barrier	"Many engineers get caught up in the details, lose big picture of efforts"
	"Team have to avoid analysis paralysis"
Political Influences Deter CST	"Personal agendas and external pressures get in the way"
	"Politics lead to poor systems thinking"
A Reluctance to Communicate is a Barrier to CST	"Problems occur when organizations have a culture where engineers don't talk to each other"

Table C.10: Supporting Text for All Abbreviated Case Study Codes: Part 2

Process-Related Codes	
Using Consensus Building Enables CST	"The difference between decision making on systems and non-systems is that systems require everyone to understand the points being considered through discussion and consensus building"
	"Good systems thinking leaders ask other for their input before expressing their own opinions"
	"The common denominator in achieving consensus is that all participants have an opportunity to provide input and be heard"
CST Teams Use Intelligent Questioning to Facilitate Systems Thinking	"Effective systems thinking teams ask high level questions, then drill down to the right level of detail"
	"Using the Socratic method leads to a better ends"
A Connection to the Customer and Requirements Origin is an Enabler	"Teams need a high level understanding of why the end users need the systems"
	"Teams must consider the user, maintainer, trouble shooter and assembler"
Frequent Meetings Enable CST	"We had weekly meetings to keep people aware of hot topics"
	"Regular meetings were instituted to improve interactions between the specialists and analysts–to get them communicating"
Design Reviews Stimulate Cross Discipline Communication and Greater Systems Awareness	"Gate reviews bring together people operating at multiple levels within the system"
	"Design reviews may be the only time the representatives of the entire system get together"
An Overreliance On IT Tools is a Barrier to CST	"We need to use IT correctly. We currently send too emails and this hurts us; we do not think through our thoughts before sending an email"
	"The job is so complex, the tools should make us more productivebut they are weighing us down. We are mired in process and IT overload"

Table C.11: Supporting Text for All Abbreviated Case Study Codes: Part 3

Team Trait Codes	
CST Team Leadership Provides Appropriate Levels of Guidance	"Leadership should know when to lead, when to back off, when to allow people to make mistakes"
	"When necessary, leaders should drive teams towards central goals"
Individuals with Different Levels of Systems Thinking Facilitate CST	"Not everyone can be worrying about the entire process/program"
	"Everyone should understand some amount of the context–at least one level up in the block diagram"
Team Leaders Must be Wiling to Make Decisions	"Leaders should solicit multiple inputs, but is still responsible for the final decision "
	"A strong leader gather information from the team in order to make a decision"
CST Teams have a Consistent Team Structure	"15% of my team is leadership; 50% are occasional systems thinkers; the remaining 35% are function expert who take the boundaries given them and don't ask questions"
	"System teams cannot be all systems people–we need specialists"
CST Team Leaders must have Credibility	"There is not substitute for a level of personal credibility"
	"Leaders must have sufficient credibility to be perceived as being believable: it comes down to trust."
CST Team Balance Changes with Program Phase	"Systems thinking across the design cycles depends on the role."
	"The people required for architectural systems thinking and detailed systems thinking are rarely the same people"
Smaller Teams are More Able to Engage in CST	"Small teams have more opportunity for Zen moments, for batting ideas around"
	"In my experience size has been an indicator: smaller teams are better at systems thinking"
Too Many Systems Thinkers on a Single Team is a Barrier	"Not everyone can be worrying about the entire process/program"
	"When you get more than 2 systems thinkers on a team, you need a strong leader to manage the circus that follows"
Challenging Work is an Enabler to CST	"The balance is starting to shift towards recognizing people want to think and have more opportunity to apply their own judgement within their jobs"
Personality Gaps/Mismatches on a Team are a Barrier to CST	"On large programs there are lots of 'verbose experts' and we get head butting"
	"Coping with difficult people is a barrier to systems thinking"