

A FRAMEWORK OF WORKING ACROSS DISCIPLINES IN EARLY DESIGN AND R&D OF LARGE COMPLEX ENGINEERED SYSTEMS

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Abstract

This paper examines four primary methods of working across disciplines during R&D and early design of large-scale complex engineered systems such as aerospace systems. A conceptualized framework, called the Combining System Elements framework, is presented to delineate several aspects of cross-discipline and system integration practice. The framework is derived from a theoretical and empirical analysis of current work practices in actual operational settings and is informed by theories from organization science and engineering. The explanatory framework may be used by teams to clarify assumptions and associated work practices, which may reduce ambiguity in understanding diverse approaches to early systems research, development and design. The framework also highlights that very different engineering results may be obtained depending on work practices, even when the goals for the engineered system are the same.

Keywords: Collaborative design, Early design phases, Teamwork, Human behaviour in design, Concurrent engineering (CE)

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1 INTRODUCTION

Fundamental to researching and designing engineered systems is system integration and working across technical disciplines. Engineering integration spawns significant polarities: failures and innovation, system fragility and system enhancement, team confusion and new insight, organizational turf battles and lasting amity. This research seeks to improve work practices at system integration points and ultimately improve system design by providing a detailed understanding of work practices at the earliest stage of integration – during research and development (R&D) and early design. We focus specifically on early stage cross-disciplinary, human-to-human interactive work practices of groups working on Large-Scale Complex Engineered Systems (LaCES) such as aircraft and submarines where hundreds or thousands of engineers and scientists are engaged from large, dispersed organizations. While there is extensive literature on examining cross-disciplinary practice in a variety of settings (e.g., academia, small businesses) for an array of different purposes (e.g., learning, product design), the literature on cross-disciplinary practice for LaCES is focused on Multidisciplinary Design Optimization (MDO) and toward the later stages of development such as systems engineering.¹⁻¹¹

In this research we sought not to make common assumptions on the approach engineers take toward working across disciplines in developing LaCES such as assuming: the integration followed a prescribed hierarchical path; the integration focused on connecting mathematical models and hardware; or that MDO or organizational leaders would address much of the needs of early cross-discipline work. Rather, we contribute to the literature via a theoretical and extensive empirical analysis examining current work practices in actual operational settings where LaCES are researched and designed, allowing the findings to emerge from real work practices. We asked: What are current practices and perspectives on interdisciplinary interactions during R&D and early conceptual design of LaCES and why might these prevail and persist?¹²

In this paper we summarize our findings on the four most common methods of interacting across disciplines and we derive an explanatory framework hereafter called the Combining Systems Elements (CSE) framework. Teams and organizations may use the framework to improve clarity regarding many aspects of the research and early system integration and design process. As mentioned, the context for this study was large, dispersed organizations creating very large, complex engineered systems. While the findings are not generalizable, they are transferrable to many contexts where multiple elements are being combined to create an engineered system. This paper begins with background on the framework and how best to use it, followed by an overview of the research methodology. The remainder of the document is dedicated to a detailed description of the framework. The synthesized findings include several examples from the empirical data obtained.

2 BACKGROUND AND USE OF THE COMBINING SYSTEM ELEMENTS FRAMEWORK

Several aspects of the CSE framework are presented in this section to enable the best interpretation of the data and most effective use of the framework. The framework was derived from a theoretical and empirical analysis of the data obtained and is not exhaustive. The CSE framework is descriptive rather than prescriptive: providing deep descriptions of the related engineering and organizational practices to enable a clearer understanding of work practices. As an explanatory, sensemaking framework it does not suggest best practice but rather clarifies existing practice; hence, the framework describes practices and perspectives that overlap as well as interact. The different categories of combining system elements are presented separately and contrasted for analytic clarity and convenience rather than as an ontological separation. The concurrent nature of the practices should be continually borne in mind. The findings represent the most predominant constructs that emerged from the data gathered and are not exhaustive of all work practices.

The constructs are delineated as *Connection*, *Coordination*, *Collaboration*, and *Collective*. The following terminology is used in the discussion: *System* refers to the focus of the integration effort whether it is at a macro level (an aircraft), or at a micro level (a technology), or something less tangible (a network). *Element* refers to what is being integrated into the system whether it is physical hardware (wings, metal beams), or software (mathematical models, computer programs), or the (less tangible) capabilities an individual brings to a cross-discipline team such as disciplinary knowledge, expertise, ideas, creativity, training, and culture. In all cases, the aforementioned different types of elements represent aspects that may be combined into a system.

The CSE framework may be used in a variety of different respects though predominantly it can improve clarity and reduce confusion, the latter being a common complaint of the respondents in this work. The variable and equivocal nature of cross-discipline work can create confusion via misunderstandings and misinterpretations^{1, 3, 13} resulting in inefficiencies and potential errors in the R&D and design of the system, ultimately impacting final system performance. Further, though system integration and team cross-disciplinary interactions are very common in developing large systems in engineering, there is considerable equivocality and variation in terminology, leadership, information sharing, risk, creativity, system and organizational constraints, etc. As a platform for team discussion, the framework can aid in communicating expectations and delineating organizational practices. Similarly, as a sensemaking tool, it may help organizations and teams make sense of their existing processes and potential outcomes.

3 RESEARCH METHODOLOGY

An interdisciplinary perspective informed by engineering practice and theories from organization science and psychology was adopted in the research. We examined the interdependence of the engineering disciplines and the associated non-hierarchical interactive practices between researchers focusing on human-to-human interactions rather than between mathematical models as in traditional Multi-Disciplinary Optimization (MDO). The research design consisted of a three-fold, integrative approach that combined survey, interview, and ethnographic research using a descriptive analysis approach that “attempts to understand cognitive work practices from the perspective of the subject, in the contexts where the subjects find meaning” rather than in a simulated research laboratory environment.¹⁴ The three different research methods were used to help examine different facets of the problem domain. However, the ultimate approach for this study was synthesis of the different data to enable an integrated, rigorous, and comprehensive analysis. A detailed description of the research methodology is provided in references 12 and 15.

The multi-method approach chosen used three methods. 1) Open-ended surveys to identify current perspectives¹⁶ on interdisciplinary interactions by sampling a diverse group of 62 leaders that spanned industry, government, and academia. They provided a unique assessment of current thinking and took place prior to the interviews, which also guided our interview design and analysis. The survey focused on obtaining short, written answers to seven open-ended questions such as: “*Please describe things that encourage interdisciplinary interactions*” and “*Please describe the obstacles to interdisciplinary interaction.*” 2) Semi-structured interviews to provide detailed, concrete examples of practices.¹⁷ The interview data allowed us to obtain detailed, concrete examples of cross-disciplinary practices through the purposeful participant recruitment of 20 practitioners with diverse experiences and responsibilities in aerospace R&D and conceptual design. The 20 respondents were carefully chosen to provide a balanced sample considering years of experience, job site locations, leadership and staff positions, and diversity of engineering tasks. The interviews offered comparative data “for understanding the world from the view of those studied” and helped to “unfold the meaning of their experiences.”^{17, 18} Example questions asked during these interviews included: “*I’m interested in hearing about an experience you had in working with someone outside of (their home area of work). Tell me about it.*” “*Can you describe what challenges you faced?*” “*I’d like to hear about what you gained from the experience?*” 3) Insider ethnography to provide a rich, descriptive account of cultural and organizational work life.¹⁹⁻²⁵ 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 and design entities. 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.”²⁰

3.1 Integrative Data Analysis Approach: From Codes to Synthesized Analysis

Data analysis 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).²⁶ Data analysis was also inductive, guided by constant comparison methods, in which themes were identified, continuously compared to newly emergent themes, and revised based on the comparison.²⁶ Data from all research methods were integrated and re-coded as new findings emerged and the research design was adjusted accordingly.²⁷ While a highly inductive data analysis

approach guided the findings, to prevent assiduous theory avoidance, this work has theoretical underpinnings in several genres of literature including organizational science, cross-disciplinary studies, psychology, and complex systems.^{18, 28-37}

The three research methods were integrated into an analytical approach that included first-order analysis of data from each method by itself followed by second-order analysis that integrated data and provisional findings from multiple methods to create updated findings. Then, a comprehensive synthesis incorporated relevant theories and created theoretical conceptualizations grounded in the empirical data and backed with theory. The synthesized analysis of the study data was driven by exploring patterns, processes, and relationships and sought to illuminate the actual engineering and scientific practices and perspectives on interdisciplinary interactions. Except where noted, the findings herein are a second-order synthesis of all of the codes, themes, and meta-themes from all data. Triangulation was an essential aspect of the research design.

To echo what is well documented in qualitative research theory literature, we note that a quantitative frame for analysis of the data is an inappropriate frame given the sample size and research methodology used. 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.

3.2 Synthesized Findings from all Three Methods

As noted earlier, data from all three research methods were integrated to create the synthesized findings presented below. The unit of analysis of this study is a group level of analysis. Though specific individuals served as respondents for the survey and interview portion of this research (62 from the open-ended surveys and 20 for the semi-structured interviews), their data were integrated with scores of respondents who provided input for the ethnographic portion of this research. The synthesized findings represent a triangulated analysis based on input from all sources of data.

4 DIFFERENTIATING CROSS-DISCIPLINE PRACTICE

Figure 1 provides as a graphical depiction of the four methods. A description of each method follows with an overview of the method, followed by examples and then a brief discussion of each.

4.1 Connecting

Connecting is a multidisciplinary effort to join separately developed elements and their respective individual disciplines. In this scenario, the researchers that develop the different elements work largely independent from one another until the last stages of their research. This effort is multidisciplinary in the sense that information between the different elements is exchanged yet individual disciplinary methods and theoretical concepts are not questioned or modified but rather updated with additional information such as operating or boundary conditions.³ The elements of the system are largely modular. The researchers do not interact significantly during R&D and early design though they may provide R&D results and other information to a lead integrator separately with little detailed awareness of or knowledge integration with other disciplines.

Example systems that primarily consist of *connecting* elements are computer assembly; updating existing systems with new technologies; substituting different technologies in a baseline system model to determine the change in the system's performance; and, more conceptually, a jigsaw puzzle or mosaic. One team leader with 25 years experience described a *connected* system as a "patchwork quilt." Another team leader with similar experience described a weak connection between disciplines as: "I don't see there being any connection between—a lot of the disciplines don't have much

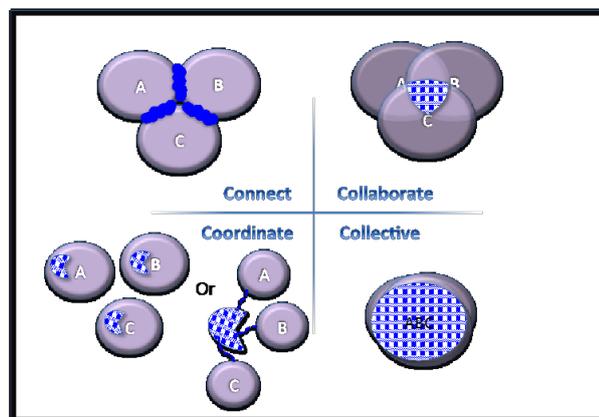


Figure 1. Graphical Depiction of the Combining System Elements Framework

connection between themselves, ...the [A] group doesn't really have to work with the [B] and [C] group or the [D] group, except for maybe saying, 'Okay, here's the boundary conditions of the [end] of my [element] to go into the [their element].' They don't have to do much interaction." As portrayed in this quote, the researchers in a *connected* system exchange information creating a multidisciplinary system but they do not conduct R&D interactively nor integrate their knowledge and adjust their understandings, methodologies, or theories in an interdisciplinary sense.

Connecting offers the least social and organizational effort since the elements need not interact until near the very end of their development. Thus, what may be considered as "program management overhead costs" may be small. Perceived (but not necessarily actual) system development risk is lower since the elements are known and defined. Traditional stepwise program management processes are easier to implement, as the elements and the system are known or are well defined. However, the lower cost and lower risk perception must be compared with a significantly decreased opportunity for creativity as compared with the other methods. Many who worked in a *connected* manner described more turf battles and myopic thinking than resulted from the other methods of interacting.

4.2 Coordinating

In *Coordinated* systems the elements are users of a networked system, such as a transportation system or Wi-Fi system or a power bus. Elements may or may not interact yet the developers and operators of the *coordinated* system must work interactively with the different elements to clarify user needs and changes. In many cases, the performance of a *coordinated* system may be improved if the users (elements) work together, however, this is not always an option. Hence, there is more of a multidisciplinary effort between the elements; however, the system developers' efforts are highly interdisciplinary and, depending on the creativity of the developers, their efforts may be trans-disciplinary.

Examples of systems primarily using efforts of *coordinating* are: hardware, software, testing platforms, etc., that are shared by many users; a laboratory or field center where many similar or disparate engineers work; or, more conceptually, a family vacation. Some project or team leaders or line managers oversee their project, team or line in a *coordinated* sense by managing several different tasks that all share a common topic area and resources (computers, offices, office staff, funding source) but the tasks are being conducted largely independently. One researcher who specializes in multidisciplinary optimization replied that: "*we do integrate from different disciplines into our model, but we do not require them to integrate.*"

Further, a system that has been developed via *coordination* is best considered to be "current" more so than "completed" as the system is often continuously being updated or transformed as users and user needs change. The development process is thus less stepwise and defined. Here, success of the system may not be the system's ability to address the current needs, but instead, success may be best measured as the system's adaptability to address changing needs, the latter being more challenging to quantitatively measure a priori and requiring larger upfront costs. For management, the constantly evolving, higher upfront costs for developing more adaptable systems, and the unknowable future state of a *coordinated* system create challenges in some traditional processes that are better suited for systems with known system states.

4.3 Collaborating

The interactive merger of different concepts and ideas creates *collaborated* systems. Here teams work together to adjust partially-developed elements to enable the elements to work cohesively together. The elements are much less modular and much more interdependent than in a *connected* system.

An example *collaborated* system is a physically-integrated system that contains two distinct but interwoven sub-systems such as a landing gear and a wing where the landing gear folds inside the wing. In this scenario, the R&D and early design teams for the landing gear and the wing may work separately for a portion of the development period (multidisciplinary effort) but the sub-system interdependence requires interactive work practices (interdisciplinary effort) much earlier than for a *connected* system. Another example of a *collaborated* system is merging and changing the capabilities of two software packages to create a new integrated software package with enhanced capabilities. Conceptually, a collaborated system may be envisioned as a tapestry or a composite.

For example, describing the start of a *collaborative* effort, a line manager with 25 years experience replies: "*Group A you're working on this, group B you're working on this. We're starting to see from*

the system studies and everything else, it seems like we could actually get the [system performance] that we're looking for if we kind of integrate the technologies that you all are bringing your respective technologies to the table together, and look at something, an integrated approach rather than just two separate approaches."

Collaborating presents greater social and organizational challenges than *connecting* and *coordinating* and is best understood as the work of an Integrated Product Team (IPT). Logistically, as teams become larger and geographic dispersion grows, the organizational overhead of enabling *collaboration* can become significant. The system design is not as constrained by contributing elements as in the *connected* system; however, this also means that defining a detailed system design requires more time.

4.4 Collective

The work of a *collective* is a highly concentrated collaboration where interaction among engineers begins early in R&D and design and team members may co-locate for extended periods to facilitate the needed interactions. *Collective* interdisciplinary interactions involve different disciplines striving to achieve a common goal (a new system or innovation) not by focusing on integrating existing technologies as is more common in *connecting* and *collaborating*, but by proactively exploiting and fusing diversity of thought that is resident in the team members. The resulting co-creation of knowledge further enhances the diversity of thought as team members re-think their incoming assumptions. *Collective* efforts are inherently interdisciplinary and often trans-disciplinary – the resulting need for significant face-to-face time makes *collective* action challenging for highly dispersed teams. In a sense, *collective* R&D and early design is designing while researching and developing. The knowledge and experience generated from single disciplinary research and other experiences are the elements integrated into the system more so than existing hardware and software. Conceptually, *collective* action may be envisioned as creating a homogeneous alloy that gains from the various capabilities of different metals.

An experienced team leader from a single discipline group who is responsible for a highly cross-disciplinary team describes the benefits of working *collectively*: “So, you got the ‘gotta-haves’ and the ‘want-to-haves’ and the ‘it-would-be-nice-but’. Oftentimes, if you don’t understand the system you don’t understand the something that may be on that ‘it-would-be-nice-but’ can cause a revolutionary change if you can make one of those ‘it-would-be-nice-but’s into a ‘gotta-have’. ... They didn’t know that we could [do] things [in] other ways. Nobody had asked them, ‘What if you could [do] this some other way? How would you do it?’ They said, ‘Never been asked that.’ So, then they started looking under these rocks and all of a sudden they’re going: ‘Oh my gosh! There’s this whole field that we found that’s never been plowed that has some rich possibilities, very great capabilities.’ ... [Meetings are] much more dynamic. There’s a lot more interrelationships, a lot more talking back and forth and the different people in the room that are representing different disciplines are asking questions.”

Cross-disciplinary interactions that are *collective* in nature require the most interaction between disciplines. A diversity of literature addresses the theoretical basis of collective constructs and inspired the use of the term here.³⁸⁻⁴³ One exemplar that provides insights on collective interactions across disciplines is Weick’s research on “collective mind” in sensemaking theory, which describes some of the aspects of “interrelating” that are essential for developing a system collectively.^{41,42} The research on collective mind considers the cognitive processes of a group that must heedfully work together to achieve a solution. It is also important to note that collective mind (in *collective* interdisciplinary teams) can occur in underdeveloped groups provided the interrelations between group members are done heedfully. Heedful interactions may be described as: are more or less purposeful, attentive, “tied together by trust,” and are interactions where mutual respect is valued over agreement, diversity of thought and experience are embraced while coordination of action is emphasized.⁴¹ In collective mind, teams focus on “interrelating their know-how” which improves comprehension of a system.⁴¹ Madhavan and Grover also highlight the opportunities for knowledge creation: “frequent interaction among team members can contribute to the building of strong ties between them (Krackhardt 1992), which further facilitates the use and creation of knowledge within the team.”⁴³ Much of the knowledge is held tacitly or collectively, making interpersonal relations more important while simultaneously making explicitly sharing information more difficult.

All of the conceptualizations above (*connection*, *coordination*, *collaboration*, and *collective*) may embody some aspects of collective mind; however, the inconsistency and less mindful nature of interrelations in *connection* and *coordination* efforts reduce the opportunities for collective action

considerably, for collective mind is built on a well-developed mutually shared field of the heedful interrelating which is tightly coupled, but the tight coupling is social rather than technical – though most engineers focus more on the latter.⁴¹

5 DISCUSSION

Table 1 provides a comparative summary of the salient characteristics of the four methods. In all cases, the capability of the final system often transcends the sum total of the original elements/inputs. The different methods highlight several important aspects of early system development. Most importantly, the engineered system resulting from the different methods may be quite different even though the design goal and associated system requirements are the same. The system is ultimately a function of its desired performance characteristics as well as the manner in which it is developed.¹² Hence, differences in the organizational, social, and cognitive aspects can lead to unplanned variations in the engineered system. These differences include proximity of the work group; the nature of social connections in the organization; cognitive challenges placed on the participants; and differing unspoken assumptions regarding integration. Though infrequently clarified early in team formulation, these assumptions influence the mental models and work practices of the dispersed teams.

For example, each of the methods has differences in engineering aspects such as: expectations about the inclusion of previously developed engineering concepts (which also may have career implications for participants); level of specificity needed upfront regarding the final system; and the frequency and depth of team interactions. These differences were often not clarified in practice, as most respondents to this study were not fully cognizant of the differences themselves. Nearly all respondents appeared to have clarity on the engineering goal of their interactions with other disciplines yet lacked clarity on the different methods by which to do so and were not clear which method was expected of them. Most respondents expressed some frustration as they described their efforts in trying to accomplish one method of interacting while others with whom they were interacting had different expectations. Further, despite the different needs and constraints of each method, some upper management evaluated the output of each of these four methods with the same lens. For example both *collaborative* and *collective* efforts become greatly strained as teams become larger and more dispersed. Correspondingly, regardless of the goal, respondents tended toward more *connected* or *coordinated* action as team size grew or as team members became more geographically dispersed.

Commonly used system integration terminology is also a source of equivocality in combining system elements and creates confusion in the organization. For example, the terms interface, interaction, interdependency, and decomposition are used extensively in describing the relationships between elements in an engineered system. While the academic definitions of these and other system integration terms were clear to nearly all the respondents, the variations in their approach were not clear among most in the organization and the resulting variations in assumptions and perspectives have widespread impacts on engineering practice.

One example is the term *interface*. Literally meaning “the common boundary between two bodies,”⁴⁴ the term *interface* is used to describe the place of connection between two or more elements in a system. Interface specifics have been used for decades as a way of communicating system integration details; as such they provide a common way for engineers and scientists to make sense of an integrated system. For highly modular systems, interfaces are appropriate, and modularity is an essential element in the design of many systems.⁴⁵ However, clear interfaces between some system elements (and hence disciplines) do not exist for some large engineered systems. Further, attempts to create clear interfaces to simplify practice may result in setting up the R&D and early design effort in a manner that does not lead to the integrated system performance desired.

For example, interfaces are most critical in a system integrated by *connection* because the system may be described as a combination of modular elements. Interface has less meaning in a system integrated by *collaboration* because the elements were designed to integrate more cohesively and distinct interfaces begin to blur. To an even greater extent, the term interface may have little meaning in a system integrated by a *collective*, as boundaries between elements can be abstruse. The term interface has many meanings in a *coordinated* system as elements of the system may or may not interact yet they share a common system. And, the ambiguous nature of interfaces in a *coordinated* system, such as a transportation system, makes interface documentation, required in some organizations, a less useful process.

Table 1. Comparative Summary of Principal Characteristics of the Methods in the Combining System Elements Framework (Source: A. R. McGowan)

	Connecting	Coordinating	Collaborating	Collective
Synopsis	Connecting separately developed elements into a system	Integrating user needs to create a common or shared artifact. This multi-user artifact is the system.	Creating a heterogeneous combination using aspects of different elements	Creating a homogeneous mixture or solution from different elements.
System description	System is a combination of different joined elements	System is dynamic and evolves as elements (user needs) change.	System is a combination of different integrated elements. The original elements have been partially modified during the integration.	System is a collective (or somewhat of a fusion) of diverse elements.
Element description	Elements used to develop the system are generally tangible articles or components of physical or cyber hardware, software, mathematical models, etc.	Elements of the system are diverse user needs.	Elements used to develop the system may be physical or cyber objects, as well as personal experience, knowledge bases, etc.	Elements used to develop the system include a wide diversity of constructs, from tangible hardware to personal experience, knowledge, and culture.
Nature of the combination of elements	Individual elements are physically connected but distinct, with little (relative to element size) modification to facilitate connection.	Elements of the system (user needs) are inherently dynamic and sometimes irrational. User needs (elements) may or may not be altered due to interaction with the system.	Individual elements are partially merged and/or physically integrated to create the overall system or solution, yet the individual elements remain somewhat distinct in the system.	Individual elements are fused together, becoming irreducibly intertwined to create a new system where the original individual elements may or may not be distinctly apparent in the created homogeneous system. Contributions of the individual elements to the system are not necessarily clearly separable after forming the <i>collective</i> .
Integration summary	Task of joining and assembly.	Task of organizing, negotiating, and sharing information and resources.	Task of converging aspects of different elements (concepts, knowledge bases, etc.) to arrive at an integrated solution.	Task of co-creating a new capability or knowledge bases, etc. by drawing upon different knowledge bases (expertise, or capability, etc.) in order to conceive of a new system or to address a problem. The new system (or problem solution) is a homogeneous collective of a diversity of elements/inputs (the diversity of which was essential).
Primary focus during integration	Attention directed to the interface where the elements connect, and toward the interactions at the interface.	Attention directed to clarifying user preferences and negotiating a common ground between users.	Attention directed to interactions between elements in the integrated solution. The concept of "the interface" between elements loses significance as the integrated solution requires iteration and some modification of the elements.	Attention directed toward incorporating, fusing, and embodying different wisdom, inspiration, tacit knowledge, assumptions, experience, etc.
Nature of the interaction of the researchers, developers, or designers.	During R&D and early design of the elements, infrequent interaction between element researchers, developers, and designers generally occurs and is likely not needed. Technology maturation of each element occurs primarily within a domain area. Significant interaction is required for connecting the elements after they reach a specified state of maturity. Interaction is mostly convergent in nature.	Elements of the system may or may not interact. However, the system researchers and developers interact continuously with elements beginning early in R&D and early design. While the users may or may not physically connect or interact, the system developer interacts with different users of the system. Interaction between system and elements is convergent and divergent and interactions must begin at a very early stage in system development.	A greater level of tacit knowledge sharing is generally required compared to <i>connecting</i> , thus participants that 'own' the different elements of the system must interact in physical proximity for some portions of system development. Interaction between disciplines is very high once the elements reach a specified state of maturity. However, as the integration is a merger of different elements, requiring potentially significant changes to each element, interactions begin earlier in R&D and design than for a <i>connected</i> system. Interactions between disciplines are mostly convergent with occasional divergent discussions.	Highly divergent and convergent interactions. Divergent as the team interacts to create aspects of a new system. Convergent as they determine how to develop the final system. Emergence of a new system (or solution to a problem) with new capabilities, not previously envisioned, often occurs. Interactions require working together frequently with the highest levels of tacit knowledge sharing. Interactions between disciplines begin early in R&D and design.
Cross Disciplinarity	More of a multidisciplinary effort	More of a multidisciplinary effort between the elements; however, the system developer's effort is highly interdisciplinary and, depending on individual creativity and opportunity, it may be trans-disciplinary.	<i>Collaboration</i> typically begins with a multidisciplinary effort but often ends with an interdisciplinary effort.	Inherently interdisciplinary with frequent trans-disciplinary results

6 SUMMARY

This research focused on conducting a theoretical and empirical analysis of current work practices in actual operational settings at the earliest stages of system integration (R&D and early design) for very large engineered systems such as aircraft. For systems of this size and complexity, comprehensive knowledge of the system is dispersed among specialists whose expertise is often in one system component or discipline. The variety of methods and equivocality of terminology in combining elements to create a system often create confusion on engineering teams. A sensemaking, explanatory framework was derived that may aid engineering teams in clarifying their integration and cross discipline assumptions and processes. The Combining Systems Elements framework was presented as a means of delineating several constructs of working across different disciplines in R&D and early design of large engineered systems. The four methods of combining system elements were conceptualized as *Connection*, *Coordination*, *Collaboration*, and *Collective*. In all cases, the practices and perspectives are distinct but not fully separable, for they overlap and interact. Contrastive analyses were used to enhance clarity with the expectation that understanding of existing practices can offer a foundation for future improvements to design practice. An important finding is that each method may produce significant differences in the final engineered system even when the original system requirements or objectives are the same.

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