

The Role of Cognitive Systems Engineering in the Systems Engineering Design Process

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ABSTRACT

The article is intended to aid students and consumers of Cognitive Systems Engineering (CSE) in learning about CSE. A proliferation of terms describing CSE and related constructs makes it difficult to sort out differences and similarities across approaches. To aid the reader in exploring CSE, we examine areas of confusion surrounding CSE, define CSE, and discuss the role of CSE in the systems engineering design process. We advocate the use of CSE principles and methods as a means to incorporate worker needs, expertise, cognitive demands, constraints, and goals throughout the design process. Articulation of the value case for CSE is offered as a vehicle to foster collaboration across disciplines. © 2009 Wiley Periodicals, Inc. Syst Eng

Key words: cognitive systems engineering; systems engineering lifecycle; design

1. INTRODUCTION

The growth of cognitively complex systems has motivated researchers and practitioners from diverse traditions to study how to improve these systems' support of human work. Such studies have led to the development and evolution of Cognitive Systems Engineering (CSE) over the last 25 years. Methods and terms to describe CSE have proliferated [Eggleston and Whitaker, 2002] to the point where it is a challenge to keep up with the evolving field of work. This article is intended to provide a guide for consumers and students of CSE. (For a related but much briefer guide, please see the April 2009 issue of INSIGHT in which an earlier and much condensed version of this paper was published [Militello et al., 2009].) Towards this end, we explore areas of confusion

surrounding CSE, define CSE, and explore the role of CSE in the systems engineering design process.

CSE has grown out of a need to design systems within which people can interact effectively. For example, information technologies should help people make sense of situations and make better decisions. Experience tells us that effective sense-making and decision support systems cannot be designed by an engineer's intuition alone. The design of information technologies should be informed by knowledge of how people think and act in the context of their work environment. Clearly, information technology design teams must be knowledgeable about computer software and hardware, but if the technologies fail to support cognitive functions, they will be rejected in the workplace and marketplace.

It is possible to design information technologies without bringing in CSE specialists. Many have done so. The design team simply ignores the cognitive requirements for the systems they are specifying, and directs its energy towards meeting the physical specifications. In other cases the design team makes assumptions about cognitive requirements, extrapolating their experience to anticipate the needs of the workers.

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Occasionally their assumptions are correct. We tend to hear about the cases where their assumptions were dramatically wrong [i.e., Perrow, 1999].

The field of CSE has been crystallizing around a few key strategies or frameworks such as cognitive work analysis [Rasmussen, Petjersen, and Goodstein, 1994; Vicente, 1999], decision-centered design [Hutton, Miller, and Thordsen, 2003], situation awareness-oriented design [Endsley, Bolté, and Jones, 2003], work-centered design [Eggleston, 2003], and applied cognitive work analysis [Elm et al., 2003]. Although these five frameworks have grown out of different research traditions and applied domains, each has been influential in guiding the evolution of CSE theory and practice. (For a thorough discussion of the historical evolution and modern perspectives, see Hoffman and Militello [2008].)

- Cognitive Work Analysis is a framework that emerged in response to demands for safer nuclear power plant control rooms following the partial core meltdown of the Three-Mile Island power plant in 1979. Rasmussen et al. [Rasmussen, Petjersen, and Goodstein, 1994] advocated a formative approach in which work and its functional structure are examined in order to identify the constraints within which workers must operate. Cognitive Work Analysis has become widely influential and is now used for analysis of large-scale socio-technical systems in Japan and Australia, as well as in Europe and North America.
- The Decision-Centered Design framework evolved from research conducted following the 1988 accidental shoot down of an Iranian Airbus by the USS Vincennes. This tragic incident resulted in the death of 290 passengers on Iran Air Flight 655; it prompted the US Navy to fund a program of research named Tactical Decision Making Under Stress (TADMUS) to better understand how such an incident had occurred and how to avoid similar incidents in the future [Cannon-Bowers and Salas, 1998]. In this context, researchers developed and refined Cognitive Task Analysis (CTA) interview techniques aimed at identifying the key decisions and other cognitive requirements that would guide the design of displays and training [Kaempf et al., 1996], particularly in time-pressured, high-risk domains.
- Situation Awareness-Oriented Design [Endsley, Bolté, and Jones, 2003] has grown out of situation awareness research, which originated in the aviation domain. The concept has been traced back to WWI fighter pilots who described the pilot's need to observe the opponent's current move and anticipate the opponent's next move a fraction of a second before the opponent could observe and anticipate one's own [Spick, 1988]. In the mid 1980s the need for tools and training to support situation awareness increased significantly as advances in cockpit automation brought increased potential for information overload. In response to this need, Endsley and her colleagues conducted a series of research projects aimed at defining and measuring situation awareness that would allow for more informative testing and evaluating of new technologies under consideration for advanced aircraft and other complex systems.

- Work-Centered Design is a framework that emerged out of concern with the development of stove-piped technologies within large military socio-technical systems. In observations conducted at the US Air Force's Air Mobility Command, researchers noted multiple databases, collaborative systems, and decision support systems, each of which used different interface design conventions. This lack of a unifying structure resulted in unneeded complexity and increased likelihood of error as users were required to maintain expertise not only in the content area of the job (i.e., flight and mission planning) but also in how to use a broad range of technological interfaces. In response to this concern, Eggleston, Roth, and Scott [2003] developed a framework for a design process that leverages methods and strategies from other frameworks to identify the intrinsic elements of work, which are then used to drive design.
- Applied Cognitive Work Analysis was developed by Elm and his colleagues with a focus on designing innovative and effective decision support systems [Elm et al., 2003]. They perceived a requirement to extend Cognitive Work Analysis products to be more directly integrated with design. In response to challenges faced by the CSE community when working within the systems engineering process, Elm et al. [2003] articulated steps and corresponding artifacts to transform the cognitive demands of a complex work domain into graphical elements of an interface.

1.1. Areas of Confusion Surrounding CSE

Hoffman and his colleagues [Hoffman et al., 2002] thoroughly capture the chaos created by the proliferation of labels used to describe often very similar approaches emerging from different communities, using the term "acronym soup" [Hoffman et al., 2002: 73]. At a foundational level, Hoffman et al. claim that CSE approaches have similar goals (i.e., design tools to support human work), share a systems stance, focus on the analysis of cognitive processes, and even use similar methods. In spite of these commonalities, however, it remains difficult to uncover how similar (or not) the different approaches are, and to identify the primary differences. Many book chapters, journal articles, conference presentations, and workshops have been generated describing individual approaches and detailing underlying theory, methods, and case studies. Yet, confusion remains. We suggest several reasons for this confusion.

Approaches for studying cognition are at different levels. Some, such as cognitive work analysis, are high-level frameworks for design and do not emphasize the details of methodology. Some, such as cognitive task analysis, are lower-level methods tailored to study cognition, identify cognitive requirements, or uncover cognitive complexity (i.e., Critical Decision Method [Crandall, Klein, and Hoffman, 2006]). Others are knowledge representation or work modeling methods intended to aid in mapping patterns or constraints (i.e., the abstraction-decomposition matrix [Rasmussen, Petjersen, and Goodstein, 1994; Vicente, 1999]). Some are techniques

for modeling cognitive aspects of tasks (i.e., COGNET [Ryder et al., 1998]). Still others are design principles or admissions about how to design good systems (i.e., *Laws that Govern Cognitive Work* [Woods, 2006]). Unfortunately, the categories are not disjoint. It can be hard to distinguish a framework versus a method versus a modeling technique versus a set of design principles.

Approaches have come from different traditions with different emphases. Some, such as Decision-Centered Design, began by trying to understand how experts perform difficult cognitive tasks to inform training. Some, such as Cognitive Work Analysis, motivated by the discovery that cognitive complexity increases risk, began by trying to design safer sociotechnical systems. Some approaches are oriented around developing models; others are aimed at discovery. The resulting frameworks, methods, and modeling techniques often use similar terminology to describe their work but in fact have somewhat different approaches.

Descriptions of approaches are typically pedagogical rather than accurate. In order to communicate how CSE occurs and where it adds value, the design process is often oversimplified as a sequential, stepwise process. In fact, design rarely occurs this way, in part due to pragmatic constraints. Real world issues such as access to information, resources, and experts force project teams to work in a somewhat opportunistic and generally iterative manner. We doubt that the sequential, stepwise design process is even a desirable goal. Instead, design should be considered a dialog wherein opportunism and iteration is beneficial. While a stepwise process adds value and efficiency when solving familiar problems, design problems by their very nature are generally not familiar, but require fresh perspectives and innovation. Novel problems require exploration and discovery—processes that are stubbornly incompatible with approaches that rely solely on rigorous and systematic methods. Thus we find that descriptions of design do not align well with reality, which makes it difficult to articulate how CSE contributes to design and where it fits in the process.

In this paper, we define CSE and then address each of the areas of confusion in more detail. This article presents three ways to make Cognitive System Engineering less confusing and more accessible. The first of these is a definition that communicates the intent and practice of CSE (Section 2). This definition serves as a communication tool and a jumping off point for additional consideration of what CSE is and what CSE is not. The second contribution is delivered in the form of a concept map that interrelates computational modeling approaches, analysis methods, principles of good practice, and frameworks (Section 3). Although these different categories are interrelated, simply naming the categories and providing examples is an important step toward substantive discussion of similarities and differences in approaches. Meaningful comparisons can be made only if we understand the dimensions upon which approaches are being compared.

The third contribution involves a reexamination of the design process (Sections 4 and 5). This depiction of design as dialog increases the visibility of CSE for designing systems to support cognitive functions. In the final section of this

paper, we discuss challenges that remain for integrating CSE into the systems engineering design process (Section 6).

2. DEFINING COGNITIVE SYSTEMS ENGINEERING

Defining CSE is difficult as the term encompasses a range of approaches, traditions, and methods. Further, CSE has been applied to a variety of problems and domains. As a result, different practitioners may emphasize different aspects of CSE, making a succinct, yet meaningful definition elusive. However, without a definition, useful debate and discussion become increasingly difficult. Klein, Deal, and Wiggins [2008] take up this difficult task defining CSE as "... the effort to support the cognitive requirements of work." For the sake of clarity, we have chosen to expand on this definition to include other defining attributes of CSE.

CSE is an approach to the design of technology, training, and processes intended to manage cognitive complexity in sociotechnical systems.

In this context, the term "cognitive complexity" refers to activities such as identifying, judging, attending, perceiving, remembering, reasoning, deciding, problem solving, and planning [Klein et al, 2003]. These activities rarely reside in one individual, but instead often happen in the context of teams, as well as within human-technology interactions. This distributed and large-scale collaboration between humans and interaction with technology has been referred to as a sociotechnical system, highlighting the notion that the humans, the technologies, and the larger system are highly interdependent and are linked by human social processes of collaboration and shared goals. The aim of CSE is not to eliminate cognitive requirements, but to reduce complexity and support activities such as deciding, problem solving, and planning.

This definition is consistent with the characteristics of CSE initially articulated by Woods and Roth [1988] in their seminal chapter characterizing CSE. They characterize CSE as focusing on "human behavior in complex worlds." They go on to describe CSE as "ecological," addressing the "contents or semantics of a domain," and aimed at "changing behavior/performance in that world." As described by Woods and Roth [1988: 5–7]: "Cognitive engineering must be able to address systems with multiple cognitive agents." Cognitive engineering applies to "joint human-machine cognition" and it is "problem-driven, tool constrained."

As CSE methods and frameworks have evolved over the last 20 years, this list of characteristics remains relevant. CSE continues to be applied to complex real-world problems with the goal of improving cognitive work. This is accomplished via a number of mechanisms. Within the design process, CSE contributes to design products such as information representation, conceptual models, use cases, design concepts/wireframes, relationships, goals, and information flow.

However, a description of design products or artifacts does not adequately capture CSE contributions. CSE involves empirical inquiry to better understand how people think in a specific context. CSE does not impose a formal normative

theory of how people think (or “should” think). Instead, the study of each work domain involves a process of discovery, wherein errors are considered interesting openings for further inquiry. Errors can often be traced to misleading information technology, contradictory processes, or competing goals. CSE methods have been developed to guide this process of discovery so that the specific challenges of a work domain can be captured and addressed throughout the design process. CSE contributions to design products and artifacts can aid the design team in developing solutions and making tradeoffs that take into account the full complexity of the joint cognitive system. In the words of Hollnagel and Woods [2005, p. 24], “In a single term, the agenda of CSE is how can we design joint cognitive systems so they can effectively control the situations where they have to function.”

CSE may be considered a specialization within human factors and ergonomics. (In fact, some CSE practitioners describe their work as cognitive ergonomics.) CSE provides input to many aspects of joint cognitive systems including virtual reality, robotics, role allocation, and others.

3. MAPPING THE LANDSCAPE OF CSE

At a very general level, there is potential confusion about other terms that might be used to designate this discipline, such as Cognitive Engineering, Cognitive Task Analysis, Human Systems Integration, and Decision-Based Design. Some describe Cognitive Engineering as an early approach that focused primarily on the one human–one computer dyad, while CSE focuses on teams of humans interacting within a larger work context. In practice, however, the two terms are often used interchangeably. Cognitive Task Analysis is a set of methods for describing cognitive requirements of work and should not be viewed as a CSE design strategy (although it is an important component of a CSE design strategy). Human Systems Integration is a more general term used commonly in military settings to cover a range of issues in addition to CSE, including human factors engineering, manpower, personnel, training, health, system safety, medical factors, survivability and habitability. Decision-Based Design (not to be confused with Decision-Centered Design, which will be discussed later) has been promoted by the National Science Foundation in pursuit of establishing a science base for engineering design theory and methods. To our knowledge, CSE approaches have had few connections to Decision-Based Design. We anticipate, however, that a CSE perspective may provide valuable input to engineering design theory and Decision-Based Design.

Shifting to a more specific focus on labels used to describe elements of and approaches to CSE, we offer a concept map as a means to chart the various terms (Fig. 1). In the concept map, we distinguish between frameworks describing various CSE approaches, terms used to describe methods, techniques used to model cognition, and principles of good practice intended to guide CSE applications. Examination of the five frameworks listed in the map provides insight into the philosophies that drive CSE and the mechanisms by which CSE is achieved. Each of these draws from different theoretic and applied traditions [see Hoffman and Militello, 2008].

A broad range of methods are used in pursuit of CSE. In this map, we offer a few examples, highlighting that some methods focus primarily on knowledge elicitation [Cooke, 1994], others on knowledge representation [Militello, 2001], while others blend the two. Principles of good design represent a second category of approaches that focus on articulation of guidelines or rules of thumb to be used in design according to CSE principles. These principles tend to be relevant across frameworks. In fact, an important goal of these principles is to offer widely applicable maxims. While the examples in the concept map are clearly described as principles or laws, other more developed concepts might be included in this category, such as strategies for making automated systems team players [Christoffersen and Woods, 2002], for visual momentum [Woods, 1984], and resilience engineering [Woods and Hollnagel, 2006a]. A third category of elements found in the concept map is techniques for modeling tasks. Cognitive models of tasks are generally used to simulate human performance, thus allowing designers to predict the impact of various design options and configurations without conducting studies using actual workers.

This concept map implies that any method could be applied within any framework. While this is technically true, history tells us that the investigator’s theoretical stance, or originating community of practice, greatly influences the use of methods (for details, see Hoffman and Militello [2008]). In some cases, a set of methods is closely associated with a specific framework. For example, Decision-Centered Design began with a set of methods for cognitive task analysis (i.e., the Critical Decision Method and variants) that later evolved into a larger framework for design. It follows, therefore, that a practitioner of Decision-Centered Design is likely to use Critical Decision Method [Crandall, Klein, and Hoffman, 2006] interviews to uncover decision requirements, exploring the expert’s experience base for examples of tough decisions and the associated cues, strategies, goals, etc.

When the Critical Decision Method is used by practitioners operating within a different CSE framework, the method will be influenced by the practitioner’s theoretical stance. For example, when used in a Cognitive Work Analysis context, the Critical Decision Method might be used to uncover constraints or map decision processes in the form of recognition-action cycles in the work domain [e.g., Naikar, Moylan, and Pearce, 2006]. In this case, the investigator would still elicit incidents about challenging decisions, but would ask questions about and listen for intrinsic elements of the work domain rather than the expert decision process. A practitioner trained in the Cognitive Work Analysis tradition would most likely use the Critical Decision Method to populate the Abstraction-Decomposition Matrix or a Decision Ladder—representation techniques closely associated with Cognitive Work Analysis. (For an in-depth discussion of these representation techniques and how they can guide design, see Lintern [2009] and Vicente [1999].) The resulting representations would capture attributes of the domain at different levels of abstraction, rather than a first-person perspective of the challenges associated with work in the domain. However, this application of the Critical Decision Method is rare. In most cases, Cognitive Work Analysis practitioners would use

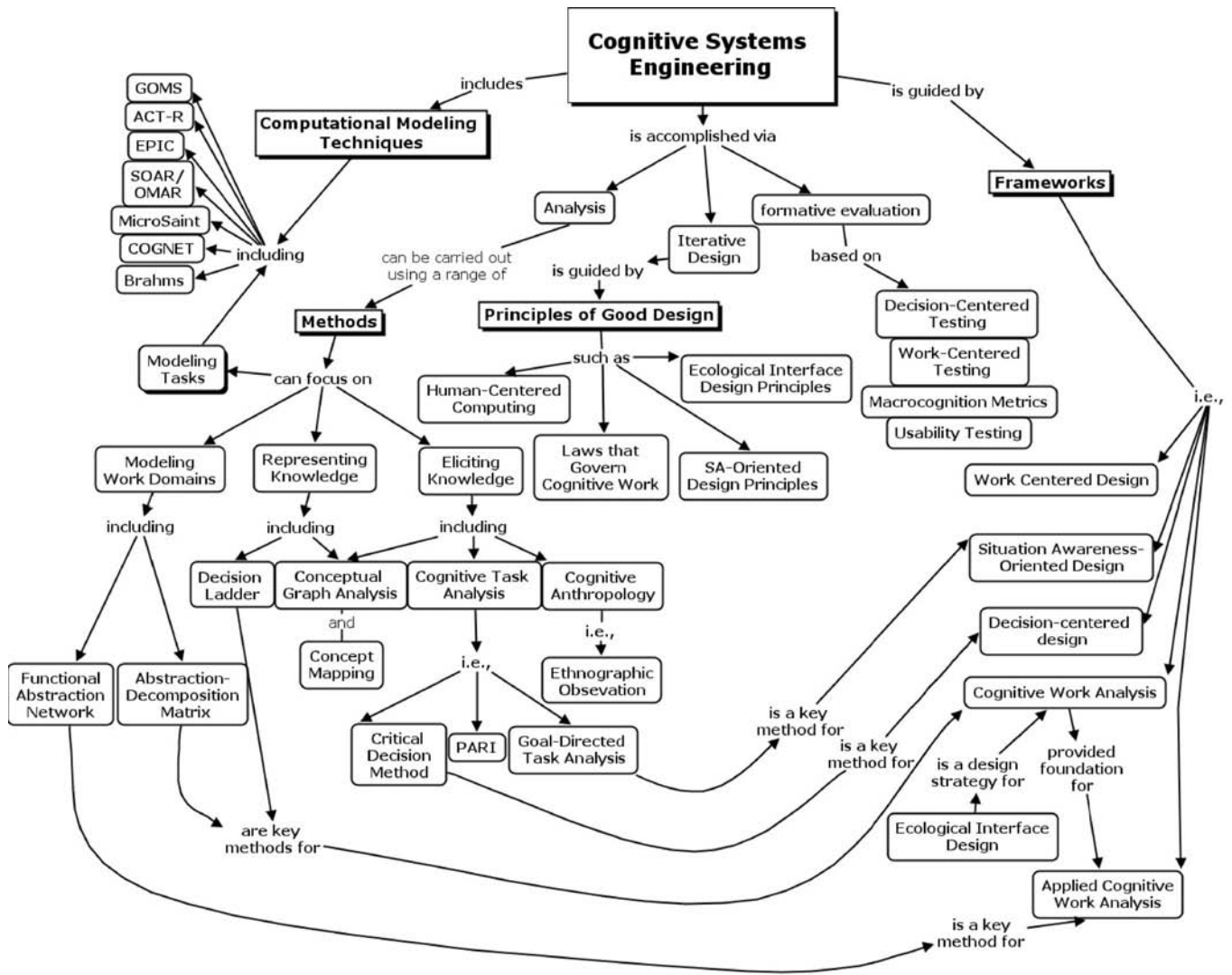


Figure 1. CSE terms can be grouped into methods, frameworks, techniques for modeling cognition, and principles of good practice.

document analysis and semi-structured interviews to populate these representations.

In some cases, the CSE framework is articulated with little emphasis placed on the methods to be used. Work-Centered Design, for example, began as a set of principles such as the *First-Person Perspective principle* suggesting that the worker’s terminology should be used as information elements in the interface display [Eggleston and Whitaker, 2002]. These and other principles evolved into a framework that is eclectic in adopting methods from different communities of practice. In all cases, the overarching theoretical framework dictates how methods are applied.

We have found the categories in this concept map to be useful in explaining and comparing different approaches. However, this is just one step toward reducing confusion. A discussion of how CSE contributes to system design is needed to further clarify the role of CSE.

4. CSE AND DESIGN

CSE focuses primarily on design issues that must be addressed in all systems such as information representation; salience of priority information; meaningful concepts, relationships, and goals; and information flow. This is in contrast to designers who develop deep expertise with the design of specific types of technologies or products (i.e., a website designer). CSE practitioners tend to apply more general CSE frameworks, methods, and principles to a broad range of complex systems.

We wish to place CSE within the larger context of systems design. However, no single agreed upon model of design within the engineering lifecycle exists. There is good reason for the many representations of the engineering lifecycle. Systems engineers participate in projects ranging from the design of very specific subcomponents to the design of large systems of systems. Different process models have been

developed in the context of different types of projects. Well-known models include waterfall, V-model, spiral, and concurrent engineering process models, as well as agile methods, V-model updates, and extensions of the spiral model (for a review of these models, see Pew and Mavor [2007]).

Recently, the National Research Council Committee on Human-System Design Support for Changing Technology [Pew and Mavor, 2007] undertook an effort to develop a comprehensive, integrated model of human systems integration within the engineering life cycle. The resulting Incremental Commitment Model was developed based on a comparison of alternative process models of the engineering life. This analysis specifically highlighted human factors considerations within the engineering life cycle. The resulting Incremental Commitment Model includes not only phases of the design process, but also stakeholder commitment review points (which correspond to the Department of Defense acquisition milestones), and strategies for assessing compatibility, feasibility, and risk based on engineering artifacts at each milestone.

While this brings us closer to our goal, we would like to more closely examine the role of CSE in Design. For this purpose, we have selected the process model accepted by consensus of Fellows of the International Council on Systems Engineering (INCOSE) (<http://www.incose.org/practice/fellowsconsensus.aspx>). The SIMILAR process (Fig. 2) described by Bahill and Gissing [1998] has provided a useful platform for discussion and evolution of ideas within the Systems Engineering community. For example, the commentary on this webpage suggests that the system engineering field needs to enrich its process by incorporation of additional elements, one being decision-based design [Friedman, 2006]. In this spirit, we would like to advance the discussion by exploring how CSE might fit within the SIMILAR model.

The “SIMILAR process” depicts a stepwise process with a series of iterative loops (Fig. 2). These steps are familiar to those who participate in design and clearly describe many key activities that take place during the design of complex systems. These include: *State the Problem*, *Investigate Alternatives*, *Model the System*, *Integrate*, *Launch the System*, *Assess Performance*, and *Re-evaluate*. Although the SIMILAR figure depicts these as sequential steps, the authors point out that the Systems Engineering Process is not sequential, but it is parallel and iterative. Furthermore, they note that there are many

variations to this process. This description of the Systems Engineering Process is just one of many that have been proposed. Some are bigger, some are smaller. But most are similar to this one.

CSE practitioners continually encounter issues with respect to integration with systems engineering processes and systems design. This is, in part, because this sort of pedagogical depiction of the design process implies that one ought to be able to point to one or more of the blocks in the model and describe how CSE will improve that part of the design process. In reality, the CSE contribution represents a shift in emphasis that will likely have benefit throughout the design process. The portions in which the CSE impact is most visible will vary depending on the design problem at hand.

Three diverse case studies are offered as illustrations of the types of impact CSE has had in the past. In each of these examples, CSE approaches contribute to the problem statement and problem reframing as more information becomes available. This foundational understanding of the problem will influence other steps of the SIMILAR process such as alternatives considered, which aspects of the system are modeled, the vision for integration, strategies for effective launch, and definition of meaningful assessment metrics.

4.1. CSE in Global Weather Management

A CSE success story described by Scott et al. [2005] takes place within the context of the US Air Force Air Mobility Command. Weather has an enormous influence over airlift missions. Missions often must be accelerated, delayed, or rerouted to avoid unfavorable weather conditions. Traditionally, airlift pilots have completed all their own flight planning. In 2001, however, as part of efforts to continually improve performance and efficiency, Air Mobility Command introduced the *flight manager* position at their control center. The flight manager is a virtual team member for airlift pilots, planning and managing flights, both preflight and en route. The flight manager works closely with weather forecasters to evaluate weather conditions at departure and arrival airfields, as well as along the planned route.

A team was hired to develop technology to support the new flight manager role. Guided by the work-centered design framework, researchers conducted three multiday site visits to interview and observe flight managers at work. These

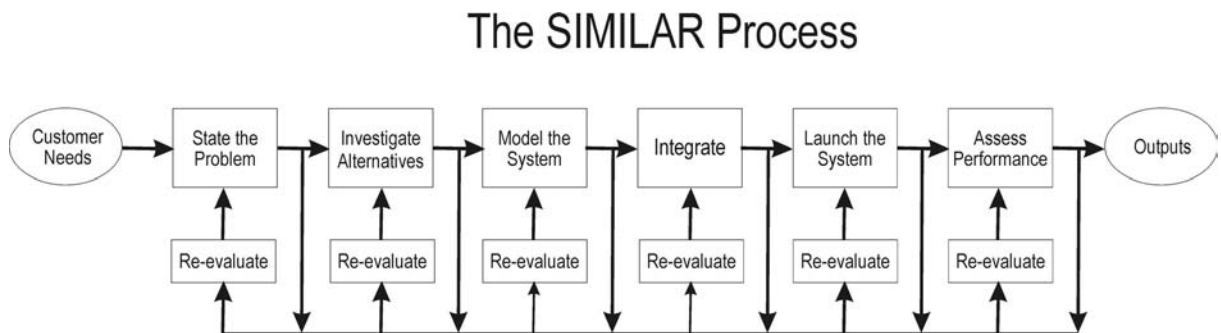


Figure 2. The SIMILAR design process. Reprinted with permission from A.T. Bahill and G. Gissing, Re-evaluating systems engineering concepts using systems thinking, IEEE Trans Syst Man Cybernet C Appl Rev 28(4) (1998), 516–527. © 1998, IEEE.

observations influenced the model of the system used for design (SIMILAR step 3), highlighting the importance of collaboration between flight managers and weather forecasters as they interpret near-term weather information and its potential impact on current and future missions. As a result, the research team focused on designing a technology that would serve as an information-sharing and collaboration tool for both flight managers and weather forecasters. The model of the work incorporated key cognitive challenges to be supported including:

- *Decision support* to aid in collating and integrating weather information from multiple, disparate sources
- Tools to support weather *product development*, such as updated and revised forecasts
- *Collaboration support* to aid the flight managers and weather forecasters in integrating weather and flight information
- *Work management support* to aid in monitoring weather conditions in multiple geographic regions, and in tracking individual missions—and in easily shifting back and forth among them.

The resulting Global Weather Management tool changed the way weather and flight information were integrated and displayed. A geographic display depicting both mission information and weather details was used, enabling effective information sharing between weather forecasters and flight managers. Intelligent agents were used to generate weather-related alerts that would appear at the appropriate geolocation on the map display. The map controls allowed for panning and zooming, as well as display of multiple layers of flight and weather information. Flight plans, satellite images, and other key information could be placed on the map. Observations could be filtered using an altitude slider. In addition, a floating window called the *sortie palette* listed all missions of interest and summarized individual mission status. Information in the sortie palette was sortable, and allowed for highlighting missions of interest. It was integrated with the map, so that an item highlighted in the sortie palette was also highlighted on the map.

The prototype version of the Global Weather Management tool was so well received that a fieldable version was immediately requested and soon available for use. As part of the initial launch (SIMILAR step 5), CSE researchers conducted follow-up observations. They examined workarounds and informal artifacts, and also monitored change requests submitted to the software design team. This analysis revealed that even in the short time since the prototype had been developed, certain aspects of the work itself had changed, including goals and priorities, scale of operations, the organizational structure, the complexity of problems, information sources and information systems, and the physical layout of the workspace. However, rather than simply refining the Global Weather Management tool to accommodate these changes, the researchers also began to look for design features that would allow end users to “finish the design” [Scott et al., 2005; Vicente, 1999] to meet changing work conditions. In addition, this assessment (SIMILAR step 6) provided input

to appropriate measures for system evaluation/reevaluation (SIMILAR step 7).

An evaluation of the Global Weather Management tool was conducted after it was fielded [Eggleston, Roth, and Scott, 2003]. Described as a work-centered product evaluation, the evaluation was guided by CSE principles. Researchers assessed the tool in terms of usability, usefulness, and impact. They found that participants understood and readily learned the major features of the Global Weather Management Tool, and that workers were generally successful in accomplishing scenario-based work. A rating scale was used to assess the impact of the tool on individual workers, the weather/flight management cell, and on larger organizational goals (from the perspective of senior management). On a scale of 1 to 5, in which 5 was the highest rating, the mean score was 4.58. In response to open-ended questions, participants reported improvements in terms of time savings, enhanced detection, and a better ability to handle hard cases.

4.2. CSE in Landmine Detection

A second example involves a project motivated by a desire to improve landmine detection [Staszewski, 2004; Cooke and Durso, 2007]. In this case, CSE shaped the statement of the problem and investigation of alternatives, as well as modeling of the system. Specifically, researchers determined that a model of the cognitive processes of operators with expertise in mine detection was most relevant for addressing this problem, and could be used to design innovative solutions in the form of improved training. CSE principles were also used to select appropriate measures of performance for assessment purposes.

Reports from actual incidents and controlled testing showed that US soldiers’ performance with standard issue mine detection equipment was substandard and that detection rates for low metal content mines were dangerously low. Staszewski [2004], a cognitive scientist with a background in expertise studies, noted that although performance was generally poor with the newer low metal content mine detection equipment, a few operators had detection rates over 90%. Armed with the knowledge that some had developed expertise using the new equipment, Staszewski hypothesized that improved training incorporating CSE principles could be used to close the performance gap.

Based on an analysis of expert strategies and processes, a model of expert perception and reasoning was developed (contributing to SIMILAR step 3) and used as a basis for improved training. Four general principles guided the design of training:

- Training content and organization were driven by the expert model.
- Detection rate was the primary measure of performance and learning.
- Instruction and tasks were organized hierarchically, using the expert’s goal structure.
- Instruction and training began with part-tasks and evolved into integrated subskills.
- Ample practice and feedback was provided for each drill.

This CSE-based training was used for both an existing demining device, and later on a second device still in development. In both cases, the training resulted in improved performance with probable detection rates of 94% for the existing device and 97–100% for the device under development.

A military board reviewed the training program developed in the first study and recommended its adoption. The training programs developed for both devices are now used to train soldiers for counter-mine operations in Afghanistan and Iraq. The US Army has adopted the policy of distributing this training program as an integrated package with the new mine-detection equipment.

4.3. CSE in the Redesign of an Emergency Operations Facility

A third example highlights the impact of CSE on the larger system, without focusing on an individual technology. Within this project involving the redesign of an emergency operations center in a nuclear power plant, CSE helped in stating the problem more accurately [Klinger and Klein, 1999; Cooke and Durso, 2007], which led to the investigation of a different set of alternatives that were integrated and incorporated into the launch of the new organization design. As a result, plant managers were able to implement a much simpler and more effective solution than anticipated.

The project was initiated by an adverse event at a nuclear power plant requiring an unplanned shutdown of the plant. As a result, the Nuclear Regulatory Commission prepared to require the plant to go from 1 to 2 formal drills per year, which would have cost the plant an additional millions of dollars.

The plant managers believed they knew the problems. During the adverse event workload had been extremely high. Therefore, they anticipated that additional information technologies combined with additional staff members could be introduced to reduce the workload and facilitate a more effective response to emergencies. However, this would not be straightforward as the facility was already crowded with the 80 members of the emergency response organization.

To implement solutions to these problems, the plant commissioned a CSE study. This study combined CTA activities such as Critical Decision Making interviews with observations of drills. These activities pointed to a different set of problems:

- The emergency response team had poorly defined roles and functions.
- Most of the key decision makers were not making any decisions at all, and some were irrelevant to emergency responses.
- The emergency director was a bottleneck.
- The layout of the Emergency Response Facility was inefficient.
- The staff size was too high, not too low.

Thus, referring to the first step of the SIMILAR model, one might say that the plant had an inadequate statement of the problem.

This reframing of the problem allowed for consideration of simpler solutions than previously anticipated. Rather than adding information technology and increasing staffing levels, positions within the facility were rearranged so that people were grouped by coordination requirements. A simple status board was established to improve situation awareness. Staff size was reduced from 80+ down to 35. Approximately 50 recommendations were made involving staff, facility, and procedures; none of them involved information technologies.

The recommendations were tested in the context of an official exercise, analogous to the launch phase in the SIMILAR process. The assessment by the plant managers and by the Nuclear Regulatory Commission was that the plant scored extremely well. They were taken off the watch list for conducting two drills a year, saving millions of dollars. Nevertheless, they continued to re-evaluate, revise and improve their responses, using 5–10-person table-top exercises that they added on their own initiative.

4.4. The Missing Link

The case studies summarized here illustrate important CSE contributions to real-world design projects. It is important to note, however, that each of these was carried out somewhat independently as a CSE project, led by CSE practitioners. In fact, this is how many CSE projects are accomplished today. CSE practitioners are often asked to explore challenging problems that have not been adequately addressed via more traditional means, and to accomplish this work separate from more traditional design activities. In the following section, we suggest that a shift in the way in which we characterize design may allow for better integration of CSE practices and principles into the systems engineering process.

5. DESIGN AS DIALOG

A key element common to CSE approaches and the SIMILAR steps—often missing from sequential depictions of a design process—is the constant reevaluation of our current understanding of the need or problem and how well we are addressing it. Anywhere in the process, as new information becomes available and the world changes, our understanding of the problem and/or the potential solutions may change. At any point, we may reframe the problem, consider a new solution, or discover potential repercussions not previously considered.

In more formal and extensive design projects, this constant reevaluation might even be considered the driver of all design activities. The design team continually works to calibrate design activities with an understanding of worker needs, customer needs, available technologies, limitations, tradeoffs, and priorities.

There is a continuous dialog throughout all of design as the team gathers more information about the world in which the eventual solution will be implemented. This evolving understanding sparks the generation of new ideas, the rejection of unsuitable schemes, and the refinement of promising design concepts. Communications and collaboration among design team members must be meaningful and frequent for this dialog to succeed.

We propose that CSE can be an integrating force at the center of this dialog. Whether or not CSE is done in development, issues such as how to support human cognition and work must be addressed for technologies to be useful, usable, and understandable [Woods and Hollnagel, 2006b]. CSE frameworks offer a perspective from which to view the environment in which the eventual solution will be implemented, taking into account worker needs, expertise, cognitive demands, constraints, goals, and key aspects of work that should be supported. CSE methods provide strategies for eliciting and representing these core constructs. The CSE community has also developed strategies and methods for gathering meaningful data during iterative evaluations [i.e., Johnston, Cannon-Bowers, and Smith-Jentsch, 1995; Long and Cox, 2007].

Although it is difficult to measure or quantify the importance of considering these core CSE constructs, many examples exist in which tradeoffs and priorities were assessed without CSE input to the dialog. Poorly designed technologies often emerge, many of which come and go without notice. Some, however, such as the highly publicized physician order entry system that was boycotted by the physicians at Cedars-Sinai in Los Angeles serve as a cautionary tale. In 2003, Cedars-Sinai Medical Center in Los Angeles rolled out a highly-anticipated, homegrown computerized physician-or-

der entry intended to reduce error and increase patient safety. After just a few days of use, however, doctors complained of problems ordering medications, test, and supplies and the hospital took the software offline [Ornstein, 2003]. The failed FBI TRILOGY system followed a similar trajectory [Eggen and Witte, 2006]. This system, however was rejected before it was ever launched. During testing, the FBI found software to be flawed and unfixable. They canceled the project in early 2005—after spending \$170 million on development. These failed systems are often very costly [Neville et al., 2007; Zachary et al., 2007]. Technologies designed without CSE input as part of the dialog are often rejected because they do not support expertise or aid workers in accomplishing important goals. By neglecting this part of the dialog, designers can easily fall into the trap of designing technologies or tools that hinder rather than support workers [Klein, 2004], resulting in automation surprises [Sarter, Woods, and Billings, 1997], and increased likelihood of error [Woods et al., 1994].

We have rearranged the elements of the SIMILAR process, making this dialog more explicit in Figure 3. The representational form of the wheel is offered as a departure from the limitations of the sequential flow representation. We think of design as a dialog in which design concepts are constantly reevaluated in light of the current understanding of the environment in which the technology will be used. It is a distrib-

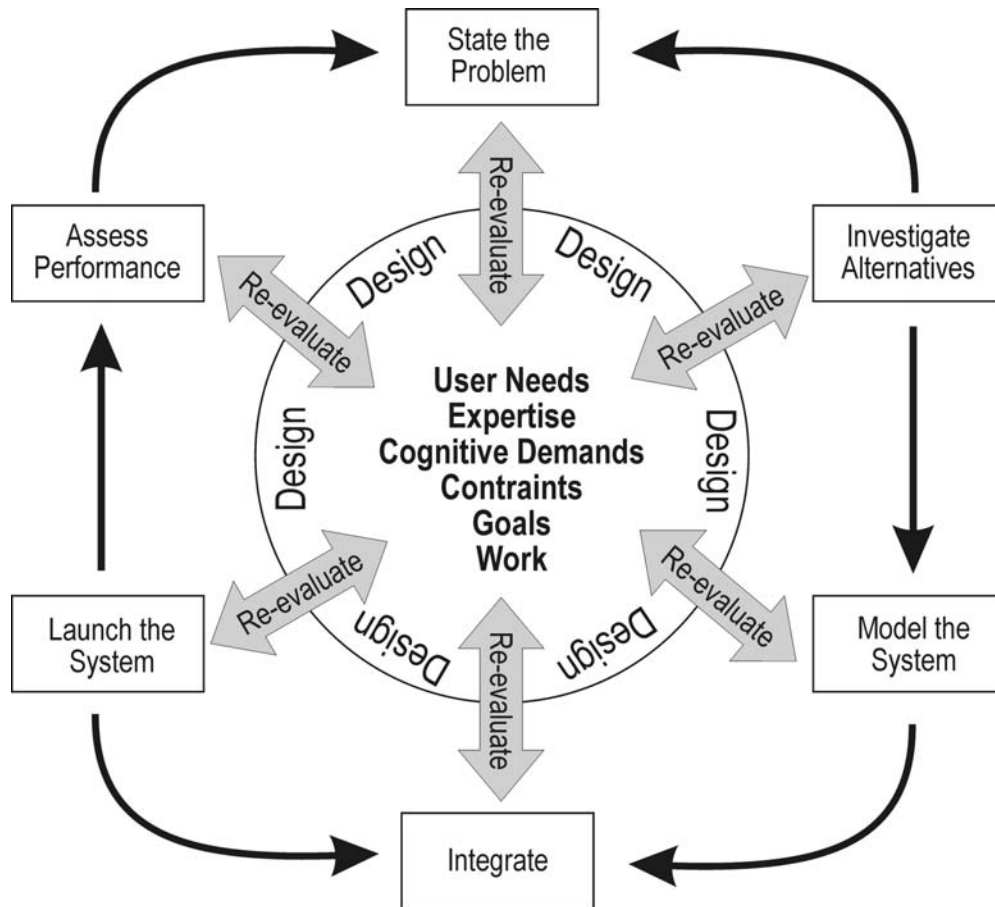


Figure 3. CSE can serve as an integrating force for design.

uted dialog that continues throughout the life of the design project.

This figure is also intended to convey the notion that design is a variable process that, to an observer, may seem opportunistic and fragmented. For example, it is commonly proposed that design specifications flow from the products of analysis, but, in our work, specifications continue to emerge as the design is being prototyped or fabricated. There is an almost universal call for design to be formalized and standardized. We regard that as both unrealistic and as counterproductive. Too much success in that direction will stifle innovation, which is the touchstone of design. CSE, in contrast, provides a focus that can help guide an opportunistic and highly-variable design process.

6. DISCUSSION

CSE methods and frameworks bring an improved understanding of the human cognition and expertise that evolve within a work system and the constraints that give form to the work system. Throughout the process the design team constantly reevaluates against the emerging understanding of worker needs, expertise, cognitive demands, constraints, goals, and work. CSE makes more or less invisible aspects of the work system explicit. It is this contextual understanding of the human cognition and work constraints that CSE brings to the table. CSE provides methods for analyzing and modeling human cognition and work. CSE also provides a rationale and specific guidelines for design, as well as strategies for iterative evaluation.

In spite of the progress made in CSE over the last 30 years, challenges remain. Perhaps the most frustrating of these is the issue of collaboration among design disciplines. As with many disciplines, CSE has evolved its own language to describe methods, principles, and frameworks. Efforts to contribute to the dialog of design are sometimes hampered by the use of jargon and representations that are not meaningful outside of the CSE community. If CSE practitioners are to become true collaborators in design, we must refrain from using our own private language and find ways to communicate with the larger engineering community. To be effective, we also need to understand systems engineering terminology and process, and frame our contributions to that process appropriately.

A second challenge is one of justification. As a relatively new approach to design, the contribution and value of CSE are not widely understood. Although examples of difficult-to-use and even failed technologies are plentiful and widely appreciated, there is a pervasive tendency to underestimate the difficulty of developing effective solutions. Resources devoted specifically to exploring worker perspectives, work constraints, and cognitive requirements are hard to justify if program managers and system designers believe issues of usability, usefulness, and impact are to be resolved as a natural byproduct of smart people using common sense. The CSE community must find ways to articulate the value added. This is not a trivial challenge, however, as often the CSE contribution is difficult, if not impossible, to isolate from the contri-

butions of others on the design team—particularly if it is done well as part of an integrated design effort.

One promising approach to overcoming this challenge is to continue to capture and share success stories in which cognitive requirements and worker perspectives are incorporated early in the design process [Cooke and Durso, 2007]. Success stories that highlight design projects where worker needs, expertise, cognitive demands, constraints, and goals are considered throughout the design may be the most convincing type of justification. These successful products that support identifying, judging, attending, perceiving, remembering, reasoning, deciding, problem solving, planning, etc. can be contrasted to projects in which features to support these cognitive processes are added as “fixes” near the end of the design process or after technologies have been fielded. Outcomes of CSE include more productive iterations during the design cycle (and often fewer false starts) and fielded systems that better support cognitive work and reduce the likelihood of error. Systems designed using CSE methods and principles are more likely to feature the flexibility required to accommodate a changing world.

These types of outcomes, however, are very difficult to quantify. Good baseline measures for comparison do not exist. It does not make sense to build one work system using CSE and one work system without CSE for comparison in terms of development costs and the impact of the final design on cognitive work and error rates. Simply comparing a new work system to the previous work system is not straightforward, as often the nature of the task or mission is transformed with the introduction of the new system, making meaningful pre-and post-comparisons difficult. Even in situations in which meaningful comparisons can be made, sponsors are often not willing to fund formal evaluation studies, choosing to rely on worker acceptance as the primary indicator of success.

While worker acceptance is an excellent indicator of success in hindsight (after the design is complete), the CSE community still faces the challenge of providing a convincing value case at the time work is scoped and planned. Sponsors and other members of the engineering community must appreciate the value of CSE if CSE practitioners are to have a voice in the dialog and a role in design throughout the design cycle. Often the only way to provide a convincing value case is to explain CSE processes and show specific work products that have resulted from previous CSE efforts. (It is important to note, as one reviewer pointed out, that there may be some danger in focusing solely on success stories as there is often much to be learned from failures. Certainly, examination of prior successes and failures has value beyond that of articulating a value case.)

A starting point in meeting these challenges is to begin to articulate a value case for CSE [Cooke and Durso, 2007]. We suggest that the value of CSE is that it can make explicit the invisible aspects of the system operation, and can provide system workers with the flexibility to deal with unanticipated situations. It can make visible the expertise needed within a system. It can make visible the potential errors that might arise if technologies are used in ways that are not intended, or in contexts that were not envisioned. Systems designed using CSE are more likely to include the flexibility required to accommodate the never ending creativity of humans as they

adapt technologies and processes to accomplish work tasks, as well as the many unexpected situations that arise in a changing world. Without CSE, the design process can be fixated on a narrow set of procedures that make it look like the technology will be very helpful. It is easy to assume that if the worker follows a set of simple, prescribed steps, then the system will operate smoothly and safely. CSE helps designers move beyond a superficial, oversimplified view of the work system to create systems that better support complexity and uncertainty in the real world.

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