INTERNATIONAL DESIGN CONFERENCE - DESIGN 2016
Dubrovnik - Croatia, May 16 - 19, 2016.

POSITION PAPER: DESIGNING COMPLEX SYSTEMS TO SUPPORT INTERDISCIPLINARY COGNITIVE WORK

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Keywords: [this will be inserted automatically]

1. Introduction: Interdisciplinary Interactions in LaCES

Designing, building, and managing Large-Scale Complex Engineered Systems (LaCES), such as modern global automobiles, nuclear power stations, or aerospace vehicles requires contributions from thousands of experts across numerous technical disciplines, often working over many years and with considerable geographical dispersion. Further complicating the design task, comprehensive knowledge of these systems is not accessible to any single designer, discipline, manager or subsystem expert. Systems-level and subsystems-level information is distributed among experts within each domain of expertise, and intensive interdisciplinary cognitive work is required to successfully transmit, receive, process, and integrate this information into a cohesive design. The systems engineering discipline aims to address this situation, but there is increasing recognition that systems engineering must be more deeply informed by knowledge residing in traditionally non-engineering fields [Griffin 2010].

Successful design of LaCES depends largely on the effectiveness of the interactions among these different discipline experts. Ignoring the contributions of even one discipline or component can have a significant effect on system design and performance with negative impact on cost and project scheduling. The study of interactions among system elements has been widely studied in systems engineering and systems design optimization, most notably in the multidisciplinary design and optimization (MDO) literature, with concepts and tools such as design structure matrices [Steward 1981, Eppinger 2012], global sensitivity equations [Sobieszczanski-Sobieski 1990, Hajela et al. 1990], coupling metrics [Alyaqout et al. 2011, Kannan, Bloebaum, and Mesmer 2014] and partitioning and coordination methods for decomposition-based design optimization [Lasdon 1970, Allison 2008]. The MDO methods are typically applicable after the embodiment design phase is completed or for a particular concept under consideration. Furthermore, they focus only on physics-based functionality of the system and thus consider only physics-based interactions among elements of the system.

However, it has been documented that, especially in early project phases where conceptual design is being firmed up, non-engineering factors are likely to be most influential on system design [Griffin 2010, Cumming 2002, De Weck et al. 2011, Berteau et al. 2009, McGowan, 2014].The “designer” of a LaCES is actually a diverse, dispersed team of researchers, and the “complex engineered system” is actually a complex cognitive work system, comprised of individuals, the artefacts with which they interact, and the relationships between these components in a work context [Lin, Chaboyer, and Wallis 2013, Hutchins 1995, Le Bot 2004]. Complex engineered systems are not typically characterized in this way, although this framework has been successfully applied in the analysis of other complex work systems [Perry & John 2003].

Studying the nature of complex engineered systems and the interactions that support them from the perspective of the social and behavioral sciences is still a nascent area of inquiry. However, many frameworks, methodologies, and tools exist in these fields that might be useful in understanding and addressing engineering problems. In particular, cognitive science and the theory of distributed cognition may be helpful in understanding the interpersonal challenges of LaCES design. This approach describes complex organizational work using three principles: cognitive processes are distributed among individual members of a group; individuals are required to interact in a meaningful context; and individuals interact with artefacts and tools in their environment in order to collaborate [Lin, Chaboyer, and Wallis 2013, Hollan et al. 2000].Insights such as this one, from cognitive science, human factors, and psychology/sociology, could augment contemporary technology-focused systems engineering methods, especially when applied to systems "distributed" over technical disciplines, large spans of time, and great geographical distances.

Thus, the purpose of this paper is to demonstrate the need for understanding complex engineered systems as complex cognitive work systems, in order to broaden LaCES design methodologies to support cognitive work.The paper provides a review of cognitive factors pertinent to complex systems design, focusing specifically on challenges posed by interdisciplinary work.

Insights from engineering practice and cognitive science inform how individual cognitive habits influence interdisciplinary interactions in LaCES, i.e., how the thinking skills each engineer "brings to the table" might shape the collaborative work. An additional goal of this work is to understand if strategies targeting the individual level can be useful in improving the effectiveness of interdisciplinary collaboration, and, if so, whether an organizational structure can be utilized as a mechanism for implementing these interventions. Madhavan et al. [1998] write that "the individual brings to the situation his or her repertoire of skills, knowledge, and strategies, which affect and are affected by the situation." This individual "repertoire of skills" and its consequences constitute the topic of inquiry. How are these skills and strategies developed? What is the situational effect? How do these processes change when they are distributed within a work organization, and can organizational structure be leveraged to better support cognitive work in engineering design and practice [McGowan 2014]?

Preliminary work by the authors has examined rare and extensive empirical data on the interdisciplinary work practices and perspectives of experienced LaCES practitioners, and two meta-themes emerged. When asked to describe the potential benefits of interdisciplinary interactions, respondents identified both system improvements and cognitive improvements, the latter garnering more responses [McGowan 2014]. These two meta-themes appeared to be linked. The current work aims to strengthen this proposition by suggesting that some system-level improvements follow from cognitive improvements at the individual level, and that, some technical system breakdowns can be ascribed to cognitive interfacing failures between individuals Therefore, it is critical that we begin to reimagine LaCES as complex cognitive work environments, so that we may develop interface controls for managing knowledge and cognition embedded within these systems.

Understanding engineering and cognitive interdependencies allows for several major benefits during R&D and early design of LaCES, as identified in [McGowan 2014]:

1. System performance can be improved and development time and cost reduced through early mitigation of interface failures between knowledge bases.

2. Organizational insights can help determine where exactly in the system these failures are likely to occur and suggest appropriate levels for intervention or change.
3. Awareness of alternatives, interactions, and complicated relationships helps researchers develop a more complete knowledge of the problem space [Newell and Simon, 1982], and enables them to select the best technologies and components for a system.
4. Creativity and innovation flourish as thought diversifies, and more resilient systems are often the end result.

The cognitive science of interdisciplinary collaboration must be examined within the context of engineering practice. Understanding the interplay between cognitive and engineering factors can inform management, policy, or other organizational decisions in LaCES. While the current work is minimally descriptive and at this point offers only basic connections between engineering practice and concepts from cognitive science, future work will hopefully yield more prescriptive contributions for facilitating cognitive work in LaCES design.

The remainder of the paper is structured as follows. Section 2 introduces basic skills, processes, and concepts from cognitive science and describes each in the context of interdisciplinary collaboration. Section 3 explains how these processes are carried out at both the individual and group levels, and describes how these two levels interact in LaCES design. Section 4 examines the current industry approach to interdisciplinary work, and suggests that a new understanding of the cognitive factors involved might help advance these practices. Section 5 summarizes the current work and offers suggestions for future research directions.

2. The Cognitive Science of Interdisciplinary Collaboration

Despite likely limited knowledge of theories or concepts from social science, experienced LaCES practitioners have little trouble identifying cognitive barriers to successful interdisciplinary collaboration. For example, several respondents in the cited study [McGowan 2014] complained that “some members of their team had a contrasting mental model of engineered systems and how cross-disciplinary interactions should take place, straining their working efforts.” Additionally, words related to cognition appeared often in interview data collected in the study, with “thinking” and “knowing” emerging as the two most common action words used by respondents. “Cognitive gaps” between multidisciplinary researchers and single-discipline researchers were also identified as a significant source of frustration in interdisciplinary interactions [McGowan 2014].

Examining interdisciplinary interactions in LaCES using cognitive science theories and frameworks, such as the distributed cognition theory, should provide formal, rigorous descriptions of some of these issues and help uncover new strategies for managing them. As Klein writes, “even powerful software, physics-based methods, and proven techniques such as the Delphi method cannot guarantee successful synthesis. Integration is a human action” [Klein 2013]. Cognitive approaches, used in combination with physics-based approaches, would result in a more holistic methodology for systems engineering and would consider and mitigate against interface failure at both the technical and interpersonal level. The result would ideally be elegant, resilient systems.

Basic cognitive skills and processes required to do interdisciplinary work have been identified by Klein [2013]. These skills are “differentiating, comparing, contrasting, relating, clarifying, reconciling, and synthesizing.” Mutual learning must also occur, which involves:

> “[the ability] to recognize one’s ignorance of a particular area, [and] solicit and gather appropriate information and knowledge. The task at hand requires analyzing the adequacy, relevancy, and adaptability of discrete pieces or elements. In the process, depth of disciplinary/professional

> contributions is balanced with breadth of perspective. Iteration enables clarification and presentation of results for mutual revision [Klein 1990, 1996, 2013].”

According to White [1975], this type of activity was best enjoyed by “divergent thinkers;” Mead [1977] suggested that “analogic thinkers” were better suited to perform integrative tasks. A constant theme persists through the literature, despite these differences in terminology: The first step to successful interdisciplinary collaboration is to understand how an individual’s cognitive skillset enables or impedes him/her from processing information generated by the collective. The study of cognitive biases is a familiar example of this relationship. The notion of cognitive biases has been explored across a variety of tasks and research fields, and these biases have been shown to affect processes such as inference, categorization, assessment, and comparison in numerous contexts [Caverni, Fabre and Gonzalez 1990]. Many similar descriptions exist in the literature, illustrating the substantial influence of individual cognitive constructs on interdisciplinary group processes [Journett 1993, Krauss and Fussell 1990, 1991, Clark and Brennan 1991, Stasser 1992]. However, little work has been done to date to understand how these biases manifest in large-scale design tasks, or how knowledge of these biases could inform the design of resilient systems.

3. Individual and Group Cognition in LaCES Design

Broadly speaking, understanding the relation between specialization and collaboration is itself a study of individual cognition as it is situated within the collective. As described in previous sections, LaCES design is an integrative, interdisciplinary process. It requires ongoing triangulation of depth, breadth, and synthesis [Klein 2013]. Klein writes,

> “Breadth connotes a comprehensive approach that draws on multiple variables and perspectives. Depth connotes competence in pertinent disciplinary, professional, and interdisciplinary approaches. Synthesis connotes creation of an interdisciplinary outcome through integrative actions.”

To successfully achieve this goal, core cognitive processes are executed using multiple types of knowledge: Retrospection, decision making, and judgment are contingent upon knowledge from intuition and insight, data, experience, and other sources of information. These steps are iterative, and processes/information sources that are commonly ascribed to individuals are also aptly ascribed at the group level [O’Donnell and Derry, 2013]. Examples include problem representation and problem solving; intake/processing/retrieval of information; coordination of tasks; and creativity [O’Donnell and Derry, 2013]. These individual processes are deeply embedded in the group social structures in which they occur.

Individual level and system level properties intersect at (a) the group’s task, and (b) the individual’s interpretation of the task; thus, limitations on an individual’s cognitive system can constrain the efficacy of the group [Ben-Bassat, and Taylor, 1982]. Research has demonstrated the selective nature of information intake and retrieval [Anderson and Pichert 1978, Donald 1987, Frey, 1986], and schema-relevant biases often dictate what information is received by various members of a group, which could have serious implications for safety-critical systems.

In order for an interdisciplinary collaboration to be successful, individual group members must understand broader group goals, adequately represent the problem under discussion, and devise and select strategies for achieving these goals. Effective task performance “requires the optimal cognitive, affective, metacognitive, and social skills be available in the group [O’Donnell and Dansereau 1992].” Social psychologists, sociologists, and other social scientists have developed an extensive research base on small-group problem solving over the last few decades [Dillenbourg 1999, Paulus 1989], although again, limited work has been done to address the issue of scaling from small groups to large engineering organizations.

Regardless, a meta-analysis of this literature would be worthwhile to determine how to achieve these so-called "optimal" cognitive and metacognitive capabilities in LaCES design tasks, while the scaling issue is a good topic for future inquiry. The nature of a task can determine whether social, affective processes rule interdisciplinary interaction, or whether cognitive and metacognitive interchanges do [O'Donnell and Derry, 2013]; deeper understanding of these mechanisms would likely have significant implications on of the development of system design tasks.

4. Facilitating Interdisciplinary Collaboration: Challenges and Solutions

Understanding the relevant factors at work is the first step required in order to utilize insights from cognitive science to improve the design of complex systems. Perhaps the most onerous challenge in interdisciplinary collaboration is overcoming the "ethnocentrism of disciplines [Campbell 2013, Sherif and Sherif 1969]" that often exists within engineering organizations. This term refers to "tribalism or ingroup partisanship in the internal and external relations of university departments, national scientific organizations, and academic disciplines [Campbell 2013]." Ethnocentrism of disciplines is problematic because it obstructs the development of a comprehensive multiscience to use in interdisciplinary interactions: Ideally, narrow specialties would overlap with other narrow specialties in a continuous texture, but what happens in practice as a result of this ethnocentrism is an erection of similar yet separated specialties and the creation of interdisciplinary gaps.

These gaps have been traditionally managed by LaCES designers by training scholars in the two (or more) overlapping disciplines; in industry practice this has been the goal of multifunctional teams comprising single function (discipline) specialists. Instead, a better approach might be to encourage narrow *specialization in interdisciplinarity*. To clarify, the distinction between training "multidisciplinary scholars" and "interdisciplinary specialists" is powerful, and is posited as particularly relevant to the goal of facilitating interdisciplinary collaboration in LaCES design. While the former training often results in simple "lowest common denominator breadth," the latter training might allow for more effective organization of specialties [Campbell 2013].

Several challenges remain. How do we define and develop the role of an "interdisciplinary specialist" in engineering design? How can we equip engineering workforces with the integrative skills and cognitive capacity for "systems thinking" required to design and manage LaCES? More fundamentally, how can we introduce subject matter experts to a potentially radical new concept such as interdisciplinarity?

Interdisciplinary leaders have been referred to as "ringmasters, gatekeepers, boundary agents, ombudsmen, polymaths, dynamos, [and] metascientists," among various other titles [Klein 2013]. Perhaps the most appropriate descriptor in the context of LaCES is Anbar's idea of the "bridge scientist [1973]." The bridge scientist is responsible for moving beyond multidisciplinary translation of a problem to interdisciplinary integration [Klein 2013]. Although the need for this role has been confirmed by interview data from LaCES practitioners, with the "translator" concept consistently appearing in both theory and practice [McGowan 2014, Klein 2013, Anbar 1973], little formal work has been dedicated to understanding how to identify, train, or use such personnel.

Cognitive approaches such as Feuerstein's Mediated Learning Experience (MLE) may offer a useful perspective for understanding and developing the role of the translator in complex systems design [Feuerstein, Falik and Feuerstein 2014, Kozulin and Presseisen 1995]. In mediated learning, competent peers place themselves between the environment and the learner with the goal of bringing subconscious information processing into conscious awareness. The mediator selects, changes, amplifies, and interprets objects and processes for the learner, with the goal of creating disequilibrium: a state of confusion or dissonance when new information does not integrate within existing schemas. This confusion motivates individuals to restore balance by updating schemas to incorporate previously inaccessible —or interdisciplinary— information [Kozulin and Presseisen 1995]. These types of cognitive interventions, while not yet empirically validated, seem to provide basic foundational frameworks for the development of this role in large-scale, complex engineered systems.

5. Conclusions and Next Steps

The paper argues that the field we can call cognitive science of interdisciplinary collaboration is an important area of study for improving design of LaCES and supporting cognitive work. The paper mostly raised questions that have been documented in earlier qualitative analysis studies, and provided possible avenues of exploration for addressing them. There are likely further contributions from additional disciplines beyond those mentioned in this paper that should be considered and integrated into such a cognitive science framework.

Knowledge and awareness of various perspectives will help to inform the types of interventions available for improving LaCES design and functionality. For example, a cognitive interpretation of interdisciplinary collaborations in LaCES elucidated the need for a “translator” or “mediator” in helping subject matter experts to transcend language boundaries, mitigate single discipline bias, support integrative activities, and correct misaligned objectives. Additional research in this direction is likely to uncover similar gaps and opportunities for improvements in practice.

In summary, R&D and early conceptual design of complex engineered systems depends on successful interdisciplinary interactions between large, distributed groups of researchers. Uncovering the conditions and methods required to facilitate these interactions using methods and knolwdge from the behavioral and social sciences is a research challenge in improving LaCES design.

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