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Developing an agent-based hierarchical modeling approach to assess human performance of infrastructure systems

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ABSTRACT

During the last decade, research works related to modeling and simulation of infrastructure systems have primarily focused on the performance of their technical factors, almost ignoring the importance of non-technical factors of these systems, e.g., human operators, consumers. In contrast, the human operator of infrastructure systems has become an essential part in daily operation and in ensuring the security and reliability of the system. In some of the most significant technological incidents of the past century, human error has played a major role. Therefore, developing a modeling approach that is capable of assessing the human performance in a comprehensive way has become crucial. In this paper, an agent-based hierarchical modeling approach is proposed, which aims at the explicit modeling of the impacts of human performance on the operation of infrastructure systems. Within this approach, the cognition component plays a major role. For this purpose, an analytical method based on the Cognitive Reliability Error Analysis Method (CREAM) is developed using a knowledge-based approach. The proposed modeling approach is a pilot work exploring possibilities of simulating performance of human factors in infrastructure systems. The applicability of this modeling approach is demonstrated by a validation experiment using the electric power supply system as an exemplary system.

1. Motivations

Infrastructure systems, e.g., power supply, telecommunication and rail transport systems, deserve increasing attention as our societies rely on the continuous supply of their goods and services. These systems are large-scale, highly integrated, and interconnected and show complex behaviors (Kröger and Zio, 2011). The attention on infrastructure systems is evolving - from concerns about aging public works (in the 1980s) to redefinition in terms of national security as a result of increased international terrorism (after September 11, 2001) and susceptibility against natural hazards (e.g., 2011 Fukushima), to unprecedented failure combinations and malicious cyber-attacks (e.g., targeted Stuxnet worm). Most research works on infrastructure systems have taken an engineering point of view, which often underestimate the importance of non-technical factors, i.e. the performance of the human components (e.g., operators, maintenance personnel) (Ferscha et al., 2011; Baxter and Sommerville, 2011). Humans involved in the operations of infrastructure systems are often susceptible to misoperations and failures during the time which follows the impact of a disruption on an infrastructure and are capable of adapting and regaining normal performance levels during the recovery period. They have direct and instant impacts on the performance of those systems (Amin, 2002; Little, 2004). A number of studies have shown that human errors are major causes for incidents occurred in electric power, railway, aviation and maritime infrastructure sectors (Johnson and Holloway, 2007; Kröger and Nan, 2014; Wreathall et al., 2003), highlighting the significance of assessing human performance, which can be conducted using advanced modeling approaches.

Modeling human performance and behaviors is not a new endeavor. The first human performance related model was developed in the early 1980s by Card in (Card et al., 1983). After that, researchers have proposed different approaches aiming at modeling and assessing human performances. According to (Laughery et al., 2007), the development of human performance models follows two types of approaches: reductionist and first-principle approach. The first approach uses human-system task sequence as the primary organizing structure. Human performance is decomposed into a sequence of tasks. In (Lawless et al., 1995), this approach is adopted as a means to predict human performance in

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the control room of a nuclear power plant by decomposing it into a series of sub functions and tasks. Other applications of this approach can be found in (Martin et al., 2001; Lebiere et al., 2009). The reductionist modeling approach is a top-down approach, which predicts human performance through extended task and system analysis. Conversely, the first-principle approach is based on the mechanisms that underlie and cause human behavior (Laughery et al., 2007). An exemplary framework based on this approach is the adaptive control of thought—rational (ACT-R) cognitive architecture, which models the steps of human cognition by a sequence of production rules (Anderson et al., 1997). The advantage of this framework is its capability of modeling basic human cognition and integrating with other domains of knowledge, e.g., rules, experiences, learning ability, etc. It is an architecture that can be used to model a wide range of human cognition, including memory retrieval, visual search, and learning physics (Anderson et al., 1998; Salvucci and Anderson, 2001). In (Lebiere et al., 2001), this framework is further applied to develop a human performance model, which aims at fulfilling a simplified air traffic control task.

In addition to the above approaches, there are parallel efforts to develop methods to model and assess human performance, e.g., human reliability analysis (HRA). HRA considers the impact of human errors on system risks; it aims at identifying, representing, and quantifying human errors and failures for the purpose of determining their contribution to system failures. HRA originates from the probabilistic risk assessment (PRA) when the probability of human failures is required to evaluate the risks to system operations (Sharit, 2012). The Technique for Human Error Rate Prediction (THERP), one of first generation HRA methods, is one of the most widely used technique to date. THERP aims at calculating the probability of successful performance of the activities, which are defined necessary for the accomplishment of a task. The calculations are based on pre-defined error rates and success is defined as the complement to the probability of making an error (Ingenieure, 2003). THERP has limitations in the human performance analysis because it focuses on errors of omission and intends to characterize each operator action with a binary path, i.e. success or failure. Moreover, the influence of Performance Shaping Factors (PSFs) on human performance is quite poor and heavily based on the assessor's experience (Konstandinidou et al., 2006; Kyriakidis, 2009). CREAM (Cognitive Reliability Error Analysis Method) is one of the best known second generation HRA methods; it overcomes the limitations of the previous methods by developing a practical approach to performance analysis and error prediction (Hollnagel, 1998). Compared to other second generation HRA methods, e.g., A Technique for Human Event Analysis (ATHEAHA), CREAM presents a consistent error classification system integrating individual, technological and organizational factors, which can be used both as a stand-alone method for accidental analysis and as part of larger design methods for interactive systems. One of the main features of this method is its integration of a useful cognitive model and framework that can be used in both retrospective and prospective analysis (He et al., 2008).

These three techniques, i.e. reductionist, first-principle, and human reliability analysis, are not mutually exclusive. Although their focus might vary, they can be mutually supportive in any given modeling task. For example, in order to implement a HRA method such as CREAM, a task or an event needs to be divided into a sequence of subtasks using the reductionist approach. On the other hand, the implementation of the reductionist approach often needs an accurate representation of behavioral phenomena by basic human behavior models, which requires elements of first-principle approaches.

Considering both technical and non-technical factors widens scope of infrastructure systems to so-called "socio-technical" systems (Mohaghegh and Mosleh, 2009; Landegren et al., 2013). Failure to include non-technical factors impacts the quantifications of system performance and as a consequence, the accuracy of the results might be questioned. According to (Little, 2002), human error has played a major role in some of the most significant technological incidents of the past century. Therefore, there is a pressing need of modeling approaches with capabilities of representing human performance with the context of infrastructure systems. In (Zio, 2009), this task is listed as one of new challenges within the research area of reliability analysis of complex infrastructure systems. In recent years, a wide range of advanced modeling approaches, e.g., Agent-based Modeling (ABM), Complex Network Theory (CNT), System Dynamic (SD), have been applied to represent technical factors of infrastructure systems. However, modeling efforts regarding the human performance mainly remain on the adoption of classical analytical approaches, e.g., probabilistic models, using a combination of fault and event tree techniques, which lacks capability of representing complex relationship between technical and non-technical factors (i.e. performance of human participants and technical components) (Boring, 2007; Mosleh and Chang, 2004). This paper proposes a modeling approach for quantifying the impact of the human performance on the operation of infrastructure systems. The approach is capable of capturing the relevant contributors to the decision-making process of a human operator. Among them, the cognition process plays a major role in the definition and quantification of the human error probability, which is used to determine whether a specific task is correctly carried out. CREAM is applied for the quantification of the error probability and for the assessment of the cognitive functions and of their failures modes based on the performance conditions which the operator is subjected to.

The rest of the paper is organized as follows: Section 2 introduces the proposed agent-based hierarchical modeling approach. Section 3 and 4 present an analytical method based on CREAM method including a knowledge-based approach to assess common performance conditions efficiently. The design of a validation experiment for the purpose of demonstrating the feasibility of the modeling approach is presented in Section 5, which considers the an electric power supply system as an exemplary system. The discussion of the simulation results is also included in Section 5. Finally, Section 6 and 7 provide the outlook of the proposed modeling approach for future work and conclusions.

2. An agent-based hierarchical model

The reductionist, first-principle approach, and HRA approaches have been widely developed and improved during last several decades in order to provide an applicable way to assess human performance. However, they present inherent limitations, i.e. the lack of objectivity and the inability to model tasks that consist of highly nested and concurrent cognitive activities. Furthermore, combining them with models for technical factors is a challenging task. These limitations hinder the possibilities of analyzing performance of infrastructure systems by the integration of the human factor in them. To overcome these limitations, the ABM can be adopted due to its capability of representing the complexity of infrastructure system, and due to its modeling flexibility and adaptability (Kaegi et al., 2009). This approach describes a system by the interaction of its individual parts (bottom-up). Each component (part) of the system is modelled by an agent, capable of modifying its internal data (parameters and variables), its behaviors (functions), its environment, and of adapting to environmental changes. An agent can be used to model both technical and non-technical elements, and different agents interact with each other directly or indirectly.