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COLLABORATIVE SYSTEMS THINKING:

A SURVEY OF LITERATURE IN SEARCH OF TEAM-LEVEL SYSTEMS THINKING WITHIN AEROSPACE TEAMS

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A survey of literature in search of team-level systems thinking within aerospace teams

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This literature review was prepared in support of research investigating team-level systems thinking. Three critical constructs were identified–team, process, and culture–and the pertinent literature is explored in this white paper. The research focused on the aerospace industry, and as such, this white paper uses illustrative examples from the aerospace industry wherever possible. A fourth construct, that of team-level or collaborative systems thinking, is also addressed. This fourth construct is a new construct put forth by the author and her advisors.

This white paper is divided into two main section. The first motivates research on team-level systems thinking as a solution to the growing gap between engineering design and engineering analysis. The second section treats the four critical research constructs identified above. For the first three constructs, a definition is provided based on available literature, examples grounded in aerospace are provided, common metrics are introduced, and threats to validity are discussed. For the fourth construct, a discussion of available literature is presented and a construct definition is proposed.

Chapter 1

Motivation

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 [107]

The above quote is just as appropriate today as it was nearly 90 years ago in aviation's infancy. Most engineering research concentrates on engineering analysis: tools and techniques for quantifying the 'goodness' of some system property and reducing uncertainty and unpredictability. But this research represents only a small part of what *engineering* actually is and ignores the large fraction of engineering knowledge that is tacit. What has changed since 1922 is the complexity of aerospace systems. As such, the gap between research and product takes more than a *single* engineer to bridge–it takes a *team* of engineers.

This literature review outlines why systems thinking is an important to the aerospace industry, some of the pertinent issues facing the aerospace industry today and how promoting systems thinking at the team level can help address these issues. The review concludes with a discussion of the critical research constructs and a summary of related literature.

1.1 Benefits of Systems Thinking: Addressing the Design-Analysis Gap

Within the past 20 years, the aerospace industry has experienced a shift in the way projects are managed and organized. Driving these changes were the end of the Cold War, greater budgetary pressures, and advances in technology that permitted more complex systems. Changes include the bringing together of different engineering disciplines earlier in the development cycle to avoid problems later in systems realization and operation. These methods go by names such as integrated product and process development (IPPD) and concurrent engineering, and all are facilitated by systems engineering. This shift has not only brought the various disciplines together earlier in design, but put an emphasis on teams within engineering, especially multi-disciplinary teams.

Despite strides towards cross-functional design, many still believe a gap exists within engineering between those who design and those who perform analysis. 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.

1.1.1 The "Two Cultures" of Engineering

The gap between engineering science and engineering design is likened by NASA administrator Michael Griffin to the cultural divide between the sciences and humanities[42]. One, engineering science, is rooted in analysis, numeric methods and the quest to build better models and minimize uncertainty and unpredictability. The other, engineering design, is based in experience and creativity, using science and technology in novel ways to solve problems and seeking to find as many ways as possible to meet a requirement. However, unlike the humanities, destined to be judged relative to individual tastes and aesthetics, engineering design is judged on the objective basis of whether or not the system meets its requirements[42].

Engineering is the skilful combination of science and art; analysis and design[42]. With design and analysis solidly rooted together, engineering was once the purview of artists. Leonardo DaVinci and his renaissance contemporaries made huge strides in engineering design by perfecting scale, perspective and exploded views in their drawings which enabled them to commit to paper their fanciful ideas for futuristic machines[34]. These improvements in drawings enabled inventors of the day to communicate their ideas to others and for ideas to be improved upon by others. In the three subsequent centuries, advances in design were complimented 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.

The 20th century has been marked by continuing improvements in analysis, much to the exclusion of design. This trend has been enabled by technology and reinforced by society. During the late 19th century and early 20th century, engineering schools made a conscious move towards an education based on scientific principles and away from more practical training in an effort to differentiate engineering from vocational training and thus improve the social acceptability of engineering as a career for "gentlemen"[7]. The advances in computing technology in the latter half of the 20th century facilitated quantitative and structured analysis, thus reinforcing the role of analysis in engineering.

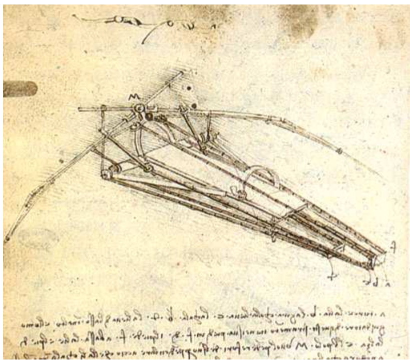

Figure 1-1: Detailed drawing by Leonardo DaVinci shows the internal workings of one of his flying machines.

As a result, most engineering research in academia focuses on furthering analytic tools and capabilities: the *science* of engineering[34]. 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. Design, once taught through apprenticeships, has become only a small portion of today's engineering curriculum. Design is not easily reduced to words, being better represented by pictures and visual images rooted in art, not science[34]. As a result the analysis-design gap has grown.

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 much of the intellectual components of technology are nonscientific and nonliterary[34]. Rather, only a small fraction of engineering decisions are based on analytic calculations, requiring consideration of social, political, and environmental issues that are difficult to model and quantify[7].

In no industry are the systems more complex or the contributing disciplines more varied than in aerospace engineering. Evidence of the industry's attempts to cope with this complexity is evident in the development of systems engineering. First developed by scientists and engineers, systems engineering grew out of the coordination of large-scale technology development projects[54]. 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. Developed during World War II and championed by the likes of Bernard Schriever, systems engineering was adopted by the military and remains today the way in which complex systems are designed[49, 53]. The benefits of these systems engineering practices were documented as early as 1949[54].

Today, systems engineering is integral to the success of aerospace systems. Griffin refers to systems engineering as the logical, aerospace developed bridge between analysis and design[42]. The Secretary of Defense cites failures to properly execute systems engineering as a leading contributor to schedule slips and cost overruns[70]. Industry too, recognizes the need for better systems engineering to address increasing system complexity[81].

1.1.2 Systems Thinking as a Skill to Bridge the Gap

Systems thinking is a necessary skill for senior systems engineers[24], and as such is a critical skill for addressing the gap between analysis and design. Systems thinking is one recognized mode of thinking that facilitates the identification and understanding of technical and social interdependencies and feedback dynamics in a system and is credited with producing better processes, better coping with technical and social complexity and aiding in the identification of interfaces and interactions and the efficient allocation of resources to manage these interfaces and interactions[24].

Within academia, attempts to address the analysis-design gap and convey systems thinking skills have been addressed through industry-academia partnerships and initiatives such as **C**onceive, **D**esign, **I**mplement and **O**perate (CDIO), which have sought to bring an awareness of the entire engineering life cycle back to engineering education[15]. However, these initiatives alone are insufficient[48], and more research is necessary to understand systems thinking, not just at the individual level, but also at the team and organizational level[24]. Within industry, training, job rotation, and continued employee education are used to promote systems thinking skill development[24].

Why the Gap is Important

Recent research shows that as complexity increases, a greater fraction of the necessary design knowledge is tacit. For simple components, 85% of the design knowledge is explicit and documented. The remaining 15% is categorized as experiential, or tacit[28]. 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 1-2[28].

With complex systems, the large fraction of tacit knowledge necessary for design is further complicated by the reliance on teams of individuals, each bringing a unique set of design experience to the team. To address the analysis-design gap within a team, it is necessary to understand how the team thinks about problems, allocates resources (mental, financial and material) and facilitates design. Systems thinking addresses these issues, and it is therefore worthwhile to understand how engineering teams execute systems thinking.

Part of the gap between analysts and designers is purely in the way they think. Traditional, analytic engineers think in convergent patterns: seeking to start with a question and converge to a single correct answer. In contrast, designers begin with a need and seek to find as many solutions as possible, thus engaging in divergent thinking[108]. Systems thinkers, by contrast, are able to engage

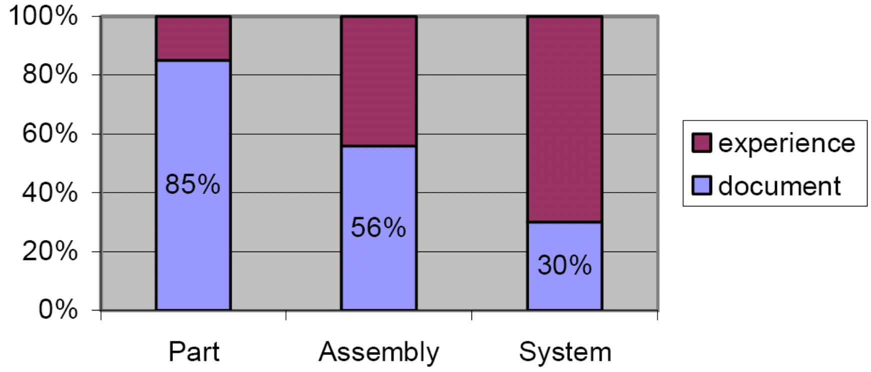

Figure 1-2: Distribution of design knowledge between documentation and experience. [28]

in both convergent and divergent thinking, thus bridging the gap between design and analysis[32, 108] and facilitating a more thorough exploration of the design space, resulting in better designs.

Addressing the Gap at the Team Level

Recent research has addressed the barriers and enablers to systems thinking development within the engineering community[24] and looked to compare and contrast engineering systems thinking with broader definitions of systems thinking used in other fields such as management and operations[37]. Experience, personal traits, and a supporting environment were found to be the greatest contributors towards individual systems thinking development[24]. However, there is still much to learn about how systems thinking develops within engineers, and especially within engineering teams.

Within engineering teams, it is proposed that synergies and tensions between standard design processes and cultural norms form enablers and barriers to an emergent mode of team thinking based on holistic systems perspectives. This construct is 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. Breaking away from traditional"turf battles," teams that express collaborative systems thinking traits should be better able to make necessary tradeoffs during design and catch potential interface issues earlier.

Because teams execute design, efficiencies are gained when a team is able to realize and make necessary design trades as opposed to having these trades facilitated by a small number of dedicated engineers who must then overcome the team's inertia to affect change.

1.2 Industry Issues Driving the Systems Thinking Shortage

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: The role of failure in successful design*

Aerospace systems are becoming more complex. Independent of the measures, be it number of components, man-hours of engineering, lines of code, or number of contributing disciplines, complexity is increasing. Because systems thinkers are better at optimizing processes, coping with social and technical complexity, and managing interfaces and interactions[24], systems thinking is an important part of ensuring future mission success.

Having established that systems thinking is an important skill for the aerospace industry, it is therefore alarming to hear the industry faces a shortage of systems thinkers[99]. This shortage is exacerbated by aging industry demographics, longer development cycles and fewer program starts.

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[6]. The average age of an engineer at NASA is 49[55]. And within the aerospace industry, 25% of the workforce will be eligible for retirement in the next five years[11]. As these workers retire, invaluable tacit knowledge regarding the design of aerospace systems, in the form of systems thinking skills, is taken with them.

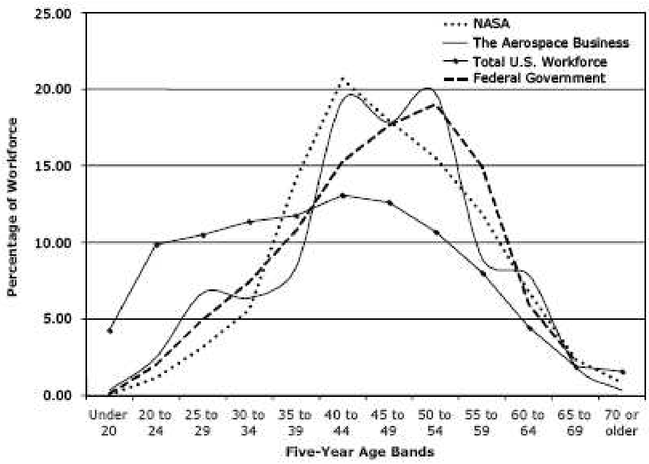

Figure 1-3: The aerospace workforce is older than the greater US workforce, with 25% of the workforce reaching retirement age within the next 5 years[11].

Because experience is a great contributor to systems thinking development, it is a great loss to lose so many of the industry's experienced workers within a short time frame. The loss of experiences workers, however, is made even worse as fewer opportunities to gain necessary design and implementation experience are presented to today's young engineers as compared to 20 or 30 years ago.

Data shows 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 1-4. This pattern is repeated in commercial jetliners, manned space flight, and planetary probes. For example, commercial jetliner program deliveries peaked in the 1990's with 16 new and derivative airframe designs being delivered, compared to the 5 airframe designs and derivatives that are expected in the first decade of the 21st century[2, 13]. Figure 1-5 shows the pattern repeated in human space flight, with a dramatic reduction in the number of human space flight programs since the 1960's.[71]

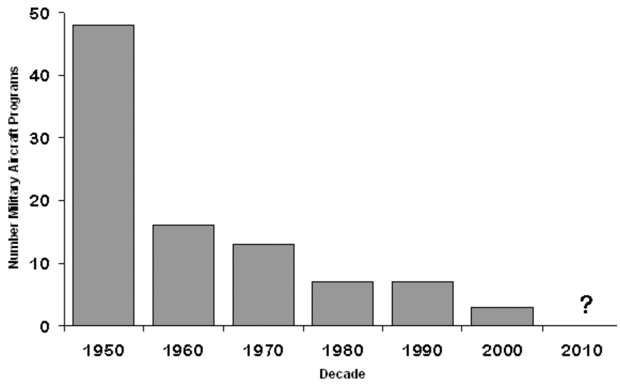

Figure 1-4: In recent decades, military aircraft starts have slowed from a high of nearly 50 program starts in the 1950's[68].

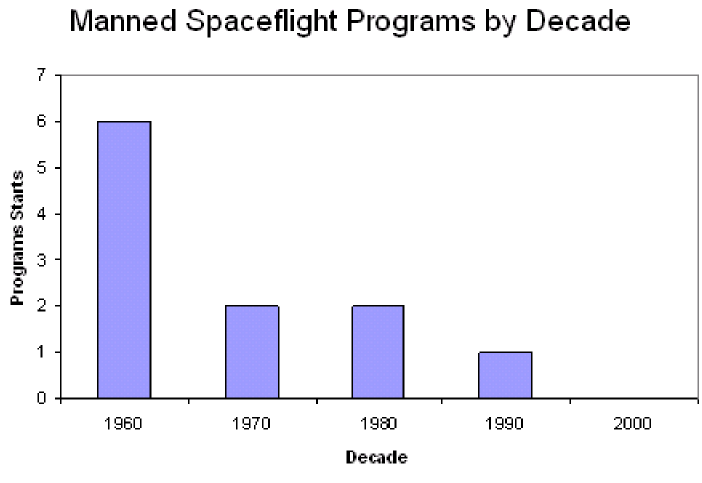

Figure 1-5: There are few opportunities today in human spacecraft development as demonstrated by the small number of program starts in recent decades[71].

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.

Recognizing the need to codify design knowledge and compensate for fewer opportunities to learn experientially, many organizations have turned to process standardization. Standardized processes offer 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 as 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 that greater than 35% of program cost growth and schedule slips are caused by failures to follow systems engineering practices and principles[59]. 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®.

These processes compliment the move towards team-based design. As engineering becomes more integrated, the interactions between subsystems group and individuals from different disciplines, result in a greater number of dependencies. These dependencies impact performance[14]. Many processes specify how these dependencies are managed, and are thus of great interest at the level of intra- and inter- team interactions, further motivating research at the team level.

Chapter 2

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 certification, a growing realization that soft issues affect the design process, and a desire to further explore systems thinking constructs at the team level, the following four research constructs were identified: teams, process, culture, and collaborative systems thinking. These constructs are shown in Figure 2-1 in a preliminary, gestural model of their interactions.

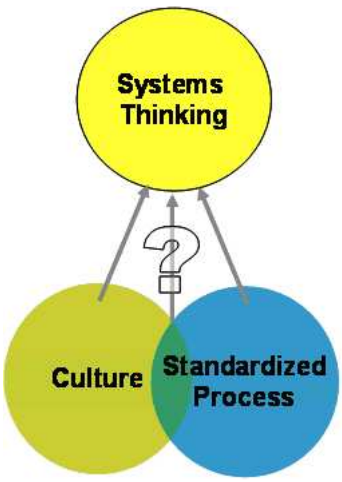

Figure 2-1: The question mark highlights the intersection of three of the research constructs within the context of engineering teams, the fourth research construct.

A natural working unit within large, complex projects, teams may offer an opportunity to leverage scarce systems thinking resources more efficiently. By expanding research into engineering systems thinking at the team level, organizations will be provided with information to inform team interventions that compliment existing individual-level efforts to develop systems thinking.

When working within and among teams, interactions are important. In addition to systems interaction and interfaces, interpersonal interactions, discipline interactions and team interactions need be considered. These interactions are often specified by processes. Process was chosen as a construct because of its role at the team level and the recent industry emphasis on process certification, which has driven many organizations to hurriedly adopt process frameworks in order to bid on contracts.

Culture offers a social compliment to the technical aspects of process, respecting that engineering is a socio-technical activity. Culture is primarily applied to large units such as organizations and countries. This research is concerned with culture at the team and organizational level, but also considers the larger scale impact of engineering culture and smaller scale subcultures of team: the unique norms, beliefs and assumptions teams develop.

Finally, this research is about understanding systems thinking as a team construct: collaborative systems thinking. A preliminary definition of collaborative systems thinking is presented as developed from pilot interviews and a wide net of literature spanning classical systems thinking to team-based design thinking, team cognition, as well as literature on team composition and decision making. Challenges to construct validity will be discussed as well as ways in which the definition might be updated based on data collected.

The following are discussions of each of the four critical research constructs. Included in each discussion is a construct definition and information on what aspects of the construct apply to this research, how these aspects will be measured, and a brief discussion of any validity concerns. The three types of validity addressed are the following: construct, convergent, and discriminant. Construct validity is the ability to clearly and unambiguously define a construct. Convergent validity is achieved when the construct definition is consistent between organizations. Finally, when constructs can be clearly discriminated between, discriminant validity is obtained.

2.1 Teams

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

2.1.1 Definition of it 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[43]. 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[87].

There are many formal definition for teams. One such definition specifies four necessary conditions: a team task, clear boundaries, specified authority, and membership stability[43]. 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[43]. Within teams, traditions and values develop over time that facilitate members working together[69]. 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[5]. 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*)[69].

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[74]. In support of this function, teams must also monitor and manage work processes and team interactions[43]. Systems design is particularly suited for teamwork because it requires coordinated inputs from several specialities[43]. To be successful, these teams require a clearly defined task or problem, sufficient time and resources, the latitude to make decisions, and some means of feedback[43, 74]. Additionally, healthy debate and dialogue within the team is important to encourage participation and ensure the solution space is well explored[74].

A diverse team membership is one way to ensure healthy debate[43]. A heterogenous team is less likely to succumb to groupthink, a condition when team members' desire for harmony blurs their ability to objectively and critically consider alternatives[50]. 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 school of thought places the heterogeneity of the team as a primary consideration and recognizes that individual need some amount of direction on *how* to interact effectively in a team setting[43]. This is because many effective team norms run counter to human tendencies[43]. These norms include seeking less obvious causes and solutions rather than just reacting to the immediate crisis and thinking critically when dealing with deadlines and political or social pressures in order to avoid groupthink[43]. Richard Hackman maintains that these productive norms can be developed gradually over time within groups with conscious effort.

A second and more structured approach to building teams is to find individuals filling preidentified roles. While clear role assignment is important to help coordinate group efforts and allow team members to effectively draw upon others' expertise and capabilities[58], team roles can relate to team administration as well as to technical contributions. One such framework for team roles is R. Meredith Belbin's nine team roles, as shown in Figure 2-2. The assertion is that individuals are more or less adept at certain roles and that teams should be composed not only considering the technical contributions of an individual, but also how that individual will contribute to team functioning[8].

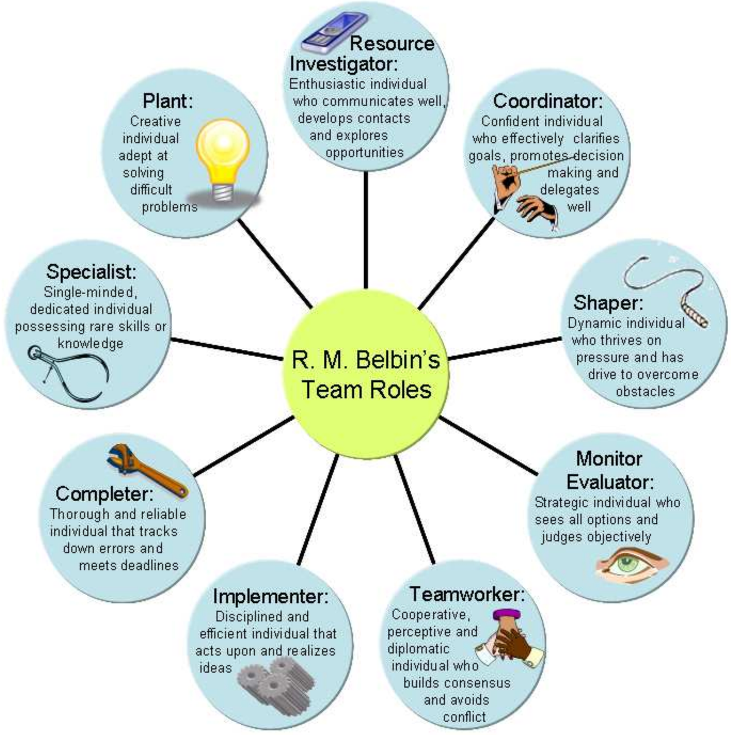

Figure 2-2: R. Meredith Belbin's nine fundamental team roles. Figure adapted from [8].

Deborah Ancona's 'X-Teams', mentioned above, is a third take on team composition. Within 'X-Teams' there are three tiers of team membership: core, operational, and outer-net. Within each tier, members have different roles and responsibilities to the team. Core members are responsible for maintaining the team's history and making important decisions[5]. 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[5]. The outer-net members are generally specialists and others who are brought onto the team when needed either for their experience or expertise[5]. Hackman's definition of a team would exclude outer-net members, yet outer-net members contribute materially to the team's ability to complete work.

Whatever the form, teams are supported in their work by information technology that allows greater access to information necessary to explore the solution space and make design decisions[60]. The reduction in communication costs have enabled teams to more easily exchange information and have also enabled team membership to change more frequently[60]. In fact, flexible team membership is one way in which knowledge is transferred between teams[57]. Some team members may participate in more than one team, and other members may switch between teams as their skills are required. While this membership fluctuation helps to spread knowledge between teams, for any given team these comings and goings can negatively impact a team's transactive memory[57], or shared pool of knowledge[110].

The movement of individuals across team boundaries drives the need for process standardization to 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 process standards[43].

Just like its individual members, teams as a collective can learn, think, and interact with the surrounding environment[3]. Team learning is the collective generation and dissemination of knowledge. Team learning includes the acquisition of knowledge, its processing, storage and the ways in which teams manipulate that knowledge. The activity is collective rather than individual because of the social interactions required to identify, interpret and recall information[3]. Team thinking, or the process of making decisions, judgements, applying creativity, and interpreting information, is closely linked to team learning[3]. Ancona's 'X-teams' exemplify the ways in which teams can interact with their environments by leveraging weak and strong ties throughout an organization to gather the information and political clout necessary to make good decisions[5].

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[113]. Perhaps more important is that a team have members with differing and complimentary skills and knowledge and a strategy to capitalize on those skills and knowledge[58]. Teams also require support from the surrounding environment in the support of clear delineations of authority, coaching, and clear and consequential goals[43]. Finally, teams must be motivated to perform. Fundamentally, individuals are motivated by achievement and conformance[46]. In a team setting, some level of conformance motivation is required to get members to move in the same direction. Yet, fundamentally, engineers find motivation in achievement as typified by engineering cultural norms and as evidenced by their resistance to standard processes[56].

2.1.2 Examples of Teams in Aerospace

Multi-disciplinary product or subsystem teams are a common way aerospace organizations leverage the benefits of teams. By bringing together several disciplines early in the design process, problems are surfaced earlier and a greater level of design optimization is possible. The aerospace industry has a heritage of functional, or single discipline, teams[9]. As such, the move towards multi-disciplinary teams is representative of a change in the way tasks work is decomposed; shifting from linear, decoupled tasks to more iterative and integrated tasks[10]. 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[36]. The objective of concurrent engineering is to get concurrent participation by a variety of disciplines throughout product development: from conception through to realization[18]. Concurrent engineering also places an emphasis on considering the entire product lifecycle during initial design[23], 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 commonly used within the aerospace industry. By bringing together different disciplines early in design, a more thorough understanding of requirements is achieved and the design space is opened up through cross-discipline discussion[80]. The result of this early discussion is greater system efficiency and shorter development times[44].

Both IPT's and concurrent engineering practices reduce the likelihood of failures due to poor communication[72].

2.1.3 Engineering Teams in Practice

Teams are everywhere in engineering. Developing complex systems requires input from a wide variety of disciplines, thus lending itself to teamwork approaches[43].

Case studies provide a valuable look into how teams are used in the aerospace industry and the problems and successes these teams encounter. Summaries of two case studies outlining dramatically different teams with the aerospace are presented here.

The first team is a high-performing software team responsible for writing and maintaining code for the Space Shuttle[35]. 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 result is a team that has been in operation for decades, all the while producing the industry's most reliable code[35].

A striking contrast to the Shuttle software team is the Jet Propulsion Laboratory's (JPL's) use of integrated concurrent engineering (ICE)[16, 17]. 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[16, 17].

The two cases illustrate that aerospace engineering teams can be small or large, short-term or long-term, and span a wide variety of ways to engineering a system. These diverse teams do not, however, operate in a vacuum. Teams must also interact with other teams in order to produce complete systems.

Training, standardization (of both processes and conventions), information technology and co-location all offer benefits for teams working together[14]. A survey of IPTs in the aerospace industry found that electronic modeling tools are a huge help in enabling inter-team interaction, as is co-location[14]. The probability of communication falls below 13% when individuals are separated by more than 35 feet, emphasizing the importance of a team's physical environment on its performance[14]. Management is also important in helping teams to operate smoothly and work well with other teams. Interface management, in particular, is important when teams are working on separate parts of a larger system.

2.1.4 Relevant Aspects of Teams

Teams can be described and quantified in a number of ways. Given the purpose of this research is to understand what team traits are linked to collaborative systems thinking, metrics related to team member experience, education, and team tenure are likely important. The following is a list of team metrics identified by surveying team literature. A brief description is included for each concept.

- Team Members

  Relevant metrics for team members include information about education, general level of experience, role and tenure on the team in question. Individual work experience is also relevant.

- Team Maturity

  The age and maturity of a team are important relative to formation of team norms. Conversations with industry executives suggest three months as the minimum time necessary for a team to socialize, develop norms, and begin operating as a productive unit.

- Team Self-Perception

  The team self-perception metrics are drawn from the team member schema similarity framework[82]. 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. Extended metrics also ask team members to describe the team using terms such as creative, productive, combative, etc.

- Team Role

  The team role refers to the position or contribution of the team relative to other teams and the system being designed. The team role can be identified as its task, or the component it is responsible for designing. The team role can also be defined relative to its interaction with other teams and their tasks or components. If team members do not have a shared conceptualization of the team role, then it could be difficult for the team to identify its goal and when that goal is achieved.

- Team Environment

  The team environment includes the physical proximity of the team members, any special team rooms, or other team spaces, be they 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[22]. Therefore, the team environment may influence specific team behaviors and norms.

- Team training

  Team training contributes to establishing good team habits. Training also ensures team members have the necessary skills and tools to complete their work.

2.1.5 Validity Concerns

Teams are widely used and therefore are a widely recognized construct. However, teams vary from organization to organization, thus posing a potential threat to convergent validity. Teams may be co-located, geographically distributed, newly formed, temporary, project based, functionally based, etc. To address convergent validity, prospective teams will be identified through conversations with participating organizations, thus leaving the researcher to identify what is or is not a team in the context of this research. 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. Teams of varying size, tenure, and geographic distribution will be considered so as to assess the impact of these variables on the ability of the teams to think systematically as a group. The final threat to validity, discriminant validity, will be verified through data collection. That is, survey and interview data will be used to verify that the teams are in fact working interactively and not as a group of co-acting individuals.

2.2 Standard 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

2.2.1 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[62]. Processes can take many forms. Processes may be standardized across an organization, agreed upon within a smaller group, or unarticulated sets of common assumptions[60]. Process is also one of the most overused words within the engineering community. The following provides an overview of what an engineering process is, why processes are used and examples of their use, success and failure. Processes relevant to this research are also identified.

Within engineering, standardized processes are used to decompose large technical problems into smaller tasks and facilitate collaboration (social interaction) among the teams and individuals addressing each task. Facilitating communication is one of the most important roles of process[83]. Communication in engineering is the transfer of meaning between individuals and process facilitates by setting rules and guidelines to ensue information is not lost or omitted[45].

One of the objectives of engineering process standardization is the accurate prediction of cost and schedule. Engineers are the most variable component of the design process[64]. Introducing standard ways of executing tasks helps to reduce this variability and facilitate scheduling and cost estimating. Standards support engineering excellence by saving engineers from 'reinventing the wheel,' and preserving efforts for true innovation[40]. The "art" of process standardization is to find right level of standardization in order to facilitate without becoming overbearing because rigid processes inhibit flexibility and the ability to capitalize on new situations[60]. Some process advocates insist the development process should be tailored to the specific product under development[62]. Others insist on more universal standards to facilitate collaboration among organizations. Regardless, no single process can be applied in every situation[83]. Some amount of process tailoring is necessary, thus requiring clear process ownership to reduce confusion[83]. Processes should also be designed to promote responsibility and initiative rather than serving as minimum checklists[40].

The goal of processes within systems engineering is to, in a systematic way, address problems across the system's lifecycle. The basic steps in the systems engineering process are the following[12]:

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

Common systems engineering process models include the waterfall, which is based on top-down approaches with highly decomposed processes; the spiral model, which is based on iterative methods with continual updating of objectives, strategies and design alternatives; and the Vee-model which combines top-down and bottom-up approaches[12]. This research is primarily concerned with steps during the design process which include defining the problem, defining the requirements, and concept exploration (roughly steps 1-8 above).

Within the aerospace industry, systems engineering processes developed as a response to increasing systems complexity. First developed by engineers and scientists, systems engineering grew out of the coordination of large-scale technology development projects[54]. These practices borrowed from those already in use at Bell Lab and Western Electric which defined formal specifications and structured relationships between engineers and manufacturers. Developed during World War II and championed by the likes of Bernard Schriever, systems engineering was adopted by the military and remains today the way in which complex systems are designed[49, 53]. As early as 1949, the benefits of systems engineering were recognized with the Ridenour Report which called for the substantial strengthening of the role systems engineering played in systems development[54].

However, adoption of systems engineering processes was scattered at best. It wasn't until 1956 that the Air Forces' Western Development Division and contractor Ramo-Woolridge came to an agreement about what systems engineering actually entailed[54]. Wernher von Braun and the Marshall Space Flight Center did not embrace systems engineering methods until 1968[54]. Yet, 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[10].

Calls for expanded and improved systems engineering efforts continue to the present day[81]. In 1997 and with interest from the Office of the Under Secretary of Defense, one of the largest projects to standardize and rate systems engineering processes was begun with the start of the Capability Maturity Model Integrated (CMMI®) Project[93]. 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[59] and the National Defense Industries Association cites an industry wide failure to recognize the importance of systems engineering or use consistent definitions and approaches[70].

2.2.2 Examples of Process Standards

The systems engineering process spans the lifetime of a product and consists of high level tasks including defining the problem, requirements analysis, functional analysis, design reviews and system operation and life cycle support. These steps span from concept through operation in the CDIO framework[12, 15]. 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®[62, 63, 91].

Most systems engineering standards come from a common heritage, Military Standard (Mil-Std) 499; an early standard aimed at the development of a project's systems engineering management plan (SEMP)[63]. 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 standards 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 2-3 shows a graphical interpretation of the standard.

Other examples of well known systems engineering standards include the International Council

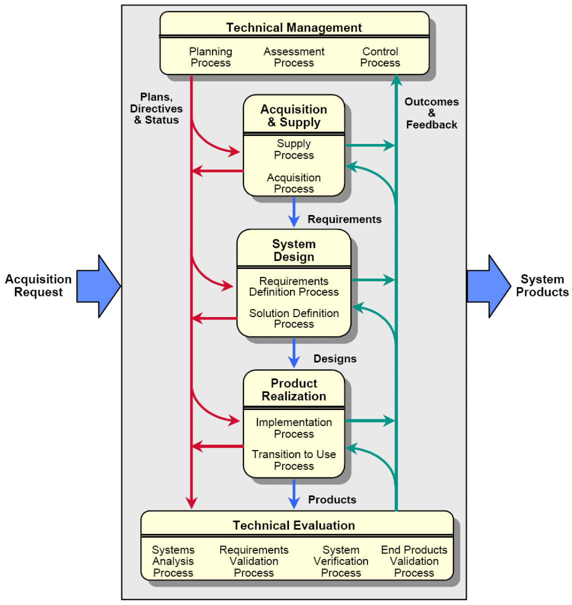

Figure 2-3: Top level view of the ANSI/EIA process for systems engineering. (From ANSI/EIA-632-1998)

on Systems Engineering (INCOSE) Handbook and the NASA systems engineering handbook[62, 91]. 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[62]. The major steps in 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. Maturity models offer a way for organizations to evaluate and improve their process implementation as well as compare their progress with others through published maturity ratings. The foundation of the CMMI® maturity rating is the belief that a mature design process will produce higher quality products and mitigate risks such as cost and schedule overruns[94].

2.2.3 Process Standards in Practice

The goal of standardized process is to reduce ambiguity and unpredictability by codifying best practices and creating a common language and set of expectations among those working on a project or within an organization. The successes of process standardization are well documented for companies such as Toyota[76, 95], Within the aerospace industry, NASA provides evidence of several process successes.

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[35]. 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[17]. 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[51]. Driven by recent high profile failures, the goal is to improve systems engineering practices by addressing people and technology in addition to the process[51].

Despite the documented benefits of standardized processes, resistance to their use still exists. There is anecdotal evidence that engineers feel restricted by processes, preferring to instead work in their own way. This is supported by the dominant behavioral preference type within aerospace engineering, Myer-Briggs type INTJ which resists following process for process' sake[20]. Others resist on the basis that they and the tasks they complete are 'different,' and therefore above or outside the process[90]. Yet others treat standard process as a test, not really absorbing the true intentions and instead falling into a checklist mentality[90].

Even when standard processes are in place and used, there is no guarantee of success. 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[78]. While process aims to reduce the variability introduced by engineers enacting design[64], 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[30]. Therefore, while the process enabled successful practices and behaviors, the true success came from those who used the process and innovated where necessary to ensure good communication during the design process.

Process standardization, like laws and rules, exist with tension between precision and flexibility[101].

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. Therefore, organizational culture becomes important. Culture, a set of shared assumptions and behavioral norms[88] is a likely predictor of how engineers will execute process and deal with ambiguity and non-routine problems and is thus important when studying process.

2.2.4 Relevant Aspects of Standard Process

There are several aspects of process that might affect a team's ability to collectively think systematically. Because the nature of this research is exploratory, a wide net is cast over a variety of possible contributors or barriers to collaborative systems thinking. The following is a list of process-related questions and metrics worth exploring. A brief description is provided where necessary.

- Process maturity

  Where available, a CMMI® capability maturity level, or similar.

- Process compliance

  Measure of how often specified design processes are–or are not–used when called for. Process compliance aims to measure differences between documented practices and how engineering is actually executed. Also of interest would be the ways in which engineers deviate from standard process.

- Process usefulness and effectiveness

  Measure of how applicable, useful and effective team members find the standard technical processes.

- Usefulness of process artifacts (e.g. process flow maps and org 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.

- Process sufficiency

  Measure of how complete, or sufficient, the existing standard process is. This measure includes to what extent the process must be tailored or supplemented by team agreed upon methods and tools. As stated above, one study showed successful product development teams use the standard process as a starting point and then developed a richer set of behaviors for interacting, thus increasing their chance of success[30].

- Level of process tailoring

  The level (e.g. team, program, division) at which process tailoring occurs.

- Impact of process on members working on multiple programs or teams

  For those individuals with membership in multiple teams, the impact of process standardization and tailoring on their ability to transition between teams and programs.

- Impact of process tailoring on inter-group collaboration

  The impact of process standardization and tailoring on the ability of teams to coordinate their efforts, communicate, and share pertinent information.

- Understanding of reasons for standardization

  This would likely be an open ended question gauging group feelings and opinions about the reason processes are standardized. 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.

Many of the above aspects of process are suitable for measurement through surveys using Likert measurement scales[85] and short answer questions. Survey results can then be further explored and clarified through followup interviews.

2.2.5 Validity Concerns

Process is one of the most overused words within the engineering community. As such, process means many different things to different people. This ambiguity and overuse is a threat to validity. Process as a construct is widely recognized and the definition is agreed upon between organizations. As such, construct validity is not a concern. However, because the definition of process may vary slightly between organizations, convergent validity is a concern. Using common touchstones such as the process terminology used in CMMI® or the INCOSE systems engineering handbook should help with convergent validity. Discriminant validity is the final area of concern. Clear terminology, and tightly worded questions will be used to address discriminant validity. Rather than asking a question about process compliance, the question may instead ask if a specific process, (e.g. define and refine system configuration) is taken during design. By intelligently framing the question, ambiguous words can be removed while maintaining sufficient generality to ensure the question is valid across organizations and contexts.

2.3 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 engineer's 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"

2.3.1 Definition of *Culture*

Culture is an amorphous property of groups, an abstraction for explaining group behavior[88]. 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[43]. But what is culture? The following is a survey of common definitions of culture.

1. Culture is a set of expressive symbols, codes, values and beliefs. These are supported by information and cognitive schemata and expressed through artifacts and practices[26].

2. Culture is a web of values, norms, rules, beliefs, and taken for granted assumptions that define the way the world is and should be[52].

3. Culture is 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[88].

4. Culture exists in inter-personal interactions, shared cognitions, and tangible artifacts shared by the group[27].

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[26]. Culture exists at the national, regional, organizational, and inter-organizational levels. 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 individual team members and their experiences[88].

Research on international project teams shows the impact of cross cultural influences on team performance[47]. In fact, group norms, one of the characteristics of culture, are key to group performance[43]. And because engineering is a socio-technical activity, culture impacts a group's creativity, problem solving and ability to generate new concepts[45]. 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[43]. This is because one characteristics of culture is its stability within a group[88]. The formation of culture begins with the formation of a group, and mirrors the stages of groups formation: forming, storming, norming and performing[105]. Once a group is formed, groups 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[88].

While culture exists a distinct levels, these levels influence each other. For instance, an organization's culture is influenced by the region where the organization is located[63, 86]. Other bases for the creation of subcultures within an organization include functional differentiation e.g. operator, engineering, and executive intra-organizational cultures, product or technology differentiation, divisionalization, and differentiation by hierarchical level[88].

At each level there are characteristics of culture with varying degrees of visibility to outside observers[88]. The most visible characteristic are the artifacts to which the culture definitions referred. Artifacts may include visible organizational structures and documented processes[88]. The lesser visible characteristics consist of the consciously supported beliefs and values within a group (e.g. strategic goals)[88]. While not directly visible, espoused beliefs and values are relatively easy to uncover 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[88] and are thusly difficult for a group member to articulate, let alone for an observer to observe.

Within an organization, culture has its origin with the beliefs, values and assumptions of the founders[88]. These are tempered by group experiences as the organization evolves and by the past experiences of those who later join the organization, which in turn results in new beliefs, values and assumptions[88].

While culture is a powerful predictor of group behavior, it is also a barrier to the introduction of new methods, tools and processes[9]. 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[25]. It is evident then that organizational culture is a contributor to team success[74]. Because trust is at the base of successful interactions[58], organizations can emphasize positive team norms and create a cultural context that supports team success[61] by fostering and sustaining intellectual curiosity, effective communications and the keeping of thorough documentation[41].

Culture is closely related to process. 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[30]. 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 followed 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[30]. Because culture is deeply ingrained in groups, it is easier to change processes than culture[109] and therefore links between culture and process help with identifying leverage points when tailoring process to a given culture.

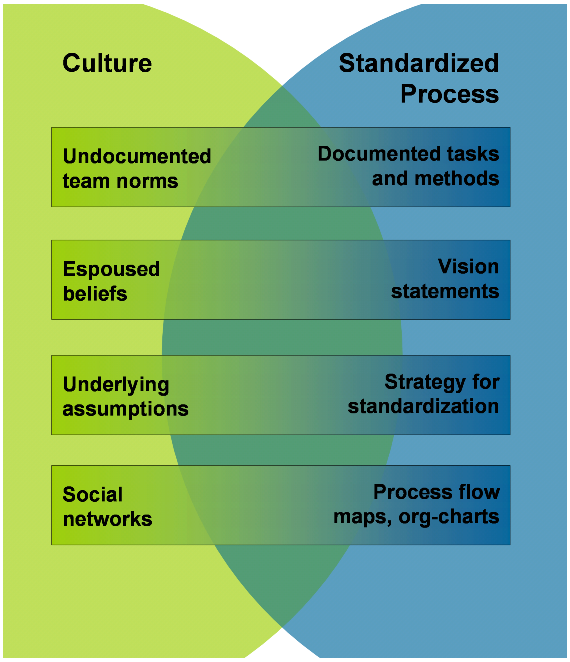

Figure 2-4: Several aspects of culture and process are complimentary.

Figure 2-4 shows a proposed set of ways in which culture and process are linked. Following Schein's framework for cultural characteristics, Figure 2-4 lists the cultural characteristics of undocumented team norms, espoused beliefs, and underlying assumptions. Added to these are social networks on the basis that culture is the result of interactions between people. Within standard process, the natural links are as follows:

- Undocumented team norms vs. Documented tasks and methods

  Norms, tasks, and methods are all observable behaviors. On the cultural end of the spectrum, team norms are emergent behavioral tendencies of group. From the process side behaviors are specified top-down, through required tasks and recommended methods for completing those tasks. When behaviors at both ends of the spectrum are complimentary, 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 and strategic goals

  Espoused beliefs are the 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 are goals and beliefs of a group as well. In this research context, the espoused beliefs occur at the level of the engineering culture and team subculture, and 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 improvements. 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 and improving process, the changes are likely to fail to result in meaningful improvements.

- Social networks vs. Process flow maps and org charts

  Culture is the result of human interactions. It therefore follows that 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 and interface, both from a social, hierarchical standpoint (org charts) and in terms of completing a task (process flow diagrams). As with the previous comparisons, the cultural extreme 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 the necessary design interactions, nor should they. The natural "short-cutting" a social network enables allows for innovation, both with the product and process.

Culture exists at many different levels. For this research, three levels of culture are potentially important. These are the intra-organizational engineering culture, the culture of the organizations in question, and the specific teams's subculture.

While engineering culture exists at a level above the organization, and therefore outside of its influence, organizations can impact their own culture and subsequently the sub-cultures within teams. To this end, leadership is the primary mechanism through which culture is created and changed[88]. 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[88]. Within an organization, a strong culture is important because it contributes to motivation, orientation and control of the organization[26]. For examples, individuals are motivated by two goals: achievement and conformance[46]. 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.

In his "Framework for Linking Culture and Improvement Initiatives to Organizations," James Detert identified eight dimensions of organizational culture. These eight dimensions, described below, provide a promising framework for investigating culture.

Eight Dimensions of Organizational Culture[26]

- A means to evaluate truth and rationality within organization

  Culture impacts people's perceptions. Culture is in many ways a shared model of how the world should work[26, 88] and therefore affects the ways in which people view and assess their environment.

- Time horizons

  Just as culture impacts perceptions, it also impacts views of the future: what is short term and what is long term. These differences are one of the key reason industry and academia collaborations fail[112]. The balance between short and long term visions also impacts decision making, planning and goal setting[26].

- Motivation

  Highlighted above, culture plays a role in motivating people. An organization's culture is based on assumptions about what motivates people, which impacts management styles and rewards structures.

- Stability vs. continual change

  Culture is a dynamic entity, formed through group interactions and experiences, but different groups react differently to these stimuli. Some organizations seek stability. Other organizations cultivate a culture of learning and change, and adjust their assumptions about the world more readily based on organizational experience.

- Relationship to work and others

  Because work is a social activity, the way people relate to their work and co-workers affects an organization's culture. The balance here is between work as a means or as an ends[56]. Differences in these relationships impact motivation and the distribution of control and responsibility.

- Individualism vs. collaboration

  Engineers tend towards the individualism end of this continuum. However, the current state of the aerospace industry requires not just individuals, but also organizations to engage in collaboration. A culture's view on individual vs. group work will impact the way work is accomplished[26] and also the receptiveness to new processes (e.g. an organization with an focus on the individual will have a more difficult time adapting to processes based on integrated team work than will an organization with an emphasis on collaboration).

- Distribution of control and responsibility

  Tightly linked to an organization's assumptions about what motivates its members is its assumptions about control and responsibility. Cultures based on conformance and the assumption that people are externally motivated will have more centralized control than cultures based on achievement in intrinsic motivation. The difference between loose and tight control will impact the existence and form of any design processes[26].

- Relationship with environment

  Because culture is an outgrowth of an organization's interactions with its environment[88], it is logical that the resulting beliefs in turn affect the way in which the organization chooses to further interact with that environment. Linking to the dimensions of individualism vs. collaboration and stability vs. continual change, organizations that engage in collaboration and continual change are more likely to have an external focus that an internal focus.

Further reinforcing the link between culture and process are many of the mechanisms through which culture is embedded. Metrics, rewards systems, promotions and training all help to embed culture[88]. In addition, supporting features such as organizational structure, process and physical environment both are a reflection of culture, but also reinforce culture within an organization[88].

Because culture affects the behavior and the way groups work, it ultimately impacts the systems being developed[97]. The following are a few observations from the literature on desirable cultural traits for designing effective systems. 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[16, 17]. To enable this seeming dichotomy, a trusting, respectful and egalitarian culture is needed[16, 17]. In a 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[51]. Finally, as organizations become more divisionalized consciously steering systems development becomes more difficult and relies on participation from all levels, an act that is supported by a culture that supports transparency in decision making and spatial communication[108].

2.3.2 The Role of Culture in Engineering

While organizational culture and team culture will be specific to the teams and organizations studied, several comments and generalizations about intra-organizational engineering culture can be made. These observations are important not only because the focus of this research is engineering teams, but also because the organizations themselves are influenced by the engineering culture because their primary product is an engineered system.

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 with others outside of engineering. The three main components of engineering culture are that it is technology centered, that engineers equate success with organizational power, and that engineers are a bit self-centered[65]. 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[56].

The five engineering archetypes are the Maverick, the Expert, the Macho, the Technophile and the Non-Communicator[56]. 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 lead to 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, and 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[56]. Because the aerospace culture is comprised of many specialists[9], 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[112].

- 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[56]. Because the aerospace culture is linked to the military and defense[79], 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[56].

- 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[56]. 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[56]. This matches with the types of beliefs and behaviors suggested by the predominate Myers-Briggs personality type within aerospace engineering: Introverted-iNuitive-Thinking-Judging (INJT). 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[56]. Yet, engineers state preferences for completing work in advance, and are often motivated by fear of failure, express a desire for ownership of their results and recognition for their accomplishments[56], and state a preference to work in an environment with moderate coordination[74].

The common engineering cultural typologies indicate that accepting standard process and working in teams represent challenges. Yet, in a world of increasing complexity, teamwork and standard process are essentially mandated to cope with complexity. It is balancing this intersection–leveraging the good in engineering culture, and tempering the not-so-good with process–that teams are able to engage in collaborative systems thinking.

2.3.3 Relevant Aspects of Culture

Because of time and access constraints, the relevant aspects of culture included in this survey will be limited to behavioral norms and team beliefs. Minimal interaction data may also be sought in reference to evaluating organizational artifacts such as process maps and organizational charts. All data collected represent the belief that culture impacts the development of systems thinking and that cultures valuing systems thinking enable its development[24]. 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.

- Stability of team environment

  This is a measure both of how consistent the team culture is over time, and also a measure of whether the team is organized or operates in an ad hoc manner. A stable culture may facilitate task completion, but some amount of learning and adapting is required to remain innovative.

- Effectiveness of accepted team behaviors

  Every team will, over time, develop its own personality. The behaviors associated with this personality may improve team effectiveness, prove a distraction, or worse. Additionally, these behaviors may be tempered or influenced by standard processes.

- Team communication preferences

  How frequently team members interact and through what means. As will be seen in Section 2.4 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 facilitate communication[20].

- 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[98]. By contrast, teams that move quickly to conclusions may miss important aspects of the problem and end up with a poorly optimized solution.

- Team motivation

  Is the work a means to an end, or fulfilling in its own right. Engineering culture would prescribe that engineers, as technophiles find motivation in the end product. However, real life engineers are more complicated and have concerns beyond work. Initial research suggests that an ability for engineers to rally around the system under design is both a motivator and an enabler of collaborative systems thinking.

- Team mentality towards decision making

  Decision making is an important team activity. While humans tend towards satisficing solutions[92], engineering design is inherently about finding good or optimal solutions. Does the team recognize the need for trade-offs in this process? Does it believe in the existence of a "right" answer?

- Individual vs. team reflection

  A team's attitudes towards issues of the individual vs. the team 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.

- Team time horizon

  Is the team looking towards the completion of the program, or only focused on the next gate review? While teams should engage in both short-term and long-term planning, an overemphasis on either can lead a team to make unbalanced decisions. A short-sighted time horizon may also lead to procrastination, a common trait of engineers.

2.3.4 Validity Concerns

Cultural analysis is subjective and time consuming. Constraints will require most data about organizational culture and team norms to be collected through surveys and interviews rather than through team observation. Because culture is an abstraction, construct validity is a concern that must be addressed by carefully specifying what is meant by culture. Because of data collection constraints, this research will limit the construct of culture to observable characteristics such groups norms, artifacts and espoused beliefs as influenced by the engineering community, the parent organization, and/or the local team. Convergent validity is tied to construct validity and therefore must also be addressed. As with process, the convergent validity of culture will be addressed through the use of tight wording and common terminology to avoid being influenced by differences in the use of the culture construct between organizations. Finally, while many definitions exist for culture, in general people can discriminate culture from other constructs such as process and therefore discriminant validity is not a concern.

2.4 Collaborative Systems Thinking

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

–Carl Sagan

Recent research supports Carl Sagan's assertion as it applies to engineering. In complex system design, upwards of 70% of the required knowledge cannot be or is not documented[28]. Rather, this knowledge is a result of experience and impacts the way individuals and teams approach the problem.

Systems thinking is one such mode of thinking that engineers engage in when designing complex systems. It enablers them to better handle complexity, make better design decisions, and to consider the dynamic interfaces and interrelationships of the system[24]. Within teams, this type of thinking is thought to emerge at the intersection of process (how work *should* be done) and culture (the values and norms of behavior shared by the team). To paraphrase former vice president of Bell Labs, Estill I. Green, 'groups do not create ideas, individuals do'[62]. While this is true, it is through communicating ideas that design is accomplished. Design is a dynamic process and sometimes the problems encountered are a result of static views rather than dynamic thinking[89].

The following is an overview of what systems thinking is, how teams think, and a definition of collaborative systems thinking based on the intersection of systems thinking and team-based design thinking. From this rich set of literature behaviors, values and tools that may act as enablers or barrier to collaborative systems thinking are also identified.

2.4.1 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, 4, 51, 89, 96, 103, 108].

Generic definitions of systems thinking vary, defining the skill from the use of one's abilities to apply sound reasoning in a given situation[29], 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[108].

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[84]. 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"[89]. 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)[89].

Below are additional systems thinking definitions from the systems dynamics community.

- Peter Senge defines systems thinking in 1994 book *The Fifth Discipline,* as a "way of thinking about, and a language for describing and understanding, the forces and interrelationships that shape the behavior of systems"[89].

- Peter Checkland views systems thinking as an "epistemology which, when applied to human activity is based upon the four basic ideas: emergence, hierarchy, communication, and control as characteristics of systems. When applied to natural or designed systems the crucial characteristic is the emergent properties of the whole"[19].

- In Jamshid Gharajedaghi's framework, systems thinking "puts the system in the context of the larger environment of which it is a part and studies the role it plays in the larger whole"[38].

- John Sterman's definition of systems thinking is as "the ability to see the world as a complex system, in which we understand that 'you can't just do one thing' and that 'everything is connected to everything else' "[100].

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

Dr. Moti Frank based his interpretation of engineering systems thinking on Senge's 11 laws of systems thinking. Through examination of literature and interviews with engineers, Frank derived 30 laws of engineering systems thinking[37]. 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. Finally, these laws acknowledge that no one person is capable of understanding the entire system, thus requiring a team effort[37].

A second definition of systems thinking as it applies to engineering contexts was developed by Dr. Heidi Davidz through a series of interviews will 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, relational, contextual, and dynamic elements of the system of interest"[24]. 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.

The skills and benefits of systems thinking are associated with problem solving[51]. To this end, lists of systems thinking skills have been developed to help in understanding the role of systems thinking in system design. These skills include the ability to understand dynamic systems behavior, and to identify patterns resulting from interactions[84, 103]. The identification of feedback processes, or closed-loop thinking, is used to explain the observed patterns of behavior[84, 103], 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[84, 103]. 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[84, 103]. Recognizing the limits of assumptions and presence of non-linearities in a system are also crucial to effective systems thinking[103]. 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[103].

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[7]. But what enables systems thinking? Experiential learning, specific individual traits and a supportive environment are the greatest enablers (and barriers) to systems thinking[24].

It has been shown that environment affects an individual's perceptions and relationships with the surroundings, thus impacting thinking style[73]. Even within a given context (e.g. culture) an individual's thinking style can be influenced and modified through interventions[73]. While the environment can modify thinking styles, others believe personality type, which influence preferences and therefore behavior[106], may affect systems thinking ability[75]. Within this 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[7]. By this model, systems thinking is not a natural mode for engineers, who tend towards rational thinking[108]. Rational thinking has a tendency to dominate intuitive thinking, but in reality, both are necessary for systems design[108]. This dichotomy of thinking styles will be revisited in Section 2.4.3. 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[46].

2.4.2 Thinking as a Team Construct

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, reasons 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[3]. 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[3]. Because teams have the ability to 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 as they must be practiced as a team[89].

Team thinking is like having parallel processors: it only works with communication between the processors[66]. Team thinking emerges from the intersection of individual team members' thinking, their behaviors and team processes[21]. The result is greater than the sum of the individual thoughts[21], 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[3]. Brainstorming, team norms, and processes enable this communication[3].

While there are no agreed upon measures for team thinking, there is consensus that process and culture are influences[33]. 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[21]. 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[21].

A few proposed measures of team thinking are presented below.

- Anticipation Ratio

  Ratio of number of communications transferring information relative to the number of communications requesting information. When teams are able to anticipate each other's need for information, this ratio rises above one, indicating team members are aware of each others activities and communication becomes more efficient[66].

- Mutual Awareness

  Contributing to increases in the anticipation ratio, mutual awareness is a measure of how aware team members are of each other's activities with the design context. Teams with a greater mutual awareness communicate more efficiently[66].

- Situational 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[21].

- Explicit vs. Implicit 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 each other's needs[21].

2.4.3 Team-Based Design Thinking as a Bridge to Collaborative Systems Thinking

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[104]. 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[32].

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[32, 98]. Convergent thinking operates in the knowledge domain and consists of comparison and selection[32, 98].

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[31, 98]. 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[39]. This situation is common in engineering even thought 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[32, 98]. Characteristics of effective design thinking include the ability to tolerate uncertainty, keep sight of the big picture, make decision despite ambiguity, think and take action as a team, and to communicate using the multiple languages of design[32]. The references to big picture thinking and tolerating uncertainty draw clear parallels between design thinking and systems thinking. However, 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.

Research into design theory and thinking follows three paths: normative, empirical and design-as-art[98]. Normative research tends to propose systems methods for engineering design; processes 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 gains efficiencies by borrowing from pre-established procedures[98]. Which of these perspectives works best, depends on the problem itself.

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[99]. 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 though to explore new regions of the goal space[104]. Yet, engineers often have a "them vs. us" attitude that inhibits their own creative environment[111].

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[98]. 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[98].

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[98]. 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[98].

The difference between process one and process two is that process two requires the team to engage in early questioning. Early questioning, in turn, is most likely in heterogeneous groups with a culture that is receptive to questioning, and therefore divergent thinking styles[98].

2.4.4 Defining Collaborative Systems Thinking

Out of Dr. Davidz's research came a definition of systems thinking. This definition, grounded in over 200 interviews with engineers and validated by a panel of blue-chip systems engineers, will form the foundation for the definition of collaborative systems thinking.

Systems thinking is utilizing modal elements to consider the componential, relational, contextual, and dynamic elements of the system of interest[24].

Initial discussion with members of industry indicate that while an individual contributes to a team, the end goal of a team is to produce a finished product and as such, the definition for collaborative systems thinking should include the goal of producing a complete system. Additionally, research has shown that teams with heterogeneous composition outperform homogeneous teams. Mixes in thinking style preferences[20] and knowledge[67] are both critical.

Successful team design thinking engages a variety of thinking styles, a learning environment and a variety of means to communicate[3, 32]. These teams show curiosity towards the problem space, generate large numbers of alternative solutions and then engage in evaluation[3], following the normative design process[98]. The normative design process, referred to as process two above, proceeds from idea generation to problem analysis before transitioning to evaluation and onto detailed design. 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[32]. The willingness to ask questions, and thus engage in divergent thinking, is an indicator of a culture that support learning. Finally, for a team to effectively communicate, multiple 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[32]. Communicating enables teams to keep a clear mission[109]. Interestingly, team mental models, or shared representations of tasks, equipment and working relationships, have not been shown to positively impact team performance[67].

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 languages to consider systems attributes, interrelationships, context and dynamics towards executing systems design.

This definition will be used to execute field research, and will be updated as warranted by feedback from data collected.

2.4.5 Team Traits, Processes, and Cultural Characteristics that May Impact Collaborative Systems Thinking

The traits, processes and cultural characteristics that act as enablers and barriers to collaborative systems thinking are drawn from team thinking, design thinking and a variety of other references on team performance and management. The traits follow the enablers and barriers Davidz found for individual systems thinking: experiential learning, individual characteristics and environment. At the team level these translate to team learning, team preferences and behaviors, and the teams's internal and external environment. These traits are listed and explained below. Additional questions, to be addressed in Section **??**, will evaluate the presence and strength of a team's collaborative systems thinking.

- 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 and efficient way to transfer information, it is not an effective way to communicate[20].

Indicators of mature and effective communication are the ability to clearly articulate ideas, provide compelling reasons, listen to others and provide constructive feedback[106]. Mature communications enable higher levels of team understanding[106]. The use of sketches and other nonverbal communications improve this common understanding[32, 34].

- Engaging in divergent thinking

  The difference between natural design processes and normative design processes is that normative design processes engage in early questioning, thus enabling divergent thinking and a greater exploration of the problem space[98]. This is enabled by processes that emphasize insightful questioning, rather than early answers[61]. This process of reflection builds group cohesion and promotes systems thinking while supporting team learning[61]. By deferring judgement and considering as many ideas as possible, an environment that enabler divergent thinking is supported[77].

- Structure team interactions to respect team learning preferences

  Most engineers have a Myers-Briggs type of ISTJ or INTJ. The result is that while engineers typically have long attention spans, they require time to digest assimilate new information[102]. Situations that require engineers to act upon new information without a period of reflection is stressful and unproductive[20].

- Mutual Awareness

  Contributing to increases in the anticipation ratio, mutual awareness is a measure of how aware team members are of each other's activities with the design context. Teams with a greater mutual awareness communicate more efficiently[66].

- Situational 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[21].

- Explicit vs. Implicit 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 each other's needs[21].

- System Awareness

  Different than collaborative systems thinking and similar to situational awareness, system awareness is 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 what type of engine and where in the engine the impeller goes.

- Shared goals and motivation

  Teams with a common goal better maintain their focus. Shared beliefs that enable risk taking foster a climate characterized by trust and mutual respect[106]. These traits enable free communication which reinforces a team's goal.

- Process Awareness

  As stated earlier, most engineers have a Myer-Briggs type of ISTJ of INTJ. The 'T' refers to a preference for analytic cause-and-effect reasoning as opposed to soft metrics[20]. The 'J' refers to a preference to make decisions through the use of systematic judgement rather than via spontaneous and flexible processes[20]. Therefore, team members need not only to be aware of the existence of the process, but also need to understand the reasons for its existence and its role in reaching the team's objectives[102].

- Proper documentation of design decisions

  Proper documentation is not the for the present team, but for those that must later interact with the design and systems. Proper design documentation should not only state what a systems does, but why and how the design came to its final form enable future designers to learn not only from the design's final form, but also from the problems encountered during the design process[41]. A culture valuing intellectual curiosity and effective communication is necessary to produce effective documentation[41].

- Emphasis on 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[98]. 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.

- Creative environment

  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[104].

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

- Consistent team 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[88]. For instance, an individual who completes her work early will find it stressful to work with a team that works up against the deadline.

2.4.6 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 through experimental procedure by including measures of similar constructs (e.g. team performance, team moral, etc.) and using statistical measures to rate the level of differentiation between collaborative systems thinking and those constructs. Statistically significant differences will indicate the construct is discriminately valid.

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