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# USE OF COGNITIVE WORK ANALYSIS IN DEVELOPING A NUCLEAR POWER PLANT NEW-STATE VISION

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The United States nuclear industry needs to identify and implement a new strategy that will lower operating and maintenance costs while maintaining safety for existing plants. The industry must also have a clear and strategic vision of this transformative new state that focuses on ways in which technologies can be integrated to maximize the benefits of technology and people. While there are ongoing efforts in this area, this work discusses how the use of cognitive work analysis may offer further support. This paper provides an overview of cognitive work analysis, as well as the state of current new-state development efforts. The use of cognitive work analysis as a tool to enhance existing practices is presented to ensure the systematic and complete development of a new state vision.

## INTRODUCTION

Nuclear power has a pivotal role in the continued generation of carbon-free electricity for the United States (U.S.). However, changes in electricity market demands coupled with the adoption of emerging technologies in other electricity-generating industries has created an imminent need for the U.S. nuclear industry to identify and implement new strategies that will lower operating and maintenance costs (Joe & Remer, 2019). The U.S. nuclear industry must undergo a substantial transformation of the way in which the plants are operated, maintained, and supported (Kovesdi, St Germain, Le Blanc, & Primer, 2019). The U.S. nuclear industry must also have a clear and strategic vision of their transformative new state that focuses on ways in which technologies can be integrated to drive down costs while maintaining a strong safety record. The new state vision must holistically examine ways in which technology can serve as enabling capabilities to improve plant availability and operating efficiencies, reduce staffing requirements, improve training, remove unnecessary processes, and improve communication across the plant.

The U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program Plant Modernization Pathway is conducting targeted research and development (R&D) to support the industry in developing a transformative new state vision through several research areas. These areas focus on helping the industry look beyond like-for-like replacements of technology to develop an integrative approach that changes the way work is done through focused research that addresses the business, technical, and sociotechnical aspects that are critical to a successful new state transformation. Within human-technology integration, targeted R&D is being carried out to develop guidance that that will support industry in achieving a clear new state vision that is transformative yet achievable. This work leverages existing industry guidance and recent R&D of an advanced control room concept for a generic pressurized water reactor and builds on this foundation by adding specific industry guidance to ensure that the cost-reducing attributes seen in the advanced concept are successfully captured in the design specifications offered by vendors (Kovesdi, Mohon, Li et al., 2020).

An important aspect of this work entails linking the specific technologies seen in the advanced concept to their functional qualities that enable cost reductions and ensure safety. This work presents the use of cognitive work analysis (CWA) as a framework in establishing these links from technologies to their functional qualities (i.e., first principles) that are important for a transformative new state vision. There are four sections of this paper: an introduction to CWA and the particular strengths of CWA in supporting this goal; related efforts for developing a new state vision to provide a sense of the ways in which business, technical, and sociotechnical aspects are being addressed; how specific CWA methods may be used to support these existing efforts; and a conclusion with final remarks and next steps.

## INTRODUCTION TO COGNITIVE WORK ANALYSIS

With origins in the nuclear industry, the CWA framework offers a structured approach to system design (Hugo, 2015). CWA is goal-driven and focuses on the underlying constraints that govern the work domain, as opposed to focusing on existing tasks or ways in which work is completed (Stanton, Salmon, Walker, & Jenkins, 2017). That is, rather than focusing on how work is *currently* done as a core design basis, CWA allows for understanding what *could* be done within the defined work domain and its constraints. This fundamental philosophy of CWA makes its advantageous in the design of first-of-a-kind systems where tasks may still be ill-defined. In this specific case, where existing NPPs must undergo substantial transformation in the way in which work is currently done, CWA also seems fitting to model the underlying constraints posed on the domain. "Disruptive" solutions can therefore be offered since their design bases are not based solely on existing practices.

CWA is comprised of several phases, including work domain analysis (WDA), control task analysis (ConTA), strategies analysis (StrA), social organization and cooperation analysis (SOCA), and worker competencies analysis (WCA). It should be noted that the intent of these CWA phases is not prescriptive; rather, the application of each phase is based on its relevance to the problem at hand. Further, while there is an assumed linear progression with completing each phase as needed, the reality is that many of the phases may be performed in iterations where modifications to certain phases may indeed inform previous phases. Each phase is described next.

## Work Domain Analysis

WDA is foundational to CWA. WDA defines the goals and constraints (i.e., functional structure) of the domain (Hugo, 2015; Stanton et al., 2017). The constraints that govern the domain are either purposefully built or are artifacts of natural phenomena. An important part of WDA is the decomposition of the domain and its constraints through different levels of abstraction. These layers of abstraction comprise a mapping of higher-level system goals and associated values and priorities down to the specific physical objects, proprieties, and functions that support them. The mapping provides a hierarchy of links across these different layers of abstractions to develop means-end relations that form the basis for understanding *what* constraints govern the domain, *why* they exist, and *how* they are currently or could be achieved. The literature characterizes this mapping as the what-how-why triad (Hugo, 2015).

In complex systems like nuclear power plants (NPPs), there can be one-to-many relations across the domain hierarchy. One effective tool to characterize the relations in such situations is the abstraction hierarchy (AH) (Stanton et al., 2017). The AH provides a graphical representation of the means-end links across the layers of abstraction, representing the what-how-why triadic relationship across the layers in achieving the domain goal. The AH can be thought of as a hierarchical network graph to which each defined entity of the domain in a given layer is represented as a node and the means-end relations are represented as the edges, intersecting nodes at the different layers. For a given layer of the graph, a node (i.e., a "what") can be traced upward in abstraction to *why* it exists and downward in abstraction to *how* it is achieved within the domain. While the number of layers may be flexible, the AH is traditionally defined through five layers. These layers include the *domain purpose*, *domain values*, *domain functions*, *physical functions*, and *physical objects* (Hugo, 2015). The format of these layers is presented from top-to-bottom.

The domain purpose represents the reason why the domain exists. The domain values represent the values and priorities in determining how well the goal is achieved. The domain functions represent the purpose-related functions used to support the values and goals of the domain. These functions are presented independent of any object-specific requirements. To this end, the AH provides the physical functions at the next layer to provide object-specific functions necessary for achieving the domain functions. Finally, the bottommost layer represents the physical objects, or entities, that are comprised within the domain space.

The inputs used to perform WDA and to develop the AH come from a synthesis of multiple sources (Stanton et al., 2017). These inputs include some combination of existing documents, interviews with subject matter experts (SMEs), and observational or simulation methods. Like many other methods, the general WDA process entails first defining the objectives of the analysis and any project considerations such as time constraints, available resources, or any key assumptions important for the project. These considerations help define the boundaries of the analysis to ensure objectives are met within the scope of the project. Available resources (inputs) should be identified to develop the initial AH. The AH is then constructed using these initial inputs and modified through iterative review with SMEs until satisfactory. Stanton and colleagues (2017) offer practical insights into developing the AH. The authors suggest starting by completing the topmost and bottommost layers; once these are completed, the middle layers are completed to converge the goals and known objects through connecting the domain functions to physical functions.

The AH is one major output of WDA. The AH provides a comprehensive understanding of the entire domain in different degrees of granularity. Hence, with developing a new state vision, the analyst may use these insights to understand the bases for the existence of specific technologies and their functional capabilities. The AH can also be used to support an understanding of what combinations of technologies and their physical functions are needed to achieve the domain functions that provide value to the domain. Additionally, the AH provides prerequisite information needed for the subsequent phases of CWA.

## Control Task Analysis

ConTA complements WDA by identifying the specific situations where the identified functions from the domain are needed (Stanton et al., 2017). A contextual activity template (CAT) is developed to depict the intersection of specific functions (developed at the domain- or physical-level) from WDA to the situations where they are needed. While there are different variants of formats for CAT, the structure takes a matrix form where functions are presented by row and situations are presented by column. The end results of completing a CAT in ConTA is to develop an understanding of where specific functions do occur, where functions can occur, and where functions do not occur.

ConTA also considers aspects of decision making for the activities carried out across the work domain. A common tool used within the CWA framework entails the use of decision ladders (Rasmussen, 1986; Stanton et al., 2017). The decision ladders provide a structured way to characterize the data processing activities undergone by the entire system and the knowledge acquired at each process in accomplishing a control task. The decision ladders can model the data processing activities and knowledge acquired for both people and technology (e.g., with the use of decision support). This approach can offer insights in understanding possible decision shortcuts that could be made in the situation and their potential consequences. Further, the decision ladders can serve as a key resource in understanding the effects of automating certain decision processes. This output can support the design of automated systems and be valuable in establishing human-system performance observational criteria during testing and evaluation.

### Strategies Analysis

StrA describes the way in which the activities identified in ConTA can be completed (Stanton et al., 2017). StrA acknowledges that activities can be completed in different ways (i.e., strategies) depending on certain conditions and whether the activity is performed by automation or by a person. A visual representation of StrA is generally depicted as an information flow chart (Hugo, 2015). The chart is bounded by an initial and ending condition. Within these bounds, each strategy that can be carried out is depicted as a sequence. Where multiple strategies are possible, the chart shows each sequence in parallel.

### Social Organization and Cooperation Analysis

The SOCA phase focuses on the specific roles and responsibilities of each agent (i.e., both technology and people) within the context of team coordination (Stanton et al., 2017). SOCA first focuses on identifying the specific roles in the system. The roles contain both human and automated agents. The identified roles can then be traced across the products of WDA, ConTA, and StrA to show how each role is assigned to the functions, control tasks, and strategies previously identified. Consequently, a notable output of SOCA is an understanding of *who* is responsible for specific activities within the domain.

### Worker Competencies Analysis

The final phase of CWA is WCA. WCA identifies the human agents' psychological and physical requirements in performing specific activities for a given role (Hugo, 2015). Rasmussen's skills, rules, and knowledge (SRK) taxonomy is one such framework used in WCA to model the psychological requirements (e.g., Rasmussen, 1986; Stanton et al., 2017). Using the SRK framework, WCA can help in analyzing the way in which people make decisions depending on various conditions and level of expertise. Like SOCA, WCA complements the outputs of other CWA phases. For instance, the SRK framework can be applied to the decision ladders developed in ConTA to characterize the way in which skill-based, rule-based, and knowledge-based decision making is applied at each decision process from the ladder.

## CURRENT APPROACHES IN DEVELOPING A TRANSFORMATIVE NEW-STATE VISION

There are two notable research approaches that are focused on developing a transformative new-state vision. These two approaches are seen as complementary to comprehensively addressing the business, technical, and sociotechnical considerations.

### Application of Integrated Operations for Nuclear

The *Integrated Operations for Nuclear (ION)* provides a business-driven approach to transforming the operating model of U.S. NPPs from labor-centric to technology-centric (Thomas, Remer, Primer, Bosnic et al., 2020). ION is essentially a business model that is built on the framework of integrated operations (IO). IO can be traced from its application in transforming how work is done in the offshore Norwegian Oil industry. IO focuses on developing solutions that are based on top-down business objectives (e.g., reduce operating and maintenance cost) and broadly accounting for the impacts to people, processes, technology, and governance (PTPG); this framework is considered *capability thinking*. Another feature of IO is that capabilities of an organization can be decomposed into sub-capabilities, work functions, and work reduction opportunities, a characteristic defined as the stack model. The stack model follows a format similar to the AH in CWA. The ION framework leverages IO through these principles and expands on its application by accounting for the unique needs of the nuclear industry. To this end, there are two notable tools under development supporting ION:

1. *Integrated Operations Capability Analysis Platform (ICAP)* is a software tool that can be used to identify work reduction opportunities (i.e., candidate cases where costs can be lowered) across the plant, following the capability thinking framework of IO (Kovesdi, Thomas, Remer, & Boyce, 2020). ICAP provides a way to build out the primary NPP functional areas and work downward to the specific work functions and work reduction opportunities that offer greatest value in cost reductions. Solutions that can be defined in ICAP are based on the extent to which they synergistically address PTPG. The work reduction opportunities entered in ICAP are meant to be used across the organization to ensure "re-usability" and "re-scalability."
2. *Innovation Portal.* The ICAP provides a link to the Innovation Portal. The Innovation Portal was first introduced in an industry nuclear innovation workshop (Kovesdi et al., 2019). Here, the portal was identified as a core need for industry in identifying and selecting enabling technologies. The Innovation Portal is an ongoing effort under development. It will serve as a resource catalog of advanced technologies that should be considered when addressing the technology component of PTPG. The Innovation Portal will provide information regarding the characteristics of specific technology in terms of providing value to a new state, along with associated technical bases.

### Application of Systems and Human Factors Engineering

Systems engineering (SE) and human factors engineering (HFE) are central to developing a transformative new state. By applying SE and HFE, major changes to the plant's concept of operations can be better informed by taking a holistic approach to the design and accounting for people's cognitive and physical capabilities (Electric Power Research Institute [EPRI], 3002011816). Indeed, the application of HFE is not new to NPPs. There is a large body of literature that can be leveraged. This section highlights how HFE has traditionally addressed challenges in developing a new state vision, as well as current R&D focused on building the literature to support the industry during its transformation.

*Existing HFE guidance.* Notably, relevant HFE resources available for developing a new state vision are the U.S.

Nuclear Regulatory Commission (NRC) *Human Factors Engineering Review Model* (NUREG-0711) (2012) and EPRI documents 3002004310 (2015) and 3002011816 (2018). NUREG-0711 is a guidance document that supports regulatory reviews by the NRC for both new NPP builds and modifications to existing NPPs. The document provides a set of standardized HFE activities that should be considered across the lifespan of the effort. EPRI 3002004310 extends on NUREG-0711 by providing utility-specific guidance across the described HFE activities. Moreover, there is a focus on developing an "endpoint" vision. EPRI 3002004310 offers detailed guidance in ensuring that all considerations relevant to defining NPPs' new state are considered, although this guidance does not provide any particular set of technologies or capabilities important for transformational change. Finally, EPRI 3002011816 provides process guidance on implementing SE into NPP new builds and modifications. This guidance provides a cohesive set of engineering activities across core technical disciplines (including HFE) that are important to performing major digital upgrades for NPPs.

*Continued HFE R&D efforts in NPP new-state vision development.* Currently, the U.S. DOE LWRS Program is actively continuing R&D that will address the human-technology integration challenges associated with integrating emerging technologies for a new state vision. This initiative is doing so by leveraging prior HFE research and industry practices to develop specific design guidance for the industry that ensures the new state includes important qualities that enable cost reduction while ensuring safety. The scope of this work is to develop human-technology integration requirements for a new state that offer a cohesive strategy in complementing the strengths of both people and technology. These requirements will enable a clear vision and roadmap to successfully achieve the new state of nuclear power generation. The methodology fits within the larger SE framework described in EPRI 3002011816 and leverages tools and methods from existing guidance like EPRI 3002004310 and builds on it through the application of design criteria (first principles) that characterize the functional qualities of each new capability to the overarching goal of the new state vision. The development of first principles (or design criteria) that capture the important qualities of an advanced NPP concept are captured from previous R&D from the DOE LWRS Program described in INL/EXT-20-57862 (Kovesdi et al., 2020; see Figure 1).

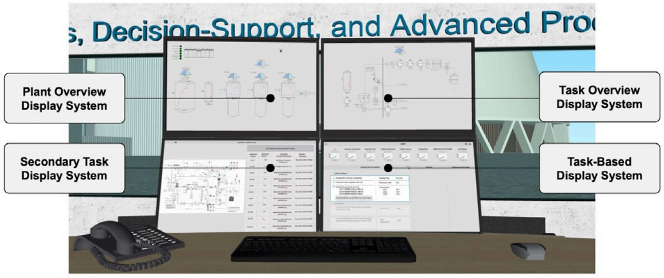

**Figure 1. Advanced NPP concept (adapted from INL/EXT-20-57862)**

## INTEGRATING CWA WITH CURRENT NEW STATE VISION DEVELOPMENT APPROACHES

There are several ways in which CWA may be used to enhance the outputs coming from ION, as well as SE and HFE to develop a transformative new state. The following section highlights how certain phases of CWA can be used to enhance these existing approaches.

### Benefits to Integrated Operations for Nuclear

*WDA.* Starting with business goals, ION utilizes the stack model to build out capabilities, sub-capabilities, work functions, and work reduction opportunities across the plant. The AH from WDA may serve to complement the stack model that is presented within the ICAP tool as an explicit means of characterizing the interrelations between stacked layers. For instance, as technologies are identified and selected (using the Innovation Portal) at specific work reduction opportunities, the AH can provide a way of visualizing the underlying structure of these synergistic benefits across work functions, sub-capabilities, and capabilities to ensure that the solutions are re-scalable and re-usable.

Figure 2 illustrates how AH may be used to map technologies to the stack model layers. As seen, there are synergistic benefits with having decision support and computer-based procedures. These enabling technologies are re-usable across both operations and maintenance capabilities and their associated sub-capabilities and work functions.

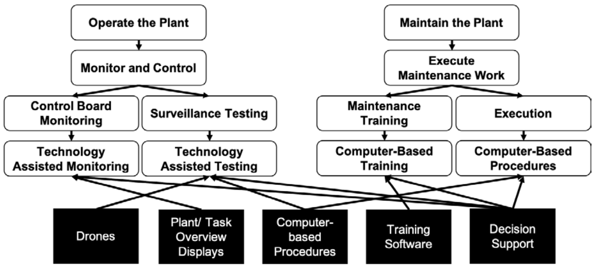

**Figure 2. Use of the AH to show the synergistic qualities of enabling technologies within the ION stack model**

### Benefits to Systems and Human Factors Engineering

*WDA:* The AH from WDA can provide unique value to the development of first principles used in the assessment methodology designed to inform how enabling technologies can best be configured to maximize their value. That is, the selection of specific capabilities in the new state should be guided by the specific qualities they can offer to promote efficient operations while maintaining safety. The first principles defined *what* the capability is and *why* it is important to the transformation. This information is used to address *how* available vendors can integrate these first principles. The AH can be used to map specific technologies to their functional characteristics that make them beneficial. These characteristics can then be mapped upward to higher-level goals. Figure 3 illustrates this mapping using the AH.

*ConTA:* The CAT can be used to identify where certain physical functions (see Figure 3, second-to-bottom layer) are used in known plant situations. These functions can then be evaluated in terms of decision processes using the decision ladder to show differences from the existing to new state.

*StrA:* Expanding on ConTA, StrA can focus on the differences in strategy from existing to new state. StrA may enable a qualitative comparison between existing NPP strategies to possible strategies of a new state NPP for a given activity. The output may offer insights into the ways technology or process changes can be best leveraged to improve efficiencies while also ensuring optimal safety. This information can identify focal areas in subsequent HFE activities like human-system interface (HSI) design and verification and validation (V&V).

*SOCA:* Roles and responsibilities can be mapped across previous CWA products. The application of SOCA provides a way to understand *who* will ultimately perform certain tasks within the new state. In the case where there already are well-defined roles, any changes identified from SOCA may be used to inform the concept of operations and subsequently any impacts to staffing and qualifications or training.

*WCA:* WCA can provide useful information regarding the human agents' requirements in performing specific activities in the domain. This information can inform subsequent industry standard NPP HFE activities described in NUREG-0711, such as function analysis, task analysis, HSI design, and V&V (Hugo et al., 2015). By understanding the effects of automation on the plant staff's decision processes, design decisions can be better informed.

## FINAL REMARKS

This work presents the use of the CWA framework to help in establishing the links from technologies to their functional qualities (i.e., first principles) important for a transformative new-state vision. CWA may also enrich existing business models, like ION, by illuminating the interrelations of technology to plant functions. Collectively, it may support convergence between approaches in developing a new state. Indeed, this work is still early. Future research is needed to understand the complete benefits of CWA in this context.

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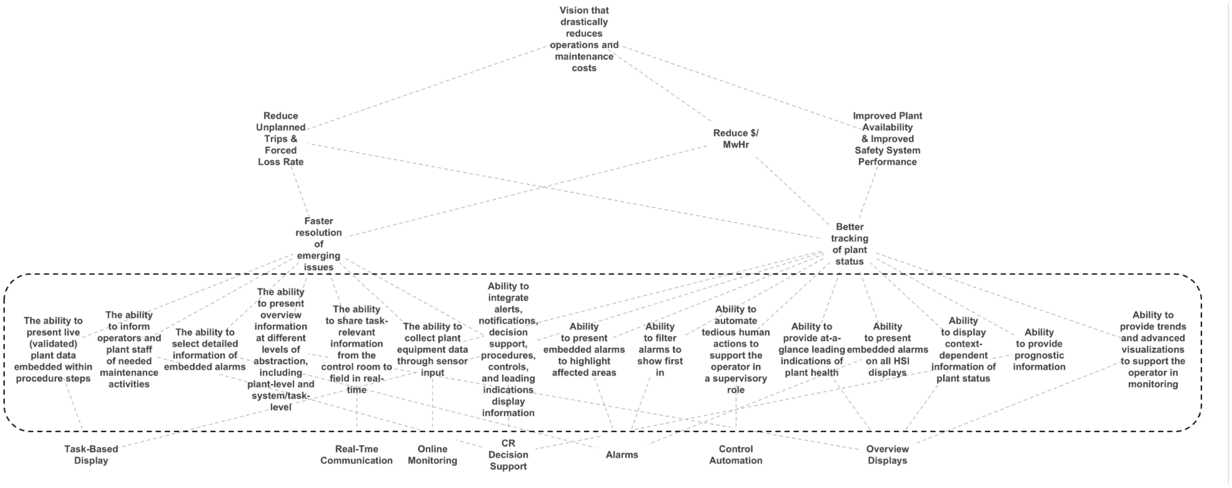

**Figure 3. Portion of the abstract hierarchy from the CWA-WDA framework to inform relations of enabling capabilities to high-level goals**