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A Socio-Technical Perspective on Interdisciplinary Interactions During the Development of Complex Engineered Systems

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Abstract

This study investigates interdisciplinary interactions that take place during the research, development, and early conceptual design phases in the engineering of large-scale complex engineered systems (LaCES) such as aerospace vehicles. These interactions occur throughout a large engineering development organization and become the initial conditions of the systems engineering process that ultimately leads to the development of a viable system. This paper summarizes some of the challenges and opportunities regarding social and organizational issues that emerged from a qualitative study using ethnographic and survey data. The analysis reveals several socio-technical couplings between the engineered system and the organization that creates it. Survey respondents noted the importance of interdisciplinary interactions and their benefits to the engineered system as well as substantial challenges in interdisciplinary interactions. Noted benefits included enhanced knowledge and problem mitigation and noted obstacles centered on organizational and human dynamics. Findings suggest that addressing the social challenges may be a critical need in enabling interdisciplinary interactions during the development of LaCES.

Keywords: Interdisciplinary, Engineering Research, System Design, Complex Systems, Socio-Technical

1. Introduction

Socio-technical systems have long been researched, particularly in the context of the interdependence between organizational development and large-scale information technology systems development.[1, 2] Research on socio-technical systems has often focused on the organizational and human interface with the technical system during operation (such as the well-developed fields of human-computer-interaction and human factors); however, the current work focuses specifically on the socio-technical aspects associated with the extensive system development effort prior to the system's operational use. For Large-Scale Complex Engineered Systems (LaCES), which are the focus of the current work, the system development effort is a lengthy, highly iterative, and interdisciplinary blend of

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processes that stretch from basic research to the completion of the systems engineering process. LaCES include systems such as aerospace (e.g., aircraft, space systems), large maritime (e.g., submarines, aircraft carriers), nuclear (e.g., power plants), and major civil infrastructure systems (e.g., water supply systems, electric power grids, offshore oilrigs, and air and ground transportation systems).[3] LaCES represent a genre of engineered systems that are critical to the infrastructure and defense needs of most industrialized nations and uniquely comprise a blend of extremes in terms of physical size, technical and financial risks, organizations, and collateral impact.

While the complex socio-technical nature of LaCES has always been present, several persistent issues during design and development of these systems have pressed many to take a contemplative look at existing engineering practice, including reexamining related non-engineering aspects of systems development. Issues that have triggered this renewed focus on engineering practice in recent years include: escalating costs during system development that far exceed inflation rates; extended system deployment timelines that exceed best predictions; growing size and intricacy of systems organizations; and increasing interdependencies or tight couplings.[3, 4] Resolution of these challenges is further complicated by the following system realities: increased societal reliance on LaCES; system failures that may approach catastrophic proportions in terms of impact to human life, national defense, or local and national economies; and ensuring the continued interoperability of critical LaCES for several decades where one system must operate precisely with other systems that are likely to change over time. These important issues have given rise to a plethora of new meetings and research directions, a few of which are noted in references [3] and [5].

This work is motivated by the challenges of addressing increasing system interdependencies while systems organizations continue to grow in size and intricacy. This research focuses on understanding interdisciplinary interactions during research and development (R&D) of LaCES, specifically aerospace systems, by 1) providing deep descriptions of the related engineering and organizational practices and, 2) deriving an explanatory integrative framework that provides a more theoretical perspective on these practices. The current paper summarizes findings from an initial study that is part of the larger research effort on this topic. Specifically, we synthesized data collected using surveys and ethnographic observations that focused on ascertaining current perspectives on interdisciplinary interactions in R&D for large-scale systems. This paper begins with background regarding system development organizations for LaCES and related socio-technical interdependencies. As the qualitative research approach is less common in the field of engineering, we describe its foundations and methods herein. The findings are presented next with connections to organizational theories. We conclude with preliminary implications for engineering practice.

2. Background

Some of the key "social" challenges with the design and development of LaCES include organizational challenges, stakeholder and political relationships,[6] economic considerations, and human-system operational considerations, the latter of which includes humans even for autonomous or highly automated systems. In this study, we examine the interdisciplinary practices during R&D for LaCES, necessarily considering the organizational context of such practices. In this work, the following definitions for system relations are used. *Cross-disciplinary* identifies all types of interactions between disciplines. *Multidisciplinary* is the combination of multiple disciplines (which may be non-integrative), where each discipline preserves its methodologies and assumptions without significant modification from other disciplines. *Interdisciplinary* refers to the fusing and integrating of several disciplines, where each discipline's methodologies or assumptions are interdependent on other disciplines. Multidisciplinary is distinguished from interdisciplinary to account for the relationship *between* the disciplines. In a multidisciplinary scenario, the relationship between disciplines "may be mutual and cumulative but not interactive".[7] In an interdisciplinary relationship, the practices and conventions of each discipline are interactively blended.

Cross-disciplinary interactions are typically considered during the latter stages of development once a system concept has taken form and the relevant disciplines engage to shape the design. These practices are well developed in physics-based mathematical processes such as multidisciplinary design optimization (MDO) and formal system integration and management processes such as systems engineering (SE). However, extensive technical interdependencies are pervasive in LaCES and warrant some degree of cross-disciplinary interactions during the R&D phase of development as well. An improved understanding of cross-disciplinary interactions during R&D, with a focus on interdisciplinary interactions, can lead to improvements in subsequent systems integration efforts such as SE. These improvements can be realized by: reducing mistakes that often occur at technical interfaces, increasing creativity that often occurs at the interfaces of disciplines[8], and better harnessing the collective wisdom needed to successfully design a large system. These improvements can ultimately lead to reducing system development cost and time while improving system performance.

The socio-technical challenges of cross-disciplinary processes are very complex and highly evolving. One goal of the current work is to gain a more holistic, socio-technical representation of the interdisciplinary interactions within a research, development, and design setting for extremely large engineered systems. To facilitate a socio-technical lens on the research topic, an interdisciplinary perspective informed by engineering practice as well as social science was adopted. The current study delves into the interdependence of the disciplines and the associated non-hierarchical interactive practices *between* researchers. The interactions (indicated by the dotted lines in Figure 1) have implications for the engineered system and related engineering organization. These interdisciplinary interactions are the focus of the current work.

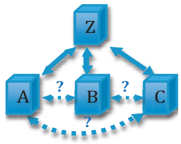

Figure 1 Cross-disciplinary interactions

3. Research Methodology

The research question posed for the survey and ethnography portion of the study is: *What are current perspectives on interdisciplinary interactions during research and development and early design of LaCES and why might these perspectives prevail?* The nature of this study is well suited to qualitative methods, particularly ethnographic studies, because it seeks to describe and conceptualize a wide variety of perspectives.[9-11] Qualitative methods are particularly fitting for "understanding the world from the view of those studied."[12] These methods are also very suitable for the current research as this work may be described as a formative study that is "intended to help improve existing practice rather than simply to determine the outcomes of the program or practice being studied." Scriven, 1967, 1991 as referenced in [13] Qualitative research strategies, particularly ethnographic methods, guide the research to take a holistic perspective that includes social, historical, and temporal contexts.[14]

Our two-fold, integrative and qualitative approach combined insider ethnography and survey research. Insider ethnography was used to provide a rich, descriptive account of the cultural and organizational work life of R&D engineers in aerospace.[11] Survey research was implemented to reach a more diverse sample of respondents. The survey responses were integrated with ethnography to discern possible underlying dimensions or patterns in the data.[15]

To improve trustworthiness of the research findings and reduce researcher bias, several steps were taken at research initiation and throughout the study. First, the research design was carefully structured to include triangulation by gathering data from two different methods as well as examining many different organizational theories to seek theoretical explanations for the findings. The survey and ethnographic approaches were designed to enable the opportunity for "negative cases" that challenged preliminary themes. Peer examination from researchers in engineering, organization science, engineering education, and psychology further aided in cross checking interpretations. Employing insider ethnography also allowed for considerable feedback in the form of sustained member checking from a wide variety of peers within aerospace R&D. Emerson, et al, note that "the task of the ethnographer is not to determine 'the truth' but to reveal the multiple truths apparent in others' lives,"[16] for "[any phenomenon] contains multiple truths, each of which will be revealed by a shift in perspective, method, or purpose… The task is not to exhaust the singular meaning of an event but to reveal the multiplicity of meanings, and… it is through the observer's encounter with the event that these meanings emerge." Mishler, 1970:10, as referenced in [16]

3.1. Data collection

Ethnographic research for this study was primarily conducted in aerospace R&D settings via 20 years of insider involvement and extensive interaction with a wide variety of aerospace R&D entities including government, industrial, and university laboratories. The long duration of the insider ethnography provided critical insight to discern "the more subtle, implicit underlying assumptions that are not often readily accessible through observation or interview methods alone."[16] Ethnography included participant observation with informal, unstructured interviews. As R&D precedes and overlaps with early design efforts, interdisciplinary interactions during conceptual system design were also examined.

The written survey was conducted at the NSF/NASA Workshop entitled "Large-Scale Complex Engineered Systems, From Research to Product Realization."[17] The senior leaders and researchers invited to participate in the workshop provided a convenience and purposeful sample of a rare participant pool.[9, 12, 18] The 62 survey respondents represented a wide variety of backgrounds and extensive experience in engineering, including practicing researchers, project leaders, systems engineers, and executives in industry and government, as well as leading academic researchers in engineering design, organization science, optimization, and economics. The respondents (most of whom did not know each other) also represented a wide variety of organizations from different government agencies, corporations, and universities. The sample size is significant considering the difficulty of garnering responses from a multidisciplinary group of LaCES experts from different organizations. While these participants were selected based on their prior experience with R&D for LaCES, there was no intent to collect a representative sample for this study. Rather, this group was selected because they are in the position, based on their extensive experience, to provide their perceptions of R&D within LaCES.[19]

The survey design was guided by the research questions and preliminary data from ethnographic observations. It included simple instructions for obtaining short, written answers to seven open-ended questions. The written instructions printed on each survey were: "*Please consider your first-hand experiences with research in large-scale, complex engineering systems.*" These instructions were followed by: 1) *How important do you think interdisciplinary interactions are for complex systems?*; 2) *Please describe the potential benefits to interdisciplinary interactions; 3) Please describe the potential negatives to interdisciplinary interactions; 4) Please describe things that encourage interdisciplinary interactions; 5) Please describe the obstacles to interdisciplinary interactions; 6) Please provide some background context for your experience: Where do you work? What do you do for your occupation? How many years of work experience do you have?*; and, 7) *Please add any other comments you wish below.* The participants completed the survey on site within 30 minutes.

3.2. Data analysis

The over-arching research approach was interpretive involving qualitative content analysis using theoretical sampling and methods of constant comparison (in keeping with the grounded theory methodology developed by Glaser and Straus).[9] As is common in a qualitative study, data from all research methods (ethnographic and survey data) were integrated and re-coded as new findings emerged and the research design was adjusted accordingly.[20] While a highly inductive data analysis approach guided our findings, to prevent assiduous theory avoidance, this work has theoretical underpinnings in organization science theory.[12, 21] For the current analysis the theory called "sensemaking" was predominantly utilized. References [22] and [23] provide an overview of several aspects of this theory. Other theories that influence the current work included high-reliability management,[24] positive organizational scholarship (POS),[25] social network analysis,[26] and related "knowledge sharing" concepts.[27]

Ethnographic and survey data were coded and re-coded via an iterative first-order and second-order analysis approach. First-order analysis of ethnographic data was documented using thematic narratives that were derived from themes that emerged from patterns in events and informant accounts.[15, 16] The narratives are presented herein as descriptive accounts of engineering practices. First-order analysis of the survey data entailed considering repetitions, similarities, and differences of concepts, being mindful of each individual respondent's answers as a whole and grouping the responses question by question.[9, 21, 28] Ethnography also aided in understanding the nuances and other characteristics of the LaCES domain that proved vital to properly interpreting the survey responses.

Subsequently, deeper (second-order) analysis was conducted by integrating ethnographic and survey data to provide more dense descriptions of emergent concepts and where possible, also provide explanatory frameworks or conceptualizations to further clarify some phenomena.[29] For a few major themes, potential explanatory perspectives from existing social science theories were also considered. In sum, this second-order analysis was focused toward providing theoretical perspectives that seek to interpret and explain the first-order analysis.[29] This "theoretical perspective is grounded in, and emerges from the first-hand data (cf. Glaser and Strauss, 1967)."[15] Second-order analysis entailed discovering meta-themes that encompassed multiple codes from individual and multiple survey questions, then integrating both meta-themes and first-order survey codes with ethnographic themes.

To echo what is well documented in qualitative research theory literature, we note that a quantitative frame for analysis of the survey data is an inappropriate frame given the sample size and research methodology. Accordingly, statistical generalizability is not the aim for this study but rather generalizability in the context of R&D in LaCES is the appropriate frame for considering potential transferability of these findings to other contexts.[18]

4. Findings

4.1. Development of an Integrative and Interdisciplinary Theoretical Framework

Initial data from ethnography and social science theories laid the groundwork for the development of an integrative theoretical framework that was created to conceptualize key elements of the socio-technical nature of the research topic. The focus for this study is three synergistic, key elements: the engineered system, the people working on the system, and the methods they use to work on the system. Or said alternatively: *what* is being worked on, *who* is doing it, and *how* they are doing it. Ethnographic observations and social science theories indicate that while known engineering interdependencies or couplings may be addressed by conventional means of documentation and physics-based models, the persistence of unknown couplings in complex systems warrants augmentative considerations such as connecting or sharing tacit knowledge and addressing organizational barriers. As noted earlier, several organizational science theories contributed to this work adding insights from dense bodies of research that focus on organizational connections and associated implications. Our findings suggest that one frame that can be used for understanding socio-technical factors during engineering development is rigorously integrating the *processes* (e.g., MDO) with the *people* involved (e.g., large distributed organization), and with the *product* under development (e.g., aircraft) as depicted in Fig. 2.

Development of this interdisciplinary framework was a principal aspect of this study for two reasons: 1) the majority of the existing engineering literature primarily frames research of cross-disciplinary processes around the engineered system and related engineering processes such as MDO, systems analysis, and SE without rigorous analysis of the social dimensions of engineering practice based on existing social science theories; and 2) social science theories, namely organization science theories, added significant depth in refining the research design and in data analysis and interpretation. Several studies note that how a problem is framed is akin to how a problem is solved.[30, 31] Some examples of engineering design and development studies that utilized social science theories are provided in references [3] and [32]. Specific examples of contributing organization science theories are provided where applicable throughout the analyses discussed below.

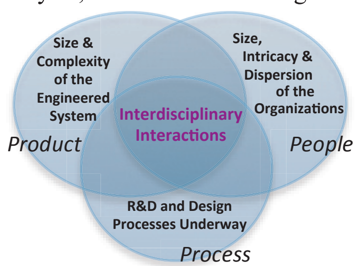

Fig. 2. 3P Integrative Theoretical Framework

4.2. First-order Codes and Meta-themes from the Survey

Table 1 provides a summary of inductive codes that emerged from the “raw” survey responses. These appear with codes derived from the greatest number of responses for a specific question at the top to the least number of responses for that question at the bottom with no effort to correlate responses among the questions. Recall that a quantitative frame for analyzing the survey data is methodologically inappropriate for this sample and this listing and approximate ordering of codes is provided to give a wide qualitative view of the data received.

Table 1 First-order codes from the survey

Q1:Importance	Q2: Benefits	Q3: Negatives	Q4: What Encourages	Q5: Obstacles
- Very Important or Essential - Potentially Very Important	- Enhanced Knowledge: Increased Understanding & Knowledge/ Diversity of Thought - Problem Mitigation and Understanding of Interfaces - Innovation and Creativity - Broader, Systems-Level Understanding and Broader Solution Space - Improved System Design or Performance - Increased Efficiencies in Sys Development & Org Practice/Communication	- Organizational Confusion, Coordination, & Conflicts - Communication Difficulties/Lack of a Common Language - Additional Time Req. - Mitigating Single Discipline Biases & Impacts - Org. Cultural Challenges - Challenges in Learning and Understanding - Potentially Wasted Resources - Negative Emotional Response - No Negatives	- Multidiscipline Experiences & Individual Openness - Relationship Building - Incentives - Org. Culture & Openness - Proactive Teaming - Mgt. Support/Leadership - Technical Need - Proximity to Colleagues - Interactive Activities - Org. Structure & Flexibility - Increased Awareness - Common Goal - Specific Org. Roles/Functions - Communication - Resources/Means	- Communication and Language Barriers - Emotional Response - Cost and Time - Group Dynamics - Culture - Organizational Structure - Career Concerns and Incentives - Lack of Requisite Skills - Org Processes - Proximity to Colleagues - Leadership

While most responses were multi-faceted, responses about the importance of interdisciplinary interactions (Q1) were overwhelmingly consistent among nearly all respondents. Responses noted the high importance of these interactions with most respondents using strong descriptors, such as "essential," "critical," "very," "extremely." The consistency of responses suggests that a high value is placed on interdisciplinarity in the R&D of LaCES.

Most responses concerning benefits of interdisciplinarity interactions in R&D (Q2) were grouped into two broad meta-themes: system improvements and cognitive improvements, the latter garnering more responses. These two meta-themes appear to be linked. For example, the "broader understanding," "shared knowledge," "emerging thoughts" noted in some responses may offer additional awareness needed to enable "new technical solutions," "unforeseen capabilities," and "fewer surprises" by reducing "'downstream surprises' of 'emergent behaviors' from un-modeled interactions," as noted by one respondent. Salient aspects of the noted benefits are: 1) they are largely realized in the long term and 2) they are very difficult or impossible to quantitatively measure or predict, particularly the cognitive benefits. An example is the highly emergent nature of learning. As new data (and hence knowledge) is acquired during R&D, the system design that integrates the R&D results is updated in a manner not always predictable *a priori* and newly acquired understandings may benefit future systems more than the one at hand.

The vast majority the responses regarding the negatives with interdisciplinary interactions (Q3) related to the process (the "how") of enabling the interactions. The top three most referenced topics appear somewhat related with common responses being "confusion," "more coordination," and "communication barriers." A sense of disorderliness with interdisciplinary interactions appears throughout many responses. This question also drew responses regarding mitigating single discipline bias and impact such as reduced single-discipline focus and a "tendency to revert to stove pipe thinking."

The predominance of responses related to what encourages interdisciplinary interaction (Q4) may be grouped into two broad meta-themes of "social" and "organizational," with minor themes related to engineered systems and planning. Numerous responses related to social concepts were articulated as "co-location", "trust", "tolerance" and "integrative teams." Organizational concepts included: "workshops", "organizational structure", "management support/patience," "incentives," and "org culture." Quite surprisingly, there were only three responses that mentioned or referred to the traditional roles of "MDO," "systems engineer," and "chief engineer."

The responses to Q5 regarding the obstacles to interdisciplinary interactions may be grouped into the four meta-themes of social, organizational, time/cost, and skills. The social meta-theme encapsulates the majority of the responses to this question examples being: "language barriers," "distributed location," "culture," "possible misaligned objectives," and several, very descriptive single word responses such as "fear," "ignorance," "tribalism," "arrogance," "elitism," and "pride." Some of these latter responses suggest a defensive reaction in interdisciplinary interactions. The organizational concepts of "rigid standards," "stove piped organizations," and "poorly formed incentives" were noted. A perceived lack of skills among individuals and leadership was also noted.

5. Discussion: Integration of Ethnography and Organizational Science Theories

In this section we look across all survey responses and ethnographic data to foster the development of an explanatory framework. Preliminary analysis of a portion of the survey data also appears in reference [32]. In aggregate, there were a few surprises: 1) the consistency of the strong responses regarding the high importance of interdisciplinary interactions; 2) responses related to social science aspects exceeded the responses related to engineering or mechanical aspects by an extremely wide margin; and, 3) the near absence of responses related to commonly used integration functions such as MDO, systems analysis, SE, and the role of a chief engineer.

The first surprise was striking, as the consistency of strong, affirmative responses appears to be in tension with the frequency of negative responses related to existing culture, poor emotional response, organizational structure, and perceived lack of incentives and leadership support. While this finding warrants further study, ethnographic observations provide some insights. Ethnography suggests that some of the noted characteristics may be unintended consequences of the strongly hierarchical organizational styles of many LaCES organizations. Many LaCES efforts (including R&D) are often organized by a decomposition of the system into smaller, simpler, and more manageable sub-systems, often organized by functions or disciplines. These decompositions usually become frameworks for SE and MDO processes as well as other, more tacit, organizational facets such as culture. The decompositions also naturally create a type of boundary in several areas: mathematical models, assumptions, incentives, processes, etc. It is possible that though interdisciplinary interactions are valued, and integrated teaming is quite common, the organizational "system" may be structured to support efforts that are more singular in nature.

A related perspective is that if the engineered system genuinely behaves as a complex system, then assessment of portions or entirety of the system is not given to a reductionist approach since the system does not respond as a sum of its subdivided parts.[33] From ethnographic data, a senior aerospace engineering faculty notes that the size of the system requires some type of division to handle it; hence, "it is not *if* we cut up the system, but do we understand what the implications are when we do so?" Further complicating interdisciplinary interactions are the size and dispersion of typical LaCES organizations where those responsible for development (R&D through SE) of just one LaCES often include hundreds to thousands of geographically dispersed engineers and scientists. System "team" members may never personally interact with large portions of the organization. The "team" also typically comprises many different organizational entities resulting in widely varying cultures, incentives, etc., within one "team."

The second surprise from the data is rather far-reaching: perceptions regarding interdisciplinary interactions in engineering R&D are more related to social science aspects than engineering aspects. An indicator is the preponderance of responses related to interrelationships between people: conflicts, coordination, relationships, proximity to colleagues, understanding others, teaming, group dynamics, interactive activities, and the most commonly referenced topics of communication and language. Interestingly, the referenced interrelation topics were not about interfaces with mathematical models, software, or hardware. The focus on human interfaces more so than engineering interfaces may relate to the third surprising finding: Only 3 responses from all questions, referenced widely used engineering integration functions. This might suggest that these traditional integration functions may not address the social and organizational aspects noted in the survey responses.

Looking over all of the responses, the over-arching story emerging from the survey suggests that interdisciplinary interactions are perceived as "messy" and uncomfortable to implement, resulting in a focus on social topics. What may drive the perceived "messiness" and discomfort?

Considering first the responses regarding benefits, they relate to concepts somewhat intangible and emergent, and thus non-predictive, in nature. For example, it is very difficult to plan when, if, or to what degree the benefits of "risk recognition," "holistic systems thinking," and "richer idea generation" will manifest themselves as cost or time reducers or performance enhancers on the engineered system. Such benefits may be largely non-deterministic because the engineered system itself is also non-deterministic in many aspects. In studying high-risk systems such as LaCES that are characterized by "extreme interdependence,"[34] one study points out that "these systems due to their complexity are formally underdetermined; that is, they are capable of assuming more conditions or system states than can be planned for or anticipated in formal designs *[and R&D]*. This means they have the capacity to confront managers *[and researchers]* with problems of high variety and significant novelty" (emphasis in brackets being ours).[35] Thus, the products of interdisciplinary interactions are likely neither precisely nor easily predictable.

The underdetermined and complex nature of LaCES also suggests that the process of interdisciplinary interactions is likely not amenable to routine, standardized, or hierarchical process models – currently favored in the LaCES work environment. The need for more highly adaptive processes and organizational structures for very dynamic work efforts is well supported in many areas of organization science literature. Sensemaking theory is one example. The importance of several active and adaptive organizational concepts such as improvisation, flexibility, updating, and continual input to keep what has been obtained within the organization are repeated in several papers as noted in reference [32]. In another study of the management of high-risk systems, researchers found that due to the dynamic nature of complex engineered systems, reliability in the engineered system "is not the outcome of organizational invariance, but, quite the contrary, results from a continuous management of fluctuations both in job performance and in overall departmental interaction. It is the containment of these fluctuations, rather than their elimination, that promotes overall reliability."[36] However, systems engineering and many other processes in most current LaCES efforts are more hierarchical and procedural, which suggests why the more flexible, dynamic, and unpredictable nature of interdisciplinary interactions may be in conflict with the prevailing culture.

Another key characteristic of LaCES that likely contributes to perceived "messiness" is the often-unknown number of technical interdependencies or couplings within the engineered system that fosters many unknown parameters in associated interdisciplinary interactions. Although the vast majority of these couplings are well understood, tested, and documented, comprehensive awareness and understanding of all interactions within the system is not feasible for larger complex engineered systems. Correspondingly, exhaustive understanding of all facets of the system is beyond the comprehension of any one individual or small team. Rather, exhaustive understanding of the system is held by the collective knowledge of the organization as a whole, and not by a group of senior leaders. This collective organizational knowledge is both explicit (and usually documented), as well as tacit (and thus transmitted through informal and undocumented means, if at all). This collective aspect of LaCES engineering effort is also conceptualized in an organizational theory called "collective mind," where cognitive processes of a group that must heedfully work together to achieve a solution are studied.[37] The literature notes that there is a "transindividual quality of collective mind. Portions of the envisaged system are known to all, but all of it is known to none."[37]

The sense of personal discomfort with interdisciplinary interactions appears laced through many of the responses related to confusion, conflict, communication challenges, career impacts, negative emotions, additional time and effort, and addressing organizational and individual culture. In particular, the most commonly reference topic of the entire survey (communication) may indicate challenges associated with ambiguity or confusion and lack of understanding due to the existence of "multiple and conflicting interpretations" of the information at hand.[38] Social science literature notes that challenges of ambiguity are best addressed with increasingly interpersonal communication whereas challenges of uncertainty (more commonly discussed in engineering) may be addressed with less interpersonal and more numeric input.[38] This appears to correlate with the large number of survey responses related to personal and organizational interrelations. Dense interrelations are also discussed in the theory of collective mind noted earlier where there is "…little room for heroic, autonomous individuals. A well-developed organization mind, capable of reliable performance is thoroughly social. It is built of ongoing interrelating and dense interrelations. Thus, interpersonal skills are not a luxury in high-reliability systems. They are a necessity."[37] Further, "narrative skills (Bruner, 1986; Weick and Browning, 1986; Orr, 1990) are important for collective mind because stories organize know-how, tacit knowledge, nuance, sequence, multiple causation, means-end relations, and consequences into a memorable plot."[37] Hence, the ability to relay engineering information via story telling may play an important role in communicating across LaCES.

6. Implications

Based on these findings, the perceived high importance and benefits of interdisciplinary interactions in developing large-scale systems is evident. However, given the challenges of implementation, the next questions may be: *When* are they important, *to what extent*, and, *how* do we implement them and address the challenges noted? Common approaches today in LaCES organizations seem to focus on improving software tools and simulation models and adding or revising oversight, requirements, or documentation. Notwithstanding, these findings resoundingly suggest alternative and augmentative approaches that address the social and organizational challenges noted. The significant obstacles in implementation mentioned suggest that the path toward enabling interdisciplinary interactions is challenging and deeply multi-faceted with no quick fixes. Communication barriers must be addressed, confusion reduced, timelines and tasks reconsidered, office locations connected, cultures altered, incentives recast, emotions heard, organizational structures adapted, and leadership rethought.

Questions remain as to which of these organizational aspects (or others) offer the most benefit for a particular system R&D and design effort. The findings suggest communication, interrelations, and disorderliness are principal concerns, the latter one possibly resolved by addressing the former two. Addressing these concerns may also mitigate other issues noted such as extra time required, culture, and, emotional responses. Some noted aspects of interdisciplinary interactions must be addressed by organizational leaders such as: incentives, organizational structure, and increased awareness that benefits of these interactions may be intangible and long term.

In sum, if interdiscipline interactions are driven by a need to communicate effectively and interrelate as suggested by the findings and best practices in sensemaking and other social science literature, then there are several important implications for engineering practice:

- *Ambiguity* should be addressed in addition to uncertainty;
- *Tacit knowledge* should be considered in addition to explicit knowledge;
- *Knowledge should be constructed socially and collectively* in addition to constructing system models numerically and additively;
- *Building social capital* in addition to building intellectual capital;
- *Organizationally implementing interdisciplinary approaches* in addition to mathematically implementing multidisciplinary approaches;
- *Improved sensemaking should be considered* in addition to improved decision making;
- *Adaptive and improvisational processes and organizational structures should be incorporated* in addition to standard operating procedures and static structures; and
- *Narrative and story-telling skills are needed* in addition to documentation skills.

This view also suggests that, in some sense, an interdependent R&D organization necessarily must function more like a symphony (or a living organism) of many diverse but *intertwined, interdependent* parts − rather than an assembly line (or mosaic) of diverse but *joined, independent* parts. The former functionality is the hallmark of a complex system where the system is not reducible to the sum of its parts; however, the latter one offers more individual sovereignty, which appears to be preferred in some arenas.

It is also important to note that “interrelations are not given but are constructed and reconstructed continually by individuals through ongoing activities.”[37] Thus, addressing some of the implications noted previously will require individuals (not just added processes) who are regularly engaged in making interdisciplinary interactions work by reducing confusion, translating terminology, facilitating knowledge transfer and collective learning, building relationships, enabling interactive activities, and crafting welcoming local cultures. High-level managers or team leaders with other significant day-to-day operational responsibilities may accomplish this to a degree. However those “closer to the ground” may more aptly or efficiently be able to address these challenges more frequently.

For example, a dedicated “interface dynamics engineer” whose day-to-day responsibilities are to address the communication and interrelation challenges noted in the findings may be effective for larger organizations. This role would be quite distinct from merely serving as a human analog to the interface control documents used in SE. Rather, the interface dynamics engineers necessarily would be trained and skilled in addressing the engineering *and social science* aspects noted in the survey. In a sense, the interface dynamics engineer would have the capabilities of the “T-shaped” people noted in reference [39]. However, a more applicable description may be a “π-shaped” person who has depth and breadth in engineering and social science. These π-shaped interface dynamics engineers would not eliminate the need for individuals who have critical depth of knowledge in single disciplines nor do they eliminate critical functions such as MDO and SE. Rather π-shaped interface dynamics engineers may be augmentative and used to interrelate and “weave” together, rather than “glue” together, deep knowledge bases and organizational functions. This will likely involve proactively and continually creating and facilitating dynamic and iterative communication pathways and building positive relationships where necessary -- likely in a non-hierarchical, horizontal manner across organizational partitions and including all levels in the organization as needed. Other literature refers to organizational roles with some of the related skills, such as: 1) the “connectors, mavens, and salesmen” described by Gladwell;[40] 2) the “energizers” described in POS literature by Baker;[41, 42] and 3) the highly desired “deep generalists” described by McMasters.[43, 44]

7. Conclusion

This paper provided analysis of current perspectives of the challenges and opportunities in enabling interdisciplinary interactions in LaCES R&D using a qualitative research methodology based on ethnographic and survey data. Our preliminary analysis indicates that interdisciplinary interactions might be highly valued and perceived benefits included cognitive and system benefits. Perceived implementation challenges focused on organizational and human dynamics such as communication difficulties and other aspects of human-to-human interrelations. These challenges present opportunities for improvements where social science considerations may be more proactively designed into engineering practice including the addition of more socio-technically trained engineering professionals.

Fundamentally, this analysis indicates that enabling interdisciplinary interactions in LaCES R&D warrants an interdisciplinary approach (combining engineering and social science) that augments traditional multidisciplinary and systems engineering approaches to address the integration of people and their complex ideas and knowledge, as well as the critical integration accomplished through computer models and interface documents. Socio-technical awareness during R&D of LaCES may ultimately foster greater efficiencies in the design and development of LaCES and improved system performance by assisting with the collective integration of interdependent knowledge bases early in the systems engineering effort.

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