Emerging Technologies and Future of Work, Vol. 117, 2023, 1–9
https://doi.org/10.54941/ahfe1004399

A Review of Sociotechnical Approaches for Nuclear Power Plant Modernization

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ABSTRACT

The current United States nuclear power plant fleet is in need of transforming the way work is performed to remain competitive with other electricity-generating sources. The use of new digital technologies can be applied to significantly reduce operating and maintenance costs. Recent research by the United States Department of Energy Light Water Reactor Sustainability Program has identified new opportunities to leverage advanced digital technologies to transform the way work is performed at existing plants. However, to ensure that the capabilities of people and advanced digital technologies are jointly optimized, a sociotechnical approach should be considered. This work explores recently introduced sociotechnical approaches to address the function allocation and data visualization considerations in the integration of new digital technologies to ensure safety, reliability, and maximizing the capabilities of proposed technological solutions that ensure the economic viability of the existing United States nuclear power plant fleet.

Keywords: Nuclear power plant modernization, Sociotechnical methods, Function allocation

INTRODUCTION

The existing nuclear power plants are critical infrastructure for continued carbon-free electricity generation in the United States (U.S.); however, these plants are becoming less competitive with other electricity generating sources as they begin to leverage digital technologies that significantly reduce their operating and maintenance (O&M) cost. The current U.S. nuclear power plant fleet is in imminent need of a digital transformation that will fundamentally change the way work is performed. To support this need, the U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program Plant Modernization Pathway is completing targeted research and development (R&D) that fulfills two complementary mission areas:

1. To deliver a sustainable business model that enables a cost-competitive U.S. nuclear industry with reduced O&M cost, and
2. To develop technology modernization solutions that address aging and obsolescence challenges and meet business needs.

One area within the LWRS Program, Integrated Operations for Nuclear (ION), focuses on the former mission area and provides a clear business case in applying technology modernization solutions that address aging and obsolescence, as well as significantly reduce O&M cost (Remer et al., 2021). The

ION research area provides a target cost reduction through enabling modernization solutions needed in the next 5 years for the nuclear industry to remain economically viable. Complementary to ION, the LWRS Program Human and Technology Integration (HTI) research area applies targeted human factors research to ensure that these modernization solutions continue to support safe and reliable operation. Together, ION and HTI are collaborating with industry across critical work domains that will significantly reduce cost needed to operate, maintain, and support the existing U.S. nuclear power plant fleet. Some of these key critical work domains include:

- Digital instrumentation and control (I&C) and control room modernization
- Work/ requirement reduction
- Mobile worker technology
- Condition-based monitoring
- Remote collaboration
- Plant automation
- Advanced analytics and assurance

The scope of ION across these critical work domains is to enable transformation of work in a way that improves plant performance and efficiencies through a holistic analysis of the work performed. ION thereby emphasizes the implementation of advanced technologies that eliminate tedious manual tasks, reduce workload, improve team situation awareness, and improve organizational decision-making. To enable the success of ION, this work suggests the need to apply a *sociotechnical approach* that carefully considers the work domain and its constraints to inform how new technologies can be incorporated (i.e., function allocation) for joint optimization and to support continued safe and reliable operation of the plant while maximizing the benefits of the new technology. Indeed, this viewpoint seems to be aligned with the greater human factors community that projects continued need of addressing function allocation in the use of advanced automation forms, including automated cars, drones, and artificial intelligence systems to name a few (Janssen, Donker, Brumby, & Kun, 2019).

Specifically, this work, extending from Kovesdi and colleagues (2022), follows recent work from Roth and colleagues (2019) and explores recently introduced sociotechnical approaches to address the function allocation and data visualization elements of an ION transformation to ensure the economic viability of the existing U.S. nuclear power plant fleet. This work is currently exploring the emerging methods described in Roth and colleagues (2019) to address function allocation across the ION-identified critical work domains at U.S. nuclear power plants for sustained safe and reliable operation with reduced cost. Specifically, this work explores the integrated approach to addressing function allocation under the following areas:

- To analyze operational demands and work requirements.
- To explore alternative distributions of work across automation and people (i.e., authors refer to this as human-machine teaming).

- To examine interdependencies between people and automation required for effective teaming.
- To explore trade-spaces of alternative human-machine teaming options.

Notable sociotechnical methods from Roth and colleagues (2019) as seen most impactful for nuclear power plant modernization are described next, followed by a discussion of how these methods are planned to be integrated in future research.

ANALYZE OPERATIONAL DEMANDS AND WORK REQUIREMENTS

Cognitive Task Analysis: Knowledge Elicitation Techniques

Cognitive task analysis (CTA) consists of a set of task data collection and knowledge representation techniques that focuses on the cognitive aspects of work (Crandall, Klein, & Hoffman, 2006). There are several different CTA approaches, and a detailed description of these methods goes beyond the scope of this work. The reader should refer to Stanton and colleagues (2013 & 2017), or Crandall and colleagues (2006). However, it should be noted that such methods may be useful in enriching knowledge elicitation when understanding existing pain points from an existing work system or defining new requirements for proposed technology being introduced in an existing work system (Kovesdi et al., 2021).

Cognitive Work Analysis: Work Domain Analysis

Complementary to CTA, cognitive work analysis (CWA) is a sociotechnical framework that begins its analysis on the work domain and governing constraints rather than tasks at hand. There are several phases to CWA, which are outlined in Table 1 (Stanton et al., 2017).

Table 1. Phases of cognitive work analysis.

Phase	Purpose	Outputs
Work domain analysis (WDA)	Describes the system's objectives and defines the bounding work under analysis.	Abstraction hierarchy, Abstraction-decomposition space
Control task analysis	Defines the work system's functions, situations, and key decisions needed to achieve the system objectives.	Contextual activity template, decision ladder
Strategies analysis	Defines the work domain's strategies that are performed using flow maps.	Information flow map
Social organization and cooperation analysis	Examines the assignment of agents to perform work within the domain.	Mapping (i.e., via color shading) of associated agents (people and technology) to the above.
Worker competencies analysis	Examines worker competencies (knowledge, skills, and abilities) required of people to perform work within the system.	Skills, rules, and knowledge inventory for assigned functions to people.

Each of these phases in CWA evaluate the work domain through different lens of abstraction. Because CWA is technology agnostic in the sense of analyzing the work domains through its goals, constraints, and functions (i.e., means-end), CWA can be applied to address function allocation by examining how such allocations can be realized across the work domain (i.e., using WDA) and across different work system situations (control task analysis). Roth and colleagues (2019) discuss how the use of the WDA abstraction hierarchy and control task analysis decision ladders can be used to analyze different assignments of function in terms of their overall impacts on decision making.

To no surprise, WDA is readily applied within the human factors community. For instance, the use of WDA in combination with social network analysis was recently applied by Schmid and colleagues (2020) to enable a reduced flight deck crew for commercial airlines through modernization of existing infrastructure that leverages increased automation. It should be noted that such problem space is similar to the existing U.S. nuclear power plant fleet needs in which technology is needed to streamline staffing requirements through increased levels of automation. Thus, the application of CWA is a notable tool in analyzing organizational and work requirements that ensure joint optimization between people and technology through new allocations of function.

EXPLORE ALTERNATIVE DISTRIBUTIONS OF WORK

Following the analysis of operational demands and work requirements, alternative distributions of work (i.e., assignment of function to technology or people) can be analyzed by using control task analysis contextual activity templates from the CWA framework (Table 1). The contextual activity template maps work functions to specific work situations in tabular format (Stanton et al., 2017), and typically is represented as the situations located as rows and functions as columns. The output of the contextual activity template specifies whether a particular identified function is performed across each of the identified situations within the work domain; it can also be extended using the social organization and cooperation analysis phase of CWA to specify which agents are responsible for the performance of each function and situation.

EXAMINE THE INTERDEPENDCIES BETWEEN PEOPLE AND AUTOMATION

Cognitive Work Analysis: Control Task Analysis Decision Ladders

Decision ladders, within CWA control task analysis, examine critical decisions made by the human-automation system (Stanton et al., 2017; Kovesdi et al., 2022). Decisions ladders are used to analyze the flow of information and to identify key decisions made by the overall system, which is a critical step in ensuring joint optimization between people and technology.

Decision ladders have been recently used to support function allocation and evaluation for a major safety-related digital upgrade at a U.S. nuclear power plant (Kovesdi et al., 2023). In this work, decision ladders were used to characterize the key decisions made for the licensed operators when mitigating specific plant transients that exercised impacts plant systems and functions from the upgrade. A key output from the decision ladders used were established performance-based acceptance criteria for the evaluation of safety-important manual actions impacted by the upgrade. The decision ladders were used as a theoretical framework for defining rule-based and knowledge-based decision making of the operators across key scenarios that encompassed specific transients that related to the upgrades.

System Theoretic Process Analysis

System Theoretic Process Analysis (STPA) focuses on the interactions between the components of a system, using the control structure as an explanatory framework (Levenson & Thomas, 2018). STPA has been applied by HTI researchers to support plant modernization, such as in the modernization of a nuclear power plant's preventative maintenance program (Joe et al., 2023). Here, the researchers were able to apply CWA WDA with STPA and a related framework, Causal Analysis based on STAMP (CAST), to develop requirements for information automation that improves (i.e., mitigating unsafe control actions through design controls) a plant's preventative maintenance program. STPA was found to be a highly useful risk analysis framework, providing rich insights into the work system's constraints, and a complementary tool to better inform design decisions for information automation.

EXPLORE FUNCTION ALLOCATION TRADE SPACE

In assigning a function to people or technology, tradeoffs must be made. A notable method that has been demonstrated in the nuclear industry to explore and analyze function allocation trade space encompasses the use of simulation and modeling techniques (Kovesdi et al., 2021; Joe & Kovesdi, 2021). Digital human models have been used in recent plant modernization analyses to address anthropometric and ergonomic considerations with digital upgrades, as well as to communicate to stakeholders (e.g., senior management and operations) the physical impacts to the control facilities to identify engineering tradeoffs early and to enable technology acceptance from end users (Mohon & Kovesdi, 2022). Complementary to digital human modeling, human-in-the-loop tests have been utilized using a glasstop testbed to evaluate human-system performance tradeoffs (Figure 1).

Simulators like in Figure 1 can be used to support iterative tests and evaluations of proposed modifications, allowing for both knowledge elicitation and performance-based tests to address tradeoffs with assignment of function for digital control systems that leveraged increased automation. Put simply, simulators enable addressing the functional (cognitive) characteristics associated with controlling the nuclear power plant, where measures include impacts to workload, situation awareness, task performance, and teamwork (Kovesdi et al., 2022). Simulation techniques that utilize glasstop testbeds (e.g., Figure 1) is considered a "gold standard" for these tests and evaluations that explore function allocation trade space (Joe & Kovesdi, 2021).

Figure 1: Human-system simulation laboratory glasstop testbed.

INTEGRATING SOCIOTECHNICAL METHODS FOR NUCLEAR POWER PLANT MODERNIZATION

Roth and colleagues (2019) offer an integrated approach to function allocation in the advent of advanced digital technologies that change the way in which work is performed. As previously addressed, a set of sociotechnical methods has been identified as being potentially useful tools to support ensuring safe and reliable use with new digital technologies. One such cross-functional between the ION and HTI research areas includes developing a framework that can be used by industry to screen and assess modernization opportunities through economic, technical, and safety risk (Spangler et al., 2023). The development of the Technical, Economic, and Risk Analysis (TERA) framework is a risk assessment tool that supports industry in modernizing through assessing these risk areas. The framework applies a combination of quantitative and qualitative analyses that provide a holistic assessment of potential modernization opportunities. Within TERA, this work focuses on developing a risk assessment strategy to enable human readiness, such as defined in ANSI/HFES-400 (2021). A proposed framework is illustrated in Figure 2, below (also see Kovesdi, Mohon, & Wilhite, 2023).

The human readiness assessment component of TERA is part of the technical risk assessment element. The methods noted in Roth and colleagues (2019), and particularly the CWA WDA phase, is an analysis framework for assessing the human readiness of introducing a particular new technology (e.g., electric work package system) to an already established work domain at nuclear power plants. As seen in Figure 2, the first phase includes defining the primary functions of the work domain. It is envisioned that the abstraction hierarchy used in CWA WDA can serve as a foundational tool to define a work domain's goals and missions, values and constraints, and high-level functions that are assumed to be modified through digital technology; this corresponds to analyzing the operational demands and work requirements as discussed earlier. Interviews with existing plant staff can be applied at this phase using CTA techniques to understand existing pain points and cognitive requirements that drive the design of future digital technology and automation.

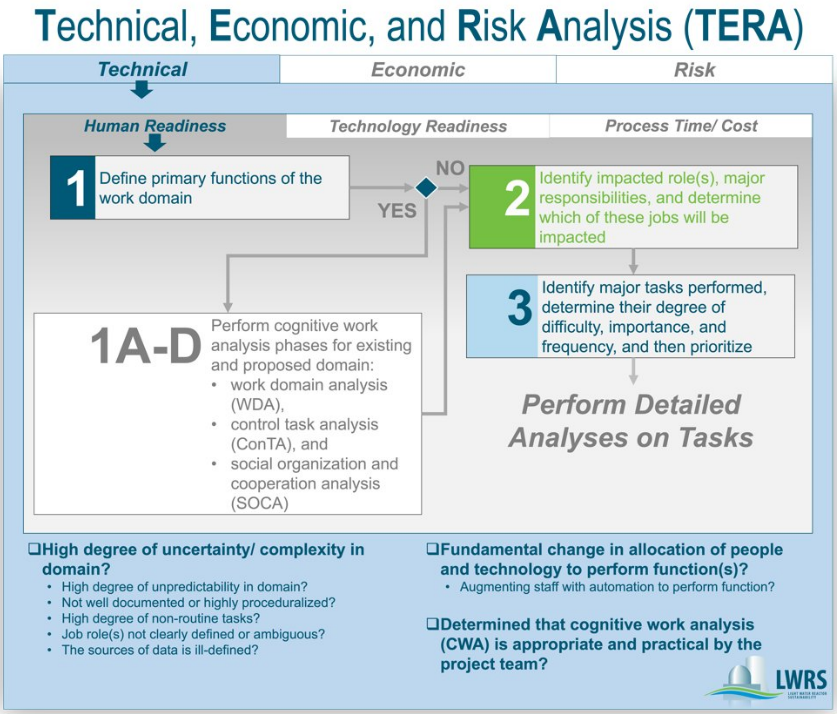

Figure 2: Technical, Economic, and Risk Analysis (TERA) Framework.

Phases 2 and 3 as seen in Figure 2 are then performed; these phases help further prioritize impacted functions and tasks that are of highest safety or economic risk. Here, impacted roles and jobs are identified through a combination of knowledge elicitation techniques and document reviews. Within the identified roles and jobs, tasks that are impacted of highest priority (i.e., to safety or economics) are identified and then analyzed using detailed human factors methods, such as extending CWA using control tasks analysis techniques (e.g., contextual activity templates or decision ladders), STPA, or applying simulation and modeling techniques. A detailed overview of proposed methods are described in detail in Kovesdi, Mohon, and Wilhite (2023), but are illustrated in Figure 3.

It is expected that this proposed framework that leverages sociotechnical approaches to address function allocation considerations and enable large-scale modernization at nuclear power plants will be demonstrated in combination with ION-lead research in future U.S. industry collaborations. Lessons learned regarding the development and use of this framework will be shared through these collaborations.

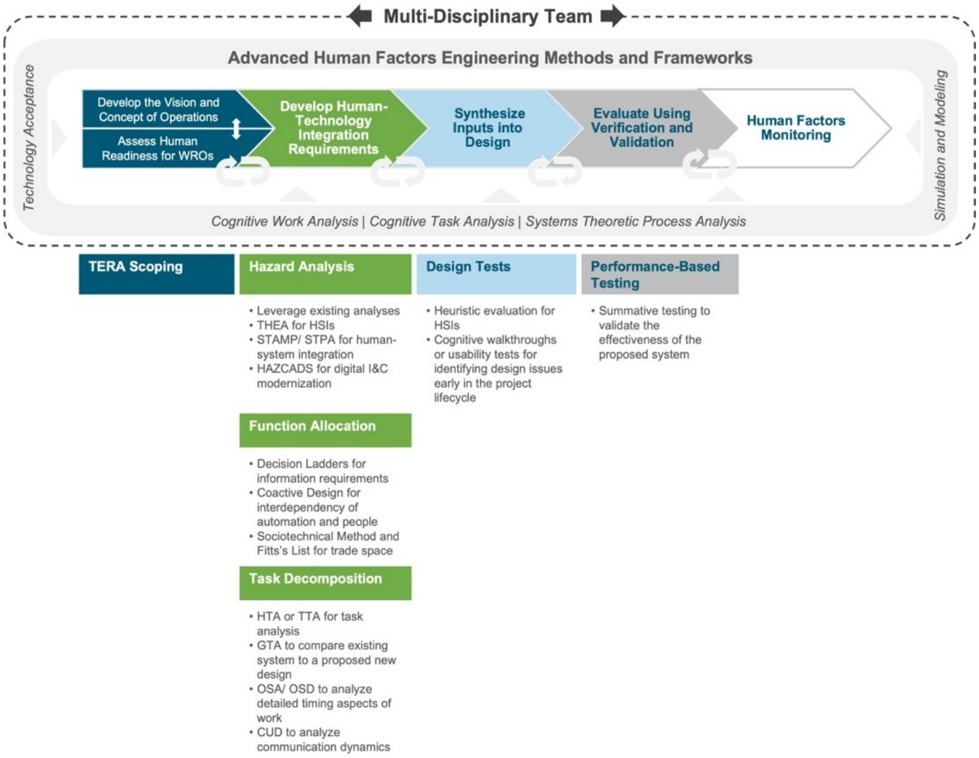

Figure 3: Expanded HTI methodology (adapted from Kovesdi, Mohon, & Wilhite, 2023).

ACKNOWLEDGMENT

This work of authorship was prepared as an account of work sponsored by Idaho National Laboratory (under Contract DE-AC07-05ID14517), an agency of the U.S. Government. Neither the U.S. Government, nor any agency thereof, nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

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