The State of the Art of Cognitive Systems Engineering Research in Nuclear Industry

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1. Introduction

Cognitive Systems Engineering (CSE) is a multidisciplinary field that is concerned with analysis, design, evaluation, and operation of a complex socio-technical system, such as nuclear power plants (NPPs) and air traffic control systems, in which human operators should interact with a work domain [1, 2]. It aims to develop frameworks, methods, and tools for realizing a better human-system interaction in those systems [2-4]. CSE has been developed mainly in the domain of process control systems including NPPs; it has much contributed towards improving the safety and productivity of NPPs [5]. Reversely, it can be said that nuclear industry has been a major work domain supporting the academic development of CSE. With this background in mind, the author would like to review the state of the art of CSE research in nuclear industry and to propose several meaningful research directions in the discipline in relation to nuclear industry.

2. CSE Research in Nuclear Industry

This section firstly reviews main research topics of CSE, particularly focusing on its application to nuclear industry. Next we examine how CSE methods can be properly used throughout systems engineering process. Then this section summarizes seven promising research issues that have a potential for enhancing the safety and productivity of NPPs.

2.1 Main Research Topics of CSE

CSE research topics can be appropriately categorized by several criteria. However it is useful to classify them in accordance with the four basic engineering activities of a system (i.e. analysis, design, evaluation, and operation). Before reviewing the main research topics of CSE in nuclear industry, it should be noted that safety-related topics are dominant because of the peculiar characteristics of NPPs as a safety-critical and high-reliable system.

Analysis offers information and insights for the other engineering activities [6, 7]. For this reason, the issue of how to conduct analysis has been a significant research topic in CSE. Here we need to consider what should be analyzed. In general, the five things need to be thoroughly analyzed for design, evaluation, and operation of human-centered NPPs. They include: work domains, users, (users') tasks, (new) technologies and contexts. Thus the development of a method and process for analyzing and understanding work domains, users, tasks, technologies and contexts has been a major research topic in CSE. For example, work domain analysis based on abstraction hierarchy (AH) and context modeling based on a set of performance shaping factors (PSFs) are such a research attempt.

In order to identify CSE research topics for design, firstly it is necessary to consider the objects of designing in a system. In general, those design objects in a safety-critical system such as NPPs include the followings: human-system interfaces (e.g. information displays, alarms, (computerized) procedures, and large mimic displays), task procedures, training materials and training systems, team and organization, automation, information aids, sensors, and database [8, 9]. Thus it can be said that a method, process and tool for systematically developing those design objects has been a major CSE research topic. In line with the development of the method, process, and tools, development of case studies demonstrating their usefulness has been another major research stream.

The problem of linking analysis to design (road from analysis to design) has been a very challenging research issue in all design-related disciplines. Development of human-centered NPPs is no exception. Thus a great deal of research attempt has been devoted to this issue in the field of CSE during the last four decades. One famous research output of those attempts is cognitive work analysis (CWA) [9, 10].

Evaluation-related research topics are mainly concerned with the development of valid and reliable cognitive human performance measures and methods for evaluating cognitive human performance. Situation awareness-related research topics are a good example [11]. Another major research stream in evaluation has been the problem of how to evaluate human-system interfaces [12, 13]. This research topic is closely related to usability engineering and user experience in the field of human-computer interaction (HCI).

Several research activities have been made to address the problem of how to safely manage NPPs. These research activities include the followings: behavior controlling and management systems (e.g. human performance tools), safety regulation systems, accident analysis and modeling methods, risk assessment methods such as human reliability analysis (HRA), and safety culture. In order to deal with safety issues from a different perspective, new safety paradigms such as Safety-II and resilience engineering have increasingly gained research interests in recent years.

2.2 Integrating CSE methods into Systems Engineering Process

A lot of CSE methods have been developed as a response to the research topics described in section 2.1. However, it should be noted that as with other methods, a CSE method has its own advantages and drawbacks; there is no perfect method without a deficiency [14], Thus, considering the characteristics of a method, researchers need to selectively use CSE methods depending on their research and design purposes.

Another issue is when to use a CSE method in the context of a systems engineering process. Regarding this, two life cycle activities are of more concern because of their importance and influence on the other life cycle activities: data gathering (knowledge capture) and analyzing cognitive requirements and linking cognitive requirements analysis to design.

Common CSE methods that are widely used for data gathering are as follows: interviews and focus groups, critical decision method (CDM), applied cognitive task analysis (ACTA), concept mapping, observations, and artifact analysis.

As described previously, analyzing cognitive requirements and connecting cognitive requirements analysis to design may be the most interesting and challenging issue to CSE researchers [9, 15]. Common CSE methods that have been frequently used in nuclear industry include: cognitive work analysis (CWA), ecological interface design (EID), applied cognitive work analysis (ACWA), situation awareness-oriented design (goal0-directed task analysis method), work-centered design, decision-centered design, contextual design, cognitive function analysis (CFA), Cognitive Analysis Design and Evaluation (COADE), Perceptual Cycle Model (PCM).

2.3 Promising Research Issues

Nuclear industry is one of the work domains that have fostered the academic development of CSE and will still be one of the most attractive work domains to CSE researchers [16, 17]. Also, CSE has contributed to improve the safety and reliability of NPPs during the past four decades. However, there remain several things to be further studied to support researchers and engineers in dealing with problems related to the safety and productivity of NPPs. The author would like to propose the following seven issues as the promising research challenges, based on the collective consideration of his personal experience, current research activities of other CSE researchers, and current demands of nuclear industry practitioners [18, 19].

- Naturalistic Decision Making (NDM) [20, 21]
- CWA and EID [9, 22]
- Computational Model of Cognition [21, 23]
- Human-Centered Automation [11, 15]
- Collaborative Decision Making [24]
- Safety Culture [25]
- Safety-II and Resilience Engineering [26, 27]

3. Conclusions

In order to help researchers to apply the conceptual and methodological tools in the field of CSE to nuclear industry more effectively, this paper introduced the past and the present CSE research in nuclear industry and suggested seven issues for advancing CSE research. Also, the effective use of CSE methods has been examined in terms of a system life cycle. It is believed that researchers can obtain several insights for applying CSE methods and tools more systematically for their research purposes from the discussions of this paper.

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