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Guidance on Including Social, Organizational, and Technical Influences in Nuclear Utility and Plant Modernization Plans

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Guidance on Including Social, Organizational, and Technical Influences in Nuclear Utility and Plant Modernization Plans

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ABSTRACT

The objective of this report is to provide the nuclear power industry with guidance on including socio-technical issues in plans developed for current and future modernization efforts. Socio-technical issues of concern include social, organizational, and related technical aspects of modernized systems. These can be addressed using a set of systematic analysis and design methods developed to address socio-technical issues of the sort facing the nuclear power industry. The next phase of this work will involve developing and implementing a modernization plan that includes socio-technical tools and methods identified and discussed in a report by Dainoff and colleagues (2020). The plan is expected to be developed and implemented in cooperation with a nuclear utility that has expressed interest in participating. The Dainoff et al. report provides the foundation for the present effort and presents a methodological tool set for analyzing socio-technical issues applicable to many modernization efforts. The tools described by Dainoff et al. are based on principles of human factors engineering, safety engineering, and systems engineering and are discussed within the specific context of nuclear utility modernization and transformation efforts. It is expected that the plan and the concepts described in the current report will be developed and implemented with a nuclear utility partner. The plan developed with the nuclear utility partner will have a substantially higher level of detail than the guidance provided in this report, particularly with regard to details of plan logistics, etc.

CONTENTS

ACRONYMS

AR	Augmented Reality
COTS	Commercial Off-The-Shelf
CWA	Cognitive Work Analysis
EID	Ecological Interface Design
EPRI	Electric Power Research Institute
HFE	Human Factors Engineering
HMI	Human-Machine Interface
HSI	Human-System Interface
IAEA	International Atomic Energy Association
IDEAS	Intervention Design and Analysis Scorecard
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Laboratory
MUIL	Manning Uncertainty Issues List
NCR	National Cash Register
NGT	Nominal Group Technique
NRC	Nuclear Regulatory Commission
NUREG	U.S. Nuclear Regulatory Commission Regulation
STAMP	System Theoretic Analysis and Modeling Processes
STPA	System Theoretic Process Analysis
UPC	uniform product code
WDA	Work Domain Analysis

GUIDANCE ON INCLUDING SOCIAL, ORGANIZATIONAL, AND TECHNICAL INFLUENCES IN NUCLEAR UTILITY AND PLANT MODERNIZATION PLANS

1. Introduction

Much of the nuclear power industry in the United States is currently considering and, in some cases, implementing a variety of substantial technical and organizational changes as part of a trend toward technical modernization and business-model transformation. In many of these scenarios, substantial changes to traditional means of conducting internal operations are anticipated. These include (1) increased reliance on computer- and internet-based technologies, such as virtual presence communications, augmented/virtual reality, expert/artificial intelligence-based systems, and drone and other robotic systems; (2) reduced staffing; and (3) significant changes to procedures, management, personnel selection and training. For clarity, we refer to these broad social, organizational, and related technical concerns as "socio-technical" issues (e.g., Noy et al. 2015; Walker et al. 2008). There is an emerging consensus within the industry that the success of future ventures of this sort largely depends on the degree to which factors associated with "people, technology, process and governance" (Droivodsmo, Reegard, & Farbrot, 2014) are effectively integrated. This is a view consistent with experience in comparable complex, transformational settings, such as in advanced military ship design (Hagan et al. 2010; Tate et al. 2005).

What has been lacking to date is a set of systematic analysis and design methods that can effectively address these types of social, organizational, and related technical issues. In a prior report in the current research effort, Dainoff and colleagues (2020) present a methodological tool set for analyzing issues of this sort, grounded in principles of systems engineering, safety engineering, and human factors engineering (HFE) and discussed within the specific context of nuclear modernization and transformation efforts. The current report is intended to further operationalize that approach by providing guidance on developing a plan to include socio-technical issues and considerations in nuclear industry modernization initiatives. Modernization efforts will include HFE, systems engineering, safety engineering, business practices, and other processes. This guidance focuses on three broad analysis and design issues: (1) identifying and developing a clear, shared understanding of the issues to be addressed in the analysis; (2) developing an analytic plan; and (3) conducting the analyses and translating the findings into useful system recommendations and documentation. These findings can then be used in supporting design processes and methods to apply physical and computational models to derive requirements and specifications leading to prototypes and test cases.

The guidance provided in this report is not intended to capture the full detail of an actual analysis plan; instead, the focus is on identifying key socio-technical issues and activities within various stages of the planning and execution processes and their relevance to effective system design and deployment. Topics are illustrated with 'side-bar' examples of potential modernization use cases drawn from an ongoing collaboration with a nuclear power operator located in the United States. Additionally, guidance is provided on matters related to the composition of cross-functional analysis teams, integration with the broader design and system engineering team, and other issues not directly related to specific socio-technical tools and techniques. Nonetheless, they are of central importance in conducting effective socio-technical analyses and are therefore discussed in this report.

The material that follows builds on findings and recommendations developed in an earlier stage of the current research program. That effort identified and described analytic tools and techniques for suggested application in nuclear power modernization efforts and similarly complex domains (Dainoff et al. 2020). The current report is intended to further operationalize the theoretical and methodological guidance laid out in this previous effort.

There is increasing recognition within the nuclear power industry of the impact of socio-technical factors on operations, particularly within the context of an economic environment that has placed significant pressure on the viability of future operations. Potential staffing reductions and related organizational restructuring, coincident with significant technical innovation and realignment, could pose unanticipated and unintended risks to system and organizational performance if their supporting analyses and design are not approached systematically. Demonstrably valid processes and techniques for analyzing issues of this sort are available, the results and findings of which can be readily applied to design processes, such as requirements development, prototype design and testing, training system development, system modeling, and other critical path activities. Many of these methods have been developed and tested within similar design contexts, notably those associated with reduced highly automated, reduced crew-size naval systems (e.g., Hagan et al. 2010; Tate et al. 2005). Appendix A provides six case studies illustrating the variety of design settings in which methods of the type discussed by Dainoff and colleagues (2020) have been applied to analyze and resolve socio-technical issues in complex system designs as well as the challenges involved in their successful application.

Dainoff et al. (2020) advocate for the application of a methodological toolset drawn from a set of well-established analytic and design techniques, most of which are drawn from HFE, safety engineering, and systems engineering principles and experience, with much of that experience being from within the nuclear industry itself (e.g., EPRI 2012, 2015, 2018; Ulrich et al. 2012). Additionally, drawing on the systems-based approaches of analysts and investigators, such as Leveson (2011), Hollnagel and Woods (2005), and Rasmussen, Pejtersen and Goodstein (1994), Dainoff and colleagues present their recommendations within the context of a broad, ‘work-system’ integration approach, focused on achieving the joint optimization of three subsystems:

- Technology—the tools, techniques, and processes used to conduct job functions
- Personnel—the makeup of the workforce (i.e., number of staff, qualifications, selection, and training requirements, etc.)
- Organizational and management—the structure and ‘behavior’ of the encompassing organization, including management policies, organizational decision-making structure, organizational culture (e.g., safety culture), raise, reward, and disciplinary policies, etc.

This approach to decomposing the work system overlaps substantially with that described by Droivodsmo and colleagues (2014), which was developed within the context of creating virtual organizations in the Norwegian offshore oil industry, whose objective was the optimal integration of “people, technology, process and governance” (p. 4). The major difference is that the work-system model includes the content and concerns of the ‘technology’ and ‘process’ domains under the common rubric of ‘technology’. The key point is that both approaches focus on the *effective integration* and *joint optimization* of these broad elements of complex, socio-technical systems and their constituent components.

Dainoff and colleagues also point out that the means by which three fundamental questions are addressed is a key determinant of success in complex analysis and design challenges:

- *How do we get the right information from the right people to satisfactorily address analysis and design issues*? Put differently, this question addresses the need to identify (a) the critical subject matter expertise—both within and outside the organization—needed to elicit knowledge regarding important socio-technical aspects of the analysis and design issues and (b) the most appropriate methods for eliciting and capturing the required knowledge and information.
- *How do we represent that information so it is useful*? There are two key aspects to this question, each involving an element of translation. The first involves translating subject matter expertise, and related analytic findings, into a form that can be used to depict various aspects of the system under design, either by means of ‘table-top’ model exercises, conceptual and/or computational models, prototype

design concepts, or some other method. A second process involves a translation of significant analytic findings into results and documentation that is consistent with the larger system design effort. These may take the form of system design requirements, personnel selection and training requirements, advanced prototype designs and test results, risk mitigation approaches and solutions, etc. An important consideration is that system representations are presented in a format (often graphical) that allows different stakeholders to form consistent, shared mental models. This becomes essential to avoid the silo problem, as described in the following section.

- *How do we achieve consensus among stakeholders and avoid the negative effects of organizational silos*? Key to the entire process described by Dainoff and colleagues, and the approach advocated in this report, is the effective leveraging of multidisciplinary, cross-functional teams. Organizational silos in analysis and design efforts, particularly with complex systems, can have significant negative effects on the system performance and user acceptance outcomes. Effective cross-functional integration is an essential, risk-reduction aspect of this approach.

The high-level analytic processes corresponding to these questions are referred to by Dainoff et al. (2020) as: (a) knowledge elicitation, (b) knowledge representation, and (c) cross-functional integration, respectively.

- *Knowledge elicitation* is involved in the identification and analysis of socio-technical issues involved in systems design. Its goal is to capture the unique perspectives and insights of design team members, subject matter experts, and representative users regarding critical elements of task performance and related social, organization, and technical factors and influences.
- *Knowledge representation* is concerned with depicting and modeling the results of elicitation processes in ways that promote a common understanding of the system within the analysis and design teams as well as within the broader project team. It is also concerned with translating analytic findings into results and documentation consistent with and directly useful to the project. These results and documents are meant to assist the daily activities of both design and operational personnel.
- *Cross-functional integration* is the overarching means by which each of the previous two processes is accomplished. Its primary objective is to ensure that representatives of all major stakeholder groups (potential end users, system developers, representatives from training, human resources and management, etc.) and topic-relevant subject matter experts are integrated in all analysis and subsequent design processes. Among its other useful aspects, cross-functional integration ensures that all relevant voices in the problem space are heard.

In this report, guidance is provided for the application of the socio-technical toolset described by Dainoff et al. (2020) in situations in which the development of novel work-system concepts is currently underway or under consideration. A set of use-case examples is provided, including potential modernization initiatives that impact broad organizational functions, such as maintenance, team communications, and decision-making. Many are based on concepts and technologies commonly associated with *virtual organizations* (e.g., Camarinho-Matos, Afsarmanesh, & Ollus 2005) and *integrated operations* (Haavik 2017). Specific use-case examples were identified in cooperation with a collaborating nuclear power operator in the United States and reflect areas of potential modernization interest. These include:

- *Virtual meeting dashboard design*, supporting timely and effective delivery of, access to, and control over key sources of information corresponding to meeting objectives
- *Capturing the expert knowledge* of an aging work force to support current and future system development and operation
- *User-specific, corrective action displays*, supporting an effective corrective action performance while maintaining appropriate levels of situation-specific awareness across the organization

- *Improved system status and monitoring displays*, supporting reduced workload and greater efficiency in information search and retrieval tasks
- *Use of augmented reality (AR)* to overlay information pertaining to a particular element in an operator or technician's field of view.

Each use case involves a key aspect of an integrated command, control, and communications (C3) capability. The objective behind their development is to safely, effectively, and efficiently meet operational goals and requirements, with fewer personnel, by leveraging the capabilities of emerging technologies (remote sensing, robotics, virtual presence, etc.) and modified approaches to personnel management, selection, and training.

The intent of this report is to provide the nuclear power industry with guidance on developing a plan to include analyses of socio-technical issues involved in current and future modernization efforts. The next phase of this work will involve conducting analyses of the type described in this report with an industry partner. The final analysis plan for that effort will have a substantially higher level of detail than the current sample overview, particularly with regard to details of plan logistics, etc. Nevertheless, it will address all of the issues raised herein.

1.1 Objectives

1.1.1 Objective One: Develop Guidance for Analysis of Socio-Technical Factors Impacting Nuclear Power Plant Modernization Efforts

The first objective is to develop guidance for the analysis of socio-technical factors impacting potential nuclear industry modernization efforts, incorporating the techniques described in Dainoff et al. (2020). The intent is to further operationalize this information in the form of guidance that analysts, engineers, and all stakeholders involved in similar efforts across the nuclear industry can use as part of their efforts.

The guidance, contained in Sections 2–4, is not intended as a template or script that can be applied without regard to the specific nature or context of the issue(s) to be addressed. Dainoff et al. (2020) describe many tools and techniques, not all of which are referenced in the examples contained within this report. The overview provided in this report describes key stages in the analysis process, particularly with respect to the analytic issues to be addressed within each. However, the specific tools and techniques discussed in relation to the use case example will not necessarily be appropriate for every type of analysis involving human activities within complex socio-technical systems. Guidance on the selection of appropriate techniques is provided in Dainoff et al. (2020) and is also discussed in Section 3 (Develop Analysis Approach).

1.1.2 Objective Two: Provide General Guidance on Analysis Plan Preparation

The second objective is to provide general guidance on analysis plan content and preparation of a plan specific to the needs of a utility. Therefore, each section of the guidance contains general discussions of the types of issues to be addressed within it. This includes:

- Assembling the cross-functional analysis team
- Developing an accurate, shared understanding of systems and issues for analysis
- Selecting appropriate analysis tools and methods
- Logistics, resource, and risk considerations
- Translating analysis results into system models, design recommendations, and project documentation.

Although all complex system analysis and design efforts are unique, including all nuclear power industry modernization efforts, they also share important areas of commonality with respect to the potential influence of socio-technical factors on individual, team, and overall system performance (e.g., Leveson 2011; Rasmussen et al. 1994). The purpose of the more detailed discussions within Sections 2–4 is to highlight those that are particularly critical to the analysis process.

1.2 Addressing Social, Organizational, and Related Technical Factors

The motivation for the framework and toolset described in the previous report was a perceived gap in the nuclear industry's guidelines and practices for system design and use. While several of these sources (summarized below and discussed in more detail in Dainoff et al. 2020) emphasize the importance of addressing social, organizational, and related technical issues in the design of new systems, there has been little guidance developed to date regarding how to approach their analysis and design.

The Electric Power Research Institute (EPRI) Digital Engineering Guide (2018) emphasizes the importance of applying systems engineering principles to the design or redesign of complex systems. In particular, the report emphasizes the central nature of multidisciplinary, cross-functional analysis and design teams (i.e., the breaking down of silos) in efforts of this sort. For example:

> *Systems engineering is a holistic, integrative discipline, wherein the contributions of structural engineers, electrical engineers, mechanism designers, power engineers, human factors engineers, and many more disciplines are evaluated and balanced, one against another, to produce a coherent whole that is not dominated by the perspective of a single discipline.*

EPRI's "Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification" (EPRI, 2015) acknowledges the importance of social and organizational factors on the design and performance of modernized control rooms but limits its specific focus to issues more directly concerned with human-computer and human-machine interface design. Clearly, guidance on how to plan and conduct valid analyses of socio-technical influences on a modernizing nuclear power industry is needed.

1.2.1 Relation to Prior Work

HFE has a long history in the nuclear power industry and has made numerous contributions toward improving the safety and efficiency of operations and maintenance. Over the years, much of this work has been formalized as guidance for control room design (e.g., EPRI 2015, 2018; IAEA 2019), maintenance activities (e.g., EPRI 2000), and other key elements of nuclear power operations. The importance of integrating HFE into design processes is further emphasized by NUREG-0711 (Rev 3, 2012), which provides a set of guidelines used by Nuclear Regulatory Commission (NRC) staff reviewing human factors plans associated with applications for construction permits, operating licenses, standard design certifications, combined operating licenses, and license amendments. The goal of the current research program is to build on HFE analysis and design tools that have proven useful in the past and apply similar principles and techniques to the development of modernized work systems for the nuclear power industry.

Similarly, Cognitive Work Analysis (CWA), with its origins in the nuclear industry (Rasmussen et al. 1994), was an important influence on the recommendations provided in Dainoff et al., (2020) and the current report CWA provides a set of modeling tools and an overlying conceptual framework for their application. The outcome of the analysis provides a perspective that allows for the development of support tools that makes the underlying system structure and dynamics transparent and allows the operator to make rapid adaptations to unforeseen events. The approach is formative in the sense that it provides a set of requirements that should be satisfied if work is to be supported effectively (Vicente 1999, chapter 5). Work Domain Analysis, discussed below, is one of the components of CWA.

Additionally, the System Theoretic Analysis and Modeling Process (STAMP) framework, developed by Leveson (2011), was also an important influence on the recommendations provided in Dainoff et al.

(2020) and the current report. STAMP extends traditional system safety, hazard analysis, and engineering methods into the domain of complex socio-technical systems. By analyzing the network of control and feedback relationships within an existing or proposed system, STAMP affords insights into performance risks and hazards that are often overlooked by traditional methods better suited to simpler and more linear systems.

Finally, Resilience Engineering, introduced by Hollnagel, Woods, & Leveson (2006), which is more of a design philosophy than a set of methods, has impacted our recommendations. In safety-critical systems, it is essential to build in the capacity for adaptive coping mechanisms to allow for unforeseen and unpredictable circumstances. These are the so called “unknown unknowns.” Humans, and the socio-technical system features supporting their work, will be the ultimate source of resilience.

2. Understand the Problem

2.1 Overview

This section provides guidance on the initial portion of the analysis effort, the principal goal of which is to develop an accurate and shared understanding of the modernization effort to be addressed and its potential socio-technical aspects and issues. An organization may have a variety of opportunities under consideration but no clear sense of which to begin to address, in what order, across what length of time, etc. In this case, the identification and clarification of the specific opportunities to be addressed and their related socio-technical aspects become the first objective. Alternatively, an organization may have already identified specific modernization efforts they plan to pursue, in which case there is still a need to develop an accurate understanding of their key socio-technical elements, as discussed below.

At this time, it is also common for the top management of the plant or utility to identify a senior management person to be responsible for overseeing the achievement of the plant improvement goal if the goal is at a high level. A middle manager might be assigned this role if the goal is more specific to a function, e.g., reduce mechanical maintenance costs. Teams and activities established to achieve the goal would be expected to report to this individual and present plans and results to this person, as requested.

It is important that this understanding, once achieved, is clearly documented and shared with all members of the cross-functional team charged with overseeing and conducting the analyses. An accurate, shared perspective on the issues, their fundamental characteristics and key socio-technical aspects, is critical to the conduct of an effective and efficient analysis process.

Major objectives in this stage of the analysis include:

- *Assembling a cross-functional analysis team.* The core of the analysis effort is the multidisciplinary, cross-functional team that guides and conducts it. At least one member of the team needs to have socio-technical analysis expertise.
- *Identifying modernization opportunity.* Several HFE methods exist that can facilitate the achievement of a group consensus. Selection of the modernization opportunity should consider associated socio-technical issues, e.g., reduction in workforce size, increased reliance on automation, etc.
- *Identifying system goals, constraints, and assumptions*. This involves identifying the system's planned functions within the broader organizational context, its anticipated benefits, constraints on its design and operation (budgetary, schedule, regulatory, etc.), and assumptions about the capabilities of novel technical, managerial, and procedural approaches central to its effective operation. Goals, constraints, and assumptions related to socio-technical issues should be identified.
- *Identify issues for analysis.* Having identified key assumptions regarding anticipated 'enablers' to system performance, the focus then turns to identifying potential socio-technical issues associated with the design. The objective is to identify those issues whose impacts on outcomes associated with system safety, performance, cost, efficiency, acceptance, etc. are likely to be greatest.

2.2 Assemble Cross-Functional Analysis Team

As discussed above, the cross-functional team is central to the process described by Dainoff et al. (2020) and is an approach that is increasingly used within industry and government to address complex issues of many sorts (e.g., Leinwand, Mainardi, & Kleiner 2016). It is also a method that has been applied to useful effect in other complex design settings involving technology-enabled reductions in staffing (e.g., Hagan et al. 2010; Tate et al. 2005) and other socio-technical influences on the safety and effectiveness of human-machine and human-computer systems. The seven case studies contained in Appendix A illustrate various aspects of the issues discussed in this report, and each illustrates the central importance of cross-functional teams.

One of the cross-functional team's initial activities is to identify areas of significant socio-technical concern or opportunity in the potential system design. When determining whether socio-technical concerns exist in a specific modernization effort, it is useful to consider the extent to which any of the following criteria are present in the design.

- *Reduced staffing*—In situations in which significant reductions in staffing are under consideration, issues related to the effective integration of job design, training, personnel selection, etc. will require analysis and resolution.
- *Novel technologies*—The use of advanced technologies, particularly in novel applications (remote sensing in support of maintenance, virtual meetings and conferences, etc.) will require an analysis of the safety and effectiveness of human-computer interactions.
- *Novel management systems*—Significant, anticipated changes to current management methods and changes to existing C3 structures and processes will also require analysis.

The team member responsible for conducting the socio-technical analyses should have relevant training and experience in HFE-related disciplines, preferably with specific expertise in the nuclear energy domain and issues related to its modernization efforts. NUREG 0711, Appendix A provides the standard, core set of knowledge and training this individual should possess, along with specific experience in the issues and domain of interest.

The term "cross-functional" means that representatives of all major stakeholder entities within the design are represented and engaged throughout the analysis process. Stakeholders include end users, HFE analysts with socio-technical expertise, organizational and technical expertise, program management, and personnel selection, training, and management expertise. A detailed description of cross-functional team makeup, requirements, and duties is provided in NUREG 0711 and is summarized below. The major components of the cross-functional team are as follows:

- *End users*—Representative end users are the most important stakeholders in any system design. Performance and acceptance of novel human-machine systems have been found to be positively influenced by the presence of end-user input in analysis and design (e.g., Francois et al. 2017). End users have unique insights into the realities and potentialities of system performance that nonexperts are often unable to detect. Their influence on analysis and design helps ensure that these activities are anchored in the realities of task and system performance. Because of heavy work schedules and other considerations, it may be a challenge to obtain the needed user participation. In situations such as these, recently retired or soon-to-be-retired end users can be particularly valuable. Note that in unionized work settings, involvement of union leadership requires careful consideration. Keeping union leadership informed of analysis plans and objectives involved in activities, such as end-user recruiting, analysis, and design processes, is highly recommended.
- *Human factors engineer/analyst*—The role of the HFE analyst will depend on the nature of the team. The HFE analyst may serve as team leader or as a member of the team. HFE analysts serve two key functions on the cross-functional team. They are responsible for (1) working with project leadership to assemble the team and organizing and facilitating its work and (2) capturing and analyzing relevant data and information from its activities and communicating its findings to the larger project team as appropriate. During team work sessions, the HFE analyst may serve as chief facilitator, ensuring that all stakeholder representatives are engaged and that analysis objectives are effectively and efficiently achieved. Note that in organizations that employ six sigma or other quality management units there may also be a need to integrate the cross-functional team within that organizational framework.
- *Organizational and technical expertise*—There are at least two broad types of organizational and technical expertise that are essential to the cross-functional team: (1) issue-specific expertise that is *internal* to the organization, familiar with how operations are conducted at present, how they might be

improved, etc. and (2) *external,* issue-specific expertise or individuals with applicable knowledge concerning key social organizational and/or technical aspects of the issue(s) under consideration.

- *Program management*—Clear lines of communication between the analysis team and program management help to ensure that the analyses remain focused on relevant objectives. Program management representation on the cross-functional team also provides a critical perspective, a 'bigger picture' of how the issues under consideration relate to system and organizational objectives. These individuals typically also have the most direct knowledge of important program constraints, such as changes in schedules, budgets, etc., that might impact the analysis process.
- *Personnel management, selection, and training*—Expertise from these domains helps illuminate issues related to the management of internal organizations and human assets, such as current and potential future personnel requirements associated with the system under consideration. These individuals also have unique insights into the limitations of current, internal organizational and human resource practices and how they might be modified to the meet the needs of the modernization effort under consideration.

This description of the cross-functional team includes its most essential members for many teams, but the specific nature of the issues under analysis will determine specific team membership. Also, there may occasionally be a need for additional expertise. For example, a technical expert may be needed to provide information on automated equipment, software and data analytics capabilities, etc. It is important to be able to adjust to the specific demands of the situation. Additionally, the size of the team should be managed to ensure that the proper expertise and stakeholders are represented without the number of individuals becoming unwieldy.

The specific makeup of the cross-functional team is likely to change over time as focus shifts from the initial identification and prioritization of issues to their more detailed analysis. As Dainoff and colleagues note, one approach to organizing and managing cross-functional teams, known as the Intervention and Design and Analysis Scorecard (IDEAS)(Robertson et al. 2013), recommends the use of two cross-functional teams in complex design settings. One serves as a steering committee and is largely responsible for setting strategic directions, such as determining which design issues will be addressed and concerns related to resources, timelines, etc. If a steering committee is not established, the manager assigned responsibility for achieving the modernization goal may provide direction to the work that is to be performed and review and approve plans.

A vital consideration in the success of the cross-functional team approach is that members must be able to commit sufficient time toward accomplishing its objectives. This can be challenging, as most members will already have busy schedules, but it is essential. The period of time during which the team will be active and the amount of time (i.e., number of hours) required depends on the complexity of the issues to be addressed and the constraints of system development schedules and budgets. The HFE analyst will need to be able to provide, and periodically update, program leadership with realistic time estimates for team members' participation.

Cross-Functional Teams Capture and Preserve Expert Knowledge

Many companies are currently facing the loss of substantial organizational knowledge as the average age of the U.S. workforce increases. Increasing rates of retirement mean that the valuable expertise gained by individuals over the span of their careers is being lost (e.g., DeLong 2004). While cross-functional teams are not the only means of capturing and documenting this expertise, its major goals are to (a) elicit such knowledge within the context of a specific analysis or design issue and (b) document it in forms that are useful to the project and the organization as a whole. Therefore, a potential by-product of its use in analysis and design in the nuclear power domain is the preservation and transfer of expert knowledge relevant to important areas of future plant design and function

2.3 Identify Modernization Opportunities

It is particularly important to identify plant functions that offer the greatest opportunities for significant improvement in performance, safety, and reduction in cost. Naturally, this has to occur very early in the process and one of the first objectives of the plant executives or possibly the manager identified to lead the modernization effort is to establish the goal(s). This identification of one or more goals is of critical importance. It is expected that the analysis and recommendations for achieving overall goals will be extensive and usually expensive. For example, the overall goal may be to reduce operating costs by 25%, reduce number of experts across the utility because of a difficulty in hiring and retaining them, or reducing time from when a maintenance problem is identified and a capable maintenance person can begin to repair the problem, etc. It is often the case that several analysis efforts will be established to address the goal of concern, e.g., multiple analysis efforts to reduce operating costs by 25%. In this example, more than one team may need to be established, with each team responsible for one or more analyses. If it is determined that group agreement on establishing a goal is desirable, a cross-functional team, in particular, rather than a broader, steering committee may be established. Dainoff et al. (2020) describe several methods that can be used to achieve group consensus in situations of this type. For example, the Nominal Group Technique (NGT) (Bagan & Derede, 2019; Delbecq et al., 1986) is a knowledge elicitation technique in which each stakeholder's perspective on an issue is documented and shared amongst the team, which then discusses each perspective and finally votes to prioritize and establish its findings. NGT has been used in many domains, such as in the U.S. Navy's USS *Zumwalt* surface combatant design program (Tate et al. 2005), and is described in more detail in the following section. Other approaches, such as Work Domain Analysis (WDA) (Simons et al. 2006; Vicente 1999), can afford a more detailed examination of the socio-technical problem space should a procedure such as NGT not achieve consensus.

In addition to identifying high priority problem areas requiring solutions, the identification of corresponding, high-level socio-technical issues is also an important **early** objective. For example, activities involving the highest cost, regulatory problems and potential costs associated with human and equipment errors should be examined by the team to identify problems to consider. Candidate problems involving socio-technical issues should then be evaluated to determine their priority for improvement.

2.3.1 Nominal Group Technique – Identification of Modernization Opportunities

NGT is a useful method for establishing group consensus regarding issues of importance to the analysis and design effort. For example, in situations in which specific modernization opportunities have yet to be identified or prioritized, NGT can provide a basis for a thorough examination of alternatives supporting a decision process in which all voices are heard. Limiting the number of individuals to 25–30 or less in a given session is advisable to help manage the discussion process. More than one session can be held on a given issue if necessary.

There are many variations of NGT, but all share the following characteristics:

- A representative cross-sample of program management and individuals with relevant expertise regarding the design issues under consideration is assembled.
- The group assembles for the purpose of discussing the options under consideration, weighing factors such as the potential cost, feasibility, and safety associated with each. A lead facilitator (usually, but not necessarily, the HFE analyst) assumes responsibility for managing the group's discussions, making sure issues are thoroughly addressed in a timely manner. These discussions are often supplemented with other data sources (cost-benefit tradeoff analyses, potential regulatory impact analyses, etc.).
- The group then votes on the options under consideration to converge on a final decision regarding the issues under discussion. In the present context, this may take the useful form of a prioritized list of modernization opportunities.

NGT has been applied in the nuclear power industry in several prior cases. For example, immediately following the 1979 accident at Three-Mile Island, the Institute of Electrical and Electronics Engineers (IEEE) convened a workshop, sponsored by the NRC, to identify required HFE projects in the nuclear industry (IEEE 1980). The projects identified and prioritized at that workshop helped establish the course of HFE's significant contributions to the nuclear industry in the intervening decades.

Nominal Group Technique and USS *Zumwalt*

In the 1990s the U.S. Navy became increasingly concerned about the high lifecycle costs of manpower and began to examine the possibility of designing systems that requiring fewer sailors to operate while still achieving high levels of performance and safety. The USS *Zumwalt*, a highly-automated, reduced crew size surface combatant, was one of the early outcomes of this effort. Over the course of its analysis and design efforts, during which virtually all legacy human-computer and human-machine systems were redesigned or replaced with commercial off-the-shelf equipment, approximately 1,000 active duty sailors served as subject matter experts. NGT was the technique most commonly used in situations in which establishing a user-based consensus on analysis and design decisions was the key objective. Case Study 1 in Appendix A provides additional information on *Zumwalt*'s design.

2.4 Identify System Goals and Timelines

Once system modernization or redesign opportunities have been identified and prioritized, clarification of system goals and timelines may then be determined by the project manager or by a steering committee. The socio-technical team member should provide system goals related to socio-technical issues. System goals can be expressed in terms of projected or desired outcomes, such as level of system performance, influence of the system of interest on other socio-technical elements of the organization, number of projected personnel required to meet staffing goals, etc. Once determined, these will help to define criteria for a successful system design as well as focusing analysis efforts and resources appropriately.

One important activity in this stage is performing an operations evaluation and lessons learned review to determine problems identified and solutions applied in other nuclear utilities and other industries. Another important activity is developing as clear of an understanding as possible of the key social, organizational, and technical assumptions underlying system performance goals. Specifically, it is important to identify the key socio-technical enablers of system and overall organizational performance objectives. For instance, the envisioned system may have significant dependencies on reduced staffing, remote/distributed management and communication systems, etc. It may also rely upon the availability and reliable performance of supporting technologies whose influence on human-system performance in the desired context may not be well understood. The identification of these enablers, along with a description of their anticipated impact on system performance will help to clarify the identification of specific issues for analysis, a topic taken up in the following section.

Eliciting and documenting stakeholder perspectives is as essential to this stage of the effort as it was in the prior stage. In addition, it is important to consider such factors as cost, availability of desired devices, regulatory requirements and other considerations. High-level, strategic decision-making at these stages determines the course of the analysis effort to follow. Conversely, inadequately incorporating the strategic inputs of stakeholders at this point can result in a serious risk that the analysis and design products will not meet organizational expectations or requirements. In other words, important perspectives on the system could be missing. Case Studies 2 and 3 (see Appendix A) illustrate the benefits of adopting this approach in one case involving a complex design problem and the risks involved with not securing key full stakeholder consensus at this stage in another.

2.5 Identify Issues for Analysis

Having developed and documented a set of key, strategic directions and system-enabling assumptions in the prior two stages, the focus in this stage turns to the more detailed level of identifying specific issues for HFE analysis.

The social, organizational, and technical assumptions identified in the previous stage can focus team discussions aimed at the identification of specific analytic issues in this stage. Analytic priorities should be devoted to those areas of the design with the greatest potential influence on the success of the system, or upon which key parameters of system performance have the greatest dependence. For instance, if one of the key parameters or criteria for system success is a significantly reduced staff size, an analysis of the performance, workload, and situation awareness in execution of representative tasks will be of interest. Similarly, if the design makes assumptions about the performance and usability of technical systems, such as AR or virtual meeting interfaces, these become a priority for an analysis within the context of their intended use cases. NGT, supplemented by data from supporting cost and technical feasibility studies, can also be used as a consensus-building approach in this phase of the team's work.

Another potentially useful method for identifying and prioritizing analysis issues is Klein's premortem approach (Klein 2007). Using this method, team members are asked to imagine that the project on which they are about to work has reached its end (at some point in the future) and has failed. Participants brainstorm and discuss potential reasons for project failure and identify and prioritize issues to analyze, perhaps using a technique similar to that in NGT (Section 3.1.1). The premortem approach has been shown to useful in a variety of complex systems settings, such as medicine (Mills & McKimm 2017), and as a complement to a variety of techniques, such as engineering fault tree analysis (Eckert 2015).

Augmented Reality for Maintenance Procedures—Analysis Issues

Augmented Reality (AR) is frequently mentioned as a potential technical enabler of more efficient and effective performance of complex, procedures-driven processes, such as system maintenance. For example, AR is increasingly being used to support aircraft maintenance procedures (e.g., Palmarini et al. 2018) where it has shown promise in reducing error frequency and increasing efficiency. However, to be effective, AR systems have to be tailored to the specific contexts of their intended use. Determining the amount and type of information to make available to users within the context of specific plant maintenance procedures is a necessary step to avoid issues such as information overload, absence of key information, timing of information delivery, etc.

2.6 Summary

This section has presented guidance for initiating an analysis of socio-technical issues involved in potential nuclear power industry modernization efforts. Beginning with the development and documentation of a shared understanding of a project's goals, constraints, timelines and, importantly, assumptions about potentially enabling social, organizational, and technical assumptions, this initial stage concludes with the identification of specific issues for analysis.

There may be an occasion for these processes to be revisited from time to time, particularly over the course of a complex project. New constraints (e.g., altered program schedules), issues (e.g., emergence of a previously unforeseen human-system performance problem) and opportunities (e.g., appearance of a new technology with a significant, potential benefit to the program) may arise. In situations such as these, it may be appropriate for the cross-functional team to adjust its analysis efforts to meet the demands of the new program context.

3. Develop Analysis Approach

3.1 Overview

The guidance in this section focuses on major activities involved in developing a systematic approach for analyzing the issues identified in the initial stage. Once again, the cross-functional team is the central locus of activity. While much of the responsibility for selecting appropriate analytic methods will fall on the lead HFE, systems engineering, or safety engineering analyst, this should only occur after review, discussion, and input from across the team.

Major objectives in this stage include:

- *Develop analysis objectives.* Planning at this stage involves developing and communicating a description of the analytic objectives associated with each issue, particularly regarding the human-system integration and performance concerns to be addressed.
- *Select analysis tools.* The core of this stage of the planning process is the selection of appropriate analysis tools and methods. 'Appropriate,' within this context, refers to validated tools and methods (described in Dainoff et al. 2020) whose prior application in the analysis of comparable, complex socio-technical systems has been shown to produce information of significant value to their design and use. In addition, some HFE methods not directly applicable to socio-technical analysis but applied in nuclear plant control room modernization efforts may be needed. The cross-functional team, in most cases, will be responsible for not only identifying and applying appropriate socio-technical methods but also "traditional" HFE methods (e.g., hierarchical task analysis, operational systems analysis, and link analysis). Appendix B provides a table of many of the more commonly applied methods of this sort.
- *Develop logistical plan.* The tactical planning portion of the efforts involves identifying and securing required resources and developing an integrated, master schedule of analysis activities. It also involves the identification of critical dependencies in the plan, such as the availability of subject matter experts, whose schedules are typically busy and whose availability must be secured well in advance of when it is needed. Risks to plan execution and corresponding mitigation steps should also be documented.

Experience suggests that systems analysts often have preferred tools and methods and may be consciously or unconsciously biased in favor of their use, regardless of their actual value for specific analysis goals. Colloquially, these are referred to as 'solutions in search of problems.' The guidance in this report is instead intended to help analysts acquire and document a shared understanding of the design context and related socio-technical issues (see Section 2) in order to develop a coherent analysis plan and select the appropriate tools or methods to address the issues at hand

3.2 Develop Analysis Objectives

Having identified socio-technical issues of concern in the previous stage, the next stage focuses on developing and documenting analysis objectives. Several basic aspects of human-system integration and system performance can provide a starting point for team discussions focused on identifying analysis objectives:

- *Staffing*—Reductions in the number of personnel conducting tasks will, in nearly all cases, require careful analysis to determine if work can be safely and effectively performed. Human-system performance implications of staffing levels, qualifications, and training requirements are important topics for HFE analysis.
- *Human-machine and human-computer interfaces*—If the design involves the use of new (to the organization) technologies, an analysis of their human-system performance implications will be

required. The degree to which individual users and teams are able to efficiently and effectively obtain task-relevant information and control system activity is a critical concern.

- *Management policies and procedures*—As discussed by Dainoff et al. (2020), changes to management policies and procedures associated with modernization efforts have direct implications for the safety and effectiveness of human-system performance. Besides specifying how work is to be accomplished, by whom, etc., management policies and procedures have important effects on the organizational culture within which work occurs, with a significant impact on job performance. Notably, the NRC (2011) has issued a policy statement regarding safety culture, including a list of organizational traits, such as leadership safety values and actions, problem identification and resolution, personal accountability, questioning attitude, work processes, continuous learning, and others (see also Dainoff et al. 2020, Section 4.1.8).
- *Communications*—Most aspects of team function rely on timely and informative communications between team members. Effective on-the-job communications are a function of many factors, including each of those previously mentioned (i.e., policies, procedures, equipment, and staffing). Insufficient or faulty communications are a key influence in many accidents and issues related to poor system performance (Leveson, 2011) and are a vital HFE concern.
- *Automation*—Automation, expert systems, and artificial intelligence/machine learning are likely to play important roles in reduced staffing contexts with key dependencies on technical solutions. The design of the underlying algorithms driving these systems and the manner in which they interact with the user is an important HFE concern.
- *Data Analytics*—Advanced technologies supporting concepts, such as virtual organizations, remote sensing and operations, etc., are likely to be reliant on large, integrated datasets and supporting algorithms. The reliability and timeliness of information provided to system users will be significantly influenced by data analytics.
- *User Acceptance*—Users of the modernization effort results, including the socio-technical changes, are important in determining if the changes will be successful. User participation on the team is an important factor in determining success.

These broad focus areas will, in most cases, cover the majority of socio-technical concerns in complex modernization efforts. The more traditional concerns of HFE are also of importance. For example, new human-machine interfaces may provide opportunities to improve system performance. The relative priorities assigned to these issues and their analysis is a pragmatic decision to be made by the cross-functional team, under the direction of program management. However, from a purely HFE perspective, focusing on those issues with the most direct relation to (1) key system design objectives/outcomes and (2) key socio-technical system enablers is recommended.

Virtual Meeting Dashboard Display—Analysis Objectives

The 2020 novel coronavirus pandemic has firmly introduced the concept and technology of the virtual meeting to much of the world's population. Many organizations have found that virtual meetings accomplish all, or nearly all, of what traditional meetings were able to accomplish at a substantially lower cost and greater convenience. However, taking full advantage of these systems for dedicated use in nuclear plants will, in all likelihood, involve developing and incorporating dashboard displays containing critical, meeting-specific information. Identifying specific information requirements for various meeting functions and activities is, therefore, a key analysis objective. Subsequently, identifying the most effective means of making that information available within the constraints of potential technologies becomes another key analysis objective.

3.3 Select Analysis Tools

Selecting analysis tools and methods appropriate for a given design context is a matter of identifying those which will most effectively and pragmatically produce findings that address the issues that have been identified. As Dainoff et al. (2020) note, tradeoffs between the conceptual unity underlying a plan (e.g., a consistent user-centered analysis and design process) and pragmatic considerations associated with shifting program priorities, resources, and timelines are not uncommon in complex design environments.

Developing a clear description of each analytic issue to be addressed is a useful initial step. Much of this description may have already occurred in the previous identification of human-system performance concerns (see Section 3.2) and, as a result, the selection of the analytic method(s) might be clear. For instance, in the area of novel human-machine or human-computer interface design, it will nearly always be essential to perform an analysis of individual and team information and control requirements (to support initial design), perhaps followed by the preparation of prototypes and human-in-the-loop testing of the system's ability to support representative tasks. CWA is a commonly applied method for addressing the former concern, while a variety of simulation testing approaches can support the latter, such as cognitive walkthroughs, usability tests of different sorts (e.g., "Wizard of Oz"), and high-fidelity simulation testing. Other analytic tools and approaches, such as STAMP, are useful in analyzing existing and potential designs for C3 bottlenecks and other issues. Several tools and techniques are summarized below, along with discussions of their potential relevance to the types of analytic issues posed by nuclear modernization.

3.3.1 Cognitive Work Analysis

With its roots in the nuclear power industry, CWA is a socio-technical analysis approach well-suited to the analysis of complex systems. CWA places little emphasis on specific data collection or analysis techniques. Instead, its emphasis is on clarifying and describing the multiple forms of constraints that impact the operation of complex, socio-technical systems. It accomplishes this primarily through focused discussions on the part of the cross-functional team and relevant subject matter experts.

CWA focuses on identifying design constraints imposed by the purpose of the system, its various functional properties, properties of the activities that are conducted by humans and technology within the system, the roles played by the various human and technical components, and the strategies and skills manifested by and required of those components. WDA, one of the major areas of emphasis within CWA, provides a high-level specification of the constraints that govern the function and purpose of a system. A virtual communications system, for instance, has various high-level constraints imposed on its operation from its own inherent, technical capabilities and limitations while its intended purposes impose separate constraints related to planned applications.

Other CWA analyses focus on examining subsets of these system level constraints, eventually converging at a level of descriptive specificity that can support design activities, such as requirements generation and human-system interface (HSI) prototype development. For instance, social organization and cooperation analysis, another CWA component, is particularly applicable to nuclear modernization efforts that are dependent on close coordination between human and technical components of virtual communication systems.

Several recent publications (Gawron 2019; Stanton et al. 2017; Seamster & Redding 2017) provide useful overviews of specific methods and techniques associated with CWA. Li and Burns (2017) provide a description of the successful application of CWA in supporting function allocation decision-making in the design of advanced systems, which is a key HFE consideration in the design of the types of virtual communication systems envisioned for use in nuclear modernization settings.

3.3.2 Knowledge Mapping

A knowledge map is defined as "an association of items of information (e.g., process, network, policy, geography, etc.), preferably visual, where the association itself creates new, actionable information" (Ebener et al. 2006). Knowledge mapping is based on knowledge elicitation to obtain map content and relationships, and the maps are used for knowledge representation to show users the knowledge gaps. There are multiple knowledge mapping methods (Balaid et al. 2016 provide a recent review of specific techniques). Concept mapping, for instance, is one knowledge mapping method that has been used in the nuclear industry (e.g., Rzentkowski et al. 2011).

All knowledge mapping techniques share several features in common:

- The elicitation of system-specific expertise, often with settings similar to cross-functional teams with the participation of relevant subject matter experts. For instance, in a nuclear modernization setting focused on the design of an augmented reality-based maintenance system, this expertise may take the form of in-plant maintenance management and task performance expertise, along with other design-specific technical expertise (e.g., experts in AR systems).
- The visual representation of the relationships between socio-technical components of the augmented reality-based maintenance system.
- Focused discussion amongst the team on issues related to the possibilities and constraint of system operation.

The outcome of knowledge mapping activities can generally take the form of input to system design requirements, function allocation recommendations and decisions, and system prototype design options.

3.3.3 System Theoretic Analysis and Modeling Processes

As another example, the analysis of issues related to the effectiveness of a modernized system's proposed command, control, and communication structure and capabilities can be approached in a variety of ways. Leveson's (2011) STAMP approach has been shown to be very useful in these types of analyses and is more sensitive to the identification of potential system bottlenecks, ambiguous control and/or decision-making responsibilities, and similar system issues than traditional approaches to system analysis (Thomas & Gibson, 2020).

One of STAMP's principal systems analysis tools is the System Theoretic Process Analysis (STPA) method. STPA is easily learned and understood, particularly by those with relevant system end-use or system engineering backgrounds. Its major steps are as follows:

- *Identify potential accidents, hazards and system safety constraints*—in the area of non-safety nuclear operations, an accident or hazard may include events such as the loss of data, miscommunication of information during remote operations or other such events that result in lost resources or failed operations. System safety constraints describe the losses, accidents, and other undesired outcomes that system design must preclude.
- *Draw the system control structure*—The STPA system control structure is a schematic depiction of the communication/control and feedback relationships between the human and technical components of the socio-technical system under analysis. In a non-safety, nuclear modernization setting this could represent the network of human and technical components involved in virtual meetings and conferencing, in which a hazard might be the miscommunication of important information. The STPA control structure would represent the flow of information, modeled as a network of control and feedback relationships, across the system.
- *Identify unsafe control actions*—In this step of the analysis, actions on the part of humans or software-based agents that may possibly result in accidents are specified. In a non-safety, nuclear

modernization setting, this step would focus on the identification of those human or software-based actions whose outcomes could result in significant disruptions to business operations.

- *Identify Causal Scenarios*—This step of the STPA process involves the collaborative examination of the control structure for the purpose of identifying scenarios that could lead to operationally relevant hazards, such as the miscommunication of important information between a maintenance manager and a maintainer operating remotely. Methods of ameliorating the occurrence of these causal scenarios are then identified and evaluated.

In the end, the selection of analytic tools often boils down to an analysis of tradeoffs between the adequacy of available methods (i.e., their history of application to similar issues, their overlap with specific issues, etc.), the number of issues to be examined and the time, schedule, and resources available to accomplish the work. Two rather broad criteria for assessing the potential utility of analytic tools are provided by Naikar (2009): usefulness and feasibility. Usefulness can be assessed in terms of two subcategories, impact and uniqueness. Impact reflects the extent to which the method actually influenced practice, whereas uniqueness reflects the extent to which a novel contribution is made relative to standard techniques commonly in use. Feasibility is assessed relative to the capability of the method to be accomplished within existing project resources (e.g., schedule, staff, and financial budget). Stanton et al. (2013) provides general guidance on tool selection, which is consistent with that shown in this report. The selection is a function of the cross-functional team's consensus regarding the value of each method's analytic output to the design and the availability of time and resources to conduct it.

Appendix B provides a table of additional, more traditional HFE tools and techniques that, in many cases, will usefully supplement the socio-technical methods described by Dainoff et al. (2020). The analysis team should carefully consider whether any of these methods can shed additional, significant light on issues impacting the design.

User-Specific Corrective Action Displays—Analysis Tools and Methods

Corrective action displays provide information to different types of users (i.e., management, operations, maintenance, etc.) regarding the nature and status of ongoing corrective actions within a plant. Frequently, these displays are very cluttered, containing data and information of uncertain vintage and, frequently, of little or no direct value to a particular user. CWA provides an analytic method for identifying each user's corrective action display information and control requirements, information which can, in turn, be used to develop system design and performance specifications.

3.4 Develop Logistical Plan

The last step in this stage involves the development of a logistical plan for conducting the analyses. Important activities in this stage involve the development and dissemination of an integrated master schedule of analysis activities, developed by the cross-functional team and approved by the steering committee and other relevant program management. Forcing functions on the schedule include factors, such as program deadlines, and the availability of key physical resources (simulator facility, mock up, etc.) and personnel, notably end users and subject matter experts.

The socio-technical analysis schedule must also be integrated with other relevant program plans and schedules, an appropriate task for the steering committee. These include the overall HFE, systems engineering, safety engineering, and business plans. Modifications to these higher-level plans may have direct relevance for the socio-technical analysis plan. Therefore, it is important for the team to stay in close contact with the master planning and scheduling process and modify its own schedule in response.

Additionally, it is important to identify (and continually update) the risks against the successful completion of analysis activities. The potential lack of availability of key resources, or dependencies on other program activities, are examples of risks of this sort. This section of the plan should clearly describe the risks, their potential impact on analysis objectives, and current or anticipated mitigation strategies.

3.5 Summary

This section has presented guidance on developing an analytic approach to the resolution of issues identified early in the design process. The major activities are (1) developing strategic analysis objectives, (2) selecting appropriate tools and methods, and (3) developing a logistical plan.

As was the case in the initial stage (see Section 2), it is beneficial to revisit some of the above processes from time to time over the course of the analysis. In addition to updating the logistical plan, risk mitigation strategies, etc., new analysis opportunities might arise (e.g., sudden availability of a subject matter expert or prototype test system), in which case it might be beneficial to adapt the analytic plan to take advantage of the opportunities presented. Similarly, frequent and consistent examination of analysis outputs and products is advisable to determine if analysis objectives are being met or if a change in approach is required.

4. Conduct Analyses and Translate Findings

4.1 Overview

The guidance in this section relates to the final steps of the analysis process—conducting the analyses, describing and modeling the implications of findings for system performance and design, and translating the results into usable design guidance and project results. These processes overlap with the domains, and corresponding toolsets, of "knowledge elicitation" and "knowledge representation" as described in Dainoff et al. (2020).

Expressed somewhat differently, the major objectives in this phase of the analysis are to:

- Apply the socio-technical tools and methods identified in the planning phase to generate results applicable to the modernization effort, as identified in the first stage.
- Represent the findings by documenting, modeling, or otherwise describing their influence on key system performance parameters.
- Translate findings from the analysis and modeling into forms useful for design (e.g., system design specifications and requirement, training and personnel requirements, system prototype design and test results, etc.).

Once again, the cross-functional team is the primary locus of activity in this stage, since most analyses and translation activities will depend on the participation of key design stakeholders. Schedule changes and competing demands can make stakeholder availability difficult, so it is critical to regularly revisit the analysis plan in order to make any necessary schedule and resource adjustments in light of emerging challenges or opportunities, such as the unexpected availability of a particularly useful subject matter expert or data collection opportunity.

4.2 Conduct Analyses

The HFE analyst's role in this stage of the process combines data collection and analysis responsibilities with the requirement to successfully manage an integrated schedule of activities in a finite period of time. Conducting, or overseeing the conduct of analysis activities requires that the HFE analyst become fully familiar with the methodological details of how selected tools are to be used. Dainoff et al. (2020) provide information on applying the tools and techniques described in their report and provide extensive references to more detailed sources. The EPRI (2015) report is an example of a document that provides guidance on a process and methods that may be useful. Stanton et al. (2013) and Gawron (2019) also provide useful methodological discussions for many of these tools.

The HFE analyst also has the responsibility, if the analyst is team leader, of keeping program management, and certainly the team, informed of the progress of the analysis efforts. While this may occur within the context of periodic meetings of the steering committee, it is also frequently useful to inform stakeholders outside of the team about the progress of analyses relevant to their areas of concern in the design. This is also a useful means of acquiring information about actual or planned modifications to a particular aspect of the system, changes in schedule, appearance of new issues, etc. All of these are relevant to effectively managing the analysis process. On occasion, there may be a need to revisit and revise the analysis plan in light of emerging changes of this sort. However, the fundamental objective of the process remains the same, effectively addressing and analyzing socio-technical issues of concern to the current design concept.

Modeling Socio-Technical Systems

Modeling is a useful approach for analysis of complex systems. It is also useful for envisioning those systems, thereby providing the design team with the basis for a common mental model of its structure and operation. Physical models range from relatively simple (e.g., table-top exercises) to more complex (physical mockups, interactive prototypes, etc.). Conceptual, analytic models are also useful in this respect. For instance, Thomas and Gibson (2020) have applied the STPA component of the STAMP framework to the analysis of potential digital control systems for the nuclear industry and found it to be more effective than traditional methods at identifying potential sources of common-cause failure. The STPA method provides a conceptual model of the system referred to as a control structure that serves as a type of functional map of the system, identifying important linkages between organizational and technical components of the system. Widely used in other domains, STAMP is more recently making inroads into the nuclear industry.

4.3 Translate Findings

Having completed analysis activities and documented and shared key findings across the larger engineering design team, the final step involves the translation of HFE findings into design requirements, specifications, risk register entries, and other results. Simply put, this means that the HFE analyst is responsible for achieving consensus within the cross-functional team on the relative criticality of the findings and their relevance to specific areas of system design. Once consensus is achieved and shared with the steering committee, efforts will then focus on working with the engineering design team to create or modify system requirements to reflect analytic results. Analyses might also reveal unforeseen potential risks to system performance, which may require documentation within a formal risk register.

Physical results are also a highly useful analysis product. Simulations, physical mockups, etc., besides having clear value in terms of envisioning the system under design, also support more detailed design efforts as the project moves to completion. Interactive, human-in-the-loop simulations, though potentially costly, can provide extremely valuable information about specific aspects of system performance and can support a final ‘tweaking’ of the design in its later stages. Ecological interface design, discussed below in Section 4.3.1, is a method that has proven useful in the design of prototype human-system interfaces in nuclear industry design settings.

When a socio-technical system is developed and deployed, either partially or fully, there is still a need to monitor and assess its performance on a regular basis. Safety climate survey methods, discussed below in Section 4.3.2, provide a straightforward and reliable means of identifying potential human-system integration issues.

Improved System Status and Monitoring Displays—Use of Simulation Findings

Human-in-the-loop simulation, whether conducted in the form of a ‘cognitive walkthrough’ (e.g., Wharton et al. 1994) with a relatively simple (i.e., noninteractive) prototype or in the form of an actual performance of system tasks in an interactive simulator, is a very useful source of information for generating requirements, identifying risks and other design-relevant activities. Improving the system status and monitoring displays is a topic well suited to simulation studies as suggested in its frequent use by the U.S. Air Force in the cockpit interface design process (Hettinger & Haas 2003). Physical simulations, whether interactive or not, are also key to the conduct of A-B testing of alternative designs, the results of which translate directly to system requirements.

4.3.1 Ecological Interface Design

Ecological interface design (EID) (Bennett & Flach, 2011) is a logical outgrowth of CWA, building on its results in a manner that is very useful to the development of prototype HSI concepts. One of the key outcomes of CWA is a description of constraints on safe and effective system performance (e.g., information, control, and communication requirements). The purpose of EID is to translate those descriptions of system constraints into representations and specifications useful for HSI prototyping and design. As such, it is a very useful tool for extending the results of CWA and other relevant, prior analyses into the candidate prototype designs.

EID focuses on the development of HSIs that use visual and auditory methods to provide users with an intuitive understanding of underlying system activities and processes, freeing up the operator to focus on more complex decision-making tasks. EID is similar to other user-centered design approaches in that knowledge elicited from representative users and experts in earlier analyses support later HSI design. However, EID's focus is primarily on the work space, as opposed to the end user, and seeks to effectively represent to the user all relevant possibilities for interaction with it.

The nuclear power industry is one of the contexts in which EID has been successfully applied (e.g., Vicente 2002; Vicente & Rasmussen 1992). As a natural extension of CWA, it is a particularly useful activity that can support the design of prototype HSIs for later user testing and analysis.

4.3.2 Safety Climate

Once a new socio-technical system is in place and operating, periodic analyses of the types described above should be conducted to monitor performance and detect potential issues in their early stages. In addition, a widely used technique for the early detection of potential system problems, particularly those that could potentially impact employee safety, is the assessment of safety climate. Safety climate is defined as the employees' shared perceptions of the relative importance of safety within an organization as compared to other factors, such as productivity or efficiency (Zohar 1980). Meta-analyses of over 200 safety climate studies (Christian et al. 2009) demonstrate the value of safety climate assessments as leading indicators of the likelihood of accidents and injuries. Safety climate scales are easily deployed and are also useful indicators of employees' perceptions of system shortcomings, bottlenecks in procedures and policies, and insufficiently addressed technical and training requirements.

Safety climate is generally assessed using a survey or questionnaire that focuses on issues such as organizational policies and procedures and their impact on work performance, sufficiency of training and technical support, and other socio-technical factors. Lee et al. (2019) provide a description of the most commonly used safety climate surveys and questionnaires, which generally require no longer than 10–25 minutes for respondents to complete. Most safety climate surveys rely on the use of Likert scales to enable quantitative assessments and the tracking of scores over time, supporting the identification of important trends in employees' perceptions of the adequacy of their work systems. Periodic assessments of safety climate are recommended to support the early identification and amelioration of potential system safety and performance issues.

4.4 Summary

This section presented guidance on the conduct of socio-technical analyses as well as the translation of findings into results and documentation that are beneficial to the design process. Analysis activities should be conducted as specified in the master schedule, the latter being updated as required to reflect modifications to higher-level program schedules. Translation of findings into system design requirements, prototype designs, and operational assessments, etc. is the final stage of analysis activities.

5. Summary, Conclusions, and Recommendations

5.1 Summary

This report provides guidance for preparing a plan for the application of socio-technical methods within nuclear power industry transformation and modernization efforts. These methods include considerations of factors related to future staffing levels, job and personnel requirements, and the development/identification of enabling technical, management, and procedural supports focused on the effective integration of people, technology, process, and governance (Droivodsmo et al. 2014).

The guidance in this report is intended to further operationalize the theoretical and methodological guidance for the analysis of socio-technical issues in nuclear plant modernization provided by Dainoff et al. (2020). Specifically, the plan developed following guidance in this report will result in analysis procedures and methods overseen and conducted by a multidisciplinary, cross-functional team. The team composition will depend on the project goals but will typically include representative end users, HFE analysts with expertise in socio-technical methods, program management, and technical subject matter expertise.

The plan consists of a three-stage analysis process, beginning with the development and documentation of a shared understanding of the project's goals, resource constraints, timelines, and, importantly, assumptions about potentially enabling socio-technical assumptions. This initial stage concludes with the identification of specific issues for analysis. The second stage of the plan focuses on the selection of specific analytic and modeling procedures and methods. The major activities involve developing strategic analysis objectives, selecting appropriate tools and methods, and developing a logistical plan that is effectively integrated with higher-level program plans and milestones. Finally, the third stage centers on the conduct of the analyses and the translation of findings and results into forms useful for the design, such as formal system requirements and prototype system designs.

Several of the tools discussed by Dainoff et al. (2020) are presented with potential applications to nuclear plant modernization. While particularly useful for the analysis of complex socio-technical issues, they are not the only tools and methods available to the cross-functional team. More traditional HFE analysis techniques and methods (some of which are listed in Appendix B) are also potentially useful in the examination of issues, such as cognitive and physical workload, situation awareness, communications efficiency and effectiveness, and likelihood of human error.

5.2 Conclusions

- Macroeconomic constraints and other factors impacting the nuclear power industry are driving a trend toward the increased modernization of operations. The industry will develop numerous approaches incorporating advanced concepts, such as integrated operations and virtual organization-based business models. Many of these new concepts will require identification, analysis, and resolution of potentially significant socio-technical issues.
- The nuclear industry has a well-established body of guidance on many aspects of plant design and operation, such as control room design, maintenance procedures, and systems design, etc. However, there has been little practical guidance available to date on the analysis of the socio-technical issues, such as the impact of staffing reductions, increased reliance on automation and other technologies, etc. on overall system performance. Dainoff et al. (2020) provide an overview of this guidance, specifically focused on issues of nuclear plant modernization.
- This current report provides guidance on developing a plan to apply the methods and tools discussed by Dainoff and colleagues. The guidance provides a structured approach to developing an analysis plan focused on identifying and resolving potential socio-technical issues in a system that satisfies project goals. The major stages include: understanding the problem, developing an analysis plan, and conducting the analyses and translating the findings.

- The methods identified by Dainoff et al. (2020) have been widely used in complex design settings, including the nuclear industry. The guidance provided in the current report is also based on past experiences with complex systems design settings discussed in the report and its appendices, including nuclear energy generation.
- The guidance for developing a human factors plan, including socio-technical considerations provided in this report, should be considered by nuclear plants and utilities planning to modernize plant operations, maintenance, and support activities.

5.3 Recommendations

- Nuclear plant modernization efforts should incorporate HFE and socio-technical analyses into their systems engineering and other modernization efforts. Doing so will significantly reduce the chance of the modernization effort not achieving its project goal upon deployment.
- Where applicable, traditional HFE approaches and methods—particularly those developed and widely used in the nuclear industry—should still be considered as part of the analysis plan (e.g., NUREG 0711).

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Appendix A: Exemplary Case Studies

The following case studies are drawn from the authors' experiences on projects that have important similarities with and implications for socio-technical modernization efforts in the nuclear industry. They are presented as illustrations of the importance of addressing social, organization, and related technical issues early and throughout the system design process.

Case Study 1 – Design of a highly automated, reduced crew-size Navy destroyer

The Zumwalt class of U.S. Navy (USN) guided-missile destroyers comprises three recently constructed ships (USS *Zumwalt*, USS *Michael Monsoor*, *Lyndon B. Johnson*). The class is characterized by radical departures from legacy destroyer designs in terms of fundamental naval architecture and combat and support systems design. Most notably, the class (hereafter referred to as Zumwalt), required to significantly outperform legacy destroyers, was designed with two major system constraints in play:

- A requirement for a 'stealth' design (specifically, a significantly reduced radar signature) led to breaks in traditional ship design (e.g., the location and design of the bridge) that required new technologies and crewing concepts to accomplish critical tasks.
- A key performance parameter of a crew size of no greater than 95 personnel (excluding the air detachment).

Zumwalt was the first ship design that the USN approached from an explicitly 'sailor-centric' (as opposed to engineering-centric) perspective. Throughout the design, a significant role was played by a team of human-systems integration (HSI) professionals whose responsibilities included requirements generation, cognitive and physical workload analysis, systems design and testing, modeling and simulation, etc.

There are several key aspects of the Zumwalt design process that are of particular relevance to the nuclear modernization domain, including:

- The integration of HSI processes within a traditional, systems engineering paradigm was largely successful but required an enormous initial effort, strong leadership, and an ability to 'speak the language' of systems engineering. Bringing together key stakeholders (sailors, designers, engineers, etc.) at each phase of the design and extracting their relevant expertise for incorporation into the design was one of the HSI team's key activities.
- Development of a spreadsheet-based tool (the Manning Uncertainty Issues List [MUIL]) used to monitor the level of risk associated with the various novel technical systems—most involving automation, expert systems, remote sensing, etc.—upon which the limited crew-size concept relied. The MUIL proved to be a highly effective tool for tracking risk and conveying its implications for the manning concept to program decision-makers.

There have been recent increases in the size of the *Zumwalt*'s crew that are reportedly related to damage control issues involved in the ship's autonomic fire suppression system as well as the performance of several other systems supported by automated and remote sensing technologies. Organizational pressures on the design, a significant presence throughout, have also had an impact on crew-size growth, such as additional personnel assigned to the crew to inspect areas of the ship—an activity already reportedly well-supported by remote sensing technology. The reduced crew concept also relies upon the concept of a centralized, shore-based maintenance facility for all ships in the class. This is an attempt to reduce the number of maintenance crew on each vessel and has thus far been largely successful and well-accepted by the fleet.

Zumwalt was a highly complex systems engineering effort and HSI had a significant impact both in terms of process and product. Several key commonalities between *Zumwalt* and nuclear modernization are:

- *Safety-critical system*—U.S. Navy warships are inherently safety-critical both in terms of the risk of the overall mission and in the potential risks to the personal safety and well-being of sailors and other personnel. Improving system safety and reliability are also generally viewed as key strategic, warfighting advantages, and objectives.
- *High reliance on automation and remote sensing*—The significant reduction in crew size from legacy destroyers to *Zumwalt*, without sacrifice of operational capability, meant that enormous amounts of 'human workload' now had to be replaced with automated and expert systems as well as remote sensing technologies for inspection and damage control.
- *Operational/life cycle costs*—A significant factor underlying *Zumwalt*'s design was a desire by the U.S. Navy to control the operational and lifecycle costs associated with its surface warfare fleet. A major driver of these costs is manpower, and, therefore, the Navy sought, through significant use of automation and integrated operations, to design a ship that could be a more cost-effective replacement of its legacy class.
- *Desire to leverage emerging technologies to replace human workload and improve safety and performance*—The emergence of new expert systems and automated technologies at the turn of the 21st century was a significant driver in the Navy's decision to explore the design and development of a highly automated ship.
- *Multiple stakeholders—Significant government presence—Zumwalt's* design incorporated inputs from over 1,000 sailors during its design as one means of ensuring a 'sailor-centric' design. Additionally, inputs from across the breadth of the systems engineering team—which included multiple corporations and U.S. Navy agencies—were continually solicited and incorporated into the ship's design.
- *Reduced staffing and integrated operations*—Reducing the number of sailors onboard ships was, at the initiation of the *Zumwalt* program, a high-level U.S. Navy goal intended to support the more global objective of reducing overall costs of operation. Personnel costs (e.g., recruitment, training, retention, health costs, etc.) are by far the Navy's most significant budget item. As with the nuclear industry, reduced staffing through effective system design and integrated operations is seen as key to the Navy's future.
- *Operator fatigue*—A logical concern with reduced staffing is operator fatigue. Within the Navy, there are strong, cultural factors that can interfere with open, objective discussions of its risk factors. Fatigue and sleep-deprivation can be seen as 'part of the job.' To the extent this becomes an organizational norm, systems can find themselves at increased risk of incidents commonly attributed to 'human error.'

***Implications for nuclear power industry modernization*: The *Zumwalt* design was intended to address many similar issues and opportunities currently confronting the nuclear power industry. Faced with a need to reduce operational costs associated with manning (i.e., staff size), the Navy pursued a highly novel, culturally disruptive design, heavily reliant on automation, remote sensing, and other state-of-the-art technologies. The design process itself involved significant user input and a broad, human-systems integration.**

Case Study 2 – Redesign of escalators to reduce accidents

The research and development branch of a major manufacturer of elevators and escalators was asked to "develop changes to our escalators that will reduce rider accidents and eliminate or reduce lawsuits." The accident that stimulated this project was a 3–4 year old boy riding down an escalator to a Washington, DC subway in winter wearing a scarf. The scarf got caught in the escalator at the bottom and the child was choked to death with his parents and many people watching. No one could do anything to save the child. The publicity was horrible for the manufacturer, and the lawsuit settlement was huge. Corporate leadership mandated that something be done to improve system safety. A team was identified, and the problem statement quoted at the beginning of this paragraph was identified as the research and development focus.

Our first action was to understand the causes of these accidents. We reviewed the accident reports and lawsuit documentation, talked with lawyers who had handled some of the cases, observed escalator users around the country, and held focus groups with escalator users. We analyzed the results of the studies and identified main causes of potential safety issues: no way for people on or near escalators to stop it in case a problem developed, riders (especially children) would place their feet on the very edge of the escalator step, the step design caused some riders to become dizzy when looking at it (step top designed to minimize slipping, but design had strange appearance), users often did not hold the rail, etc.

The next step was to identify possible solutions to the problem, screen them against various criteria, mock up possible solutions, and test them using an escalator at the Division plant. In identifying possible solutions, we took several approaches. We looked at competitor products and other industries. For example, we noted that some factory production lines had a stop button that any employee could operate if a problem was observed. Some users in our focus groups suggested painting a one- or two-inch bright color along the edges of each step. A lawyer on our team suggested placing a sign at the top of each escalator urging users to hold the handrail, keep feet away from colored edge of steps, and watch children. We screened the possible solutions. For example, would they work under low or no light conditions or bad weather, such as snow, ice, and rain; could the escalator designers implement the suggested changes; would the solutions reduce the number of riders on a given step thus reducing the number of people handled per minute; would a given change cost too much money; would building owners and managers who purchased the equipment be willing to accept the changes; were government regulations applicable that would affect implementation of any solution; were any patents existing that would interfere with the proposed solution; would maintenance companies be able and willing to maintain the proposed changes; and, importantly, were there any user concerns about the modifications.

We mocked up each of the suggestions on the manufacturer's test escalator. We tested people from the general public with no changes from the original design and then with various changes described above. We produced and analyzed video for each of the solutions mentioned above and interviewed the test subjects. Also, we had the attorneys, escalator design engineers, and a safety consulting company evaluate the various changes we had developed. We developed recommendations based on the analyses, implemented them on the test escalator, and did a test to verify that the recommendations worked. The recommendations were accepted and implemented, resulting in a dramatic reduction of injuries and lawsuits.

Implications for nuclear power industry modernization**: Successful approaches to the redesign of systems to improve performance and reduce safety risks benefit greatly from relevant cross-functional subject matter expertise and the systematic application of HFE knowledge elicitation and testing methods.**

Case Study 3 – Ergonomics for radiologists

In 2008, a behavioral sciences unit at a corporate research laboratory became involved in a collaborative study involving the Department of Radiology at a major medical center. The head of the department had recently published a paper indicating a high prevalence (58%) of musculoskeletal disorders among radiologists, and the unit was asked if they could propose an intervention. As it happens, prior to his arrival in the unit, the unit director had been consulting with the Radiology Department of a different medical center on the same problem. In the process, he had created the Work Domain Analysis (WDA) portion of Cognitive Work Analysis (CWA) to model the work functions of radiologists. Fortunately, the radiological image archiving and communication software were the same for both medical centers. The team was able to use this WDA along with video observations to identify possibilities for the reduction of muscle movements.

A modern radiologist's typical work task has two subtasks: (1) analysis: using the Picture Archiving and Communication System to scroll through a radiological record, and identify and possibly manipulate (expand, measure) regions of interest and (2) dictation of the findings. The analysis subtask is very mouse-intensive while the dictation subtask required the radiologist to manipulate a handheld controller. Based on combined analyses, the team was able to propose ergonomic solutions for both subtasks. For the analysis subtask, the majority of typical mouse movements were mapped into equivalent keyboard shortcuts. These were implemented not on a keyboard but on an off-the-shelf commercial device by the Radiology Department IT technician and resulted in a significant reduction in musculoskeletal load. For the dictation subtask, the hand controller was replaced by a foot pedal controller.

Both solutions were received favorably in user tests. However, the use of the off-the-shelf device was going to require a one-hour tutorial for all staff. Department management decided that workload was so high that they would not allow time for the tutorial. Thus, the off-the-shelf device was not adopted. However, the foot operated dictation system was widely adopted by radiological staff.

In retrospect, it became evident that, while the team had been in liaison with Radiology Department management regarding both solutions, they had not been as explicit as they could have been regarding the likely training demands. If this had been clarified, management might have been more willing to invest training time for potential long-term benefit. In fact, the team had been planned to do a systematic before/after assessment of musculoskeletal load and pain levels, but this also was cancelled due to time restraints. Thus, the team was not able to document the effectiveness of their partial intervention. They were, however, informed informally that the new dictation system was well-received.

Implications for nuclear power industry modernization: **It will be important at all stages of planning and execution to have agreement with stakeholders and partners regarding a solution's expected impact on their time and resources.**

Case Study 4 – Development of the bar scanner

National Cash Register (NCR) Co. R&D Center and Marketing Division was tasked in the mid-1960s to "develop a checkout product that will improve productivity for supermarkets." The NCR marketing division and cash register competitors were being told by supermarket customers that cash registers had been about the same for many years and, with new technology, checkout should be better. A team was formed that included a Human Factors Engineering representative.

The first step was to understand the problem and identify the best opportunity to improve productivity. The team identified the function with the most potential for improvement, which was the checkout process, and identified the tasks involved in performing this function. The team observed the checkout process and identified that the task taking the most time and involving the most errors was picking up a grocery item, rotating it to read the price, entering the price on a keyboard, and placing the item in a bag or on the stand. It was decided to quantify the time for each subtask of the checkout task. A team member visited a busy supermarket for three days and mounted a movie camera above a checkout stand. The movies were analyzed, and the use of the cash register was found to be most time consuming. Also, research found that the supermarket industry was experiencing a 2–5% clerk error rate in entering the numbers. Cashiers were interviewed and many reported disliking entering numbers on a cash register, but "it was a job."

The next step was to identify possible ways to improve the data entry subtask. The team looked at other industries to see if any possible solutions should be considered. One member of the team was a train enthusiast. He said that, in 1961, a system was first tested that involved a fixed scanner along the tracks and a unique multicolored symbol located on each railroad car. The test showed that a symbol could be read with the train going 60 mph and the specific car would be identified. Someone else on the team did a patent search and found a barcode had been patented. The team discussed placing a barcode reader in each checkout stand and a barcode located on each grocery item. There were other possible solutions that were identified and evaluated (e.g., radio-based system but was too expensive), but the barcode reader appeared to have the most promise for improving productivity. The team decided to evaluate this possible solution.

The marketing representative on the team obtained a checkout stand and it was installed in the Human Factors Laboratory. A scanner was mocked up (piece of paper pasted it on the stand), and groceries were marked with tags. Checkout personnel from local supermarkets were brought to the laboratory, and they simulated scanning each item in an order. Movies were taken of their performance and compared it with their use of a cash register. The increase in productivity was dramatic. Interviews were conducted with the test subjects, and everyone enthusiastically wanted the scanner to be developed. The team then proceeded to screen the method. The marketing person on the team talked with supermarket owners and a group of trade associations from the grocery industry. There was general agreement that a Uniform Product Code Council needed to be established, a barcode (UPC symbol) needed to be designed (a modified IBM design was selected), and a process needed to be implemented to permit manufacturers to obtain a unique code for each product. For several years, the barcode design was discussed before the UPC Council was established in 1973. The HFE group was involved in helping NCR decide on its position regarding barcode design. NCR had designed a color-coded tag while the black and white design by IBM was selected. The NCR design could contain more data but involved what was perceived as more expensive printers. A working model of a scanner was developed by NCR and both designs were tested in the Human Factors Laboratory. No difference in checker performance was found using either tag, and NCR agreed to the IBM design.

Early in the project, the team screened the concept of a scanner reading a barcode tag system. Screening criteria included cost (the barcode reader was much less expensive than the radio-based or other possible systems); the possibility and difficulty of placing a unique tag on each grocery item;

physical demands on the clerk when using a scanner rather than a cash register; checkout worker acceptance of this system; any union, OSHA, or other government concerns about system, etc.

The Human Factors Laboratory performed several studies that were important in developing specifications for the scanner. The capability to read barcodes had to be developed by NCR because no off-the-shelf scanners were available. Several high-speed cameras were placed in and around the checkout counter. Supermarket cashiers scanned tagged grocery items. Movies were analyzed, and specifications for the scanner design were prepared. The values specified included the minimum and maximum barcode scanning speed, the range of angles or tilt of the barcode, the maximum height of the barcode above the scanner, and the width of the scanner. The scanner that was designed for production met or exceeded these specifications.

The Human Factors Laboratory was provided the prototype scanner, and it was evaluated to determine that it satisfied users, met checkout performance goals, and satisfied human factors criteria regarding body size and movement (anthropometrics and biomechanics).

The team decided to evaluate the overall effect of a scanner system on a supermarket. It had a dramatic effect on cost and operations. Because of the increased speed of checkout, the number of checkout stands, checkers, and bagging personnel could be reduced (e.g., the number of checkout stands could be reduced from 10 to 8, and, thereby, the number of checkers and baggers could be reduced.) The skill to scan versus operate a cash register was less, thereby providing a larger pool of possible hires. The collection in real time of items sold reduced the need for personnel to check product shelves to determine when to reorder (e.g., could automatically determine when 150 boxes of Wheaties had been sold and it was time to reorder). Another advantage used by some supermarket managers was to automatically reorder the 150 Wheaties. Rather than requiring a person to reorder, a computer program could perform the reordering. Finally, maintenance would be lower with a scanner than with an electromechanical cash register, although a higher skill level might be required for scanner maintenance.

It was found that, after the barcode reader system was installed in supermarkets around the country, the system had more cost benefits than originally envisioned. There were really two major impacts of the system. One was to significantly improve checker productivity and accuracy by reducing the time to capture grocery item information and eliminate keyboard use on the cash register. The result was the ability to reduce number of checkers and baggers required for the same number of customers.

The second major impact was to provide data about specific items sold almost instantaneously. Data availability and software programs to analyze the data in meaningful ways had quite an impact on supermarket operations. The accurate data base about what items sold and when permitted store managers to perform an evaluation of alternatives. One example was to determine hours of operation. This was applied at all stores in one supermarket chain. The supermarket was open 24 hours a day, but corporate noted that little business occurred between certain night hours. The manager or someone could access the database to determine sales per hour over 24 hours. The manager found very few sales between 10:30 pm and 6:30 am. The store could be closed during those hours and few sales would be lost. It would be possible, then, to eliminate, for example, five workers for that shift seven days per week (e.g., two checkers, a maintenance person to clean up spills and maintain equipment, a supervisor who also does customer service, and a security guard because of concern about night robberies).

The same analysis of sales by hour helped determine how many full-time checkers and baggers were required and how many part-time workers might be brought in during peak hours. This could result in a reduction of full-time employees required, reducing costs.

Some of the analyses described above were performed before a scanner system database became available, but personnel required for these analyses could be replaced by computer programs. Of course, computers were not very user-friendly, so it would have been necessary to hire someone to plan and program the computer software for the requested analyses.

It should be noted that the supermarket industry continues to try to apply technology to reduce costs and improve profitability. For example, many stores are encouraging customers to scan, bag, and pay, eliminating some checkout personnel. At least one store is providing carts with handheld scanners so customers can scan as they shop to speed up the checkout process. Also, technology is becoming available to permit items to be placed in the cart and wheeled through a checkout area. The electronic tags would be read automatically, and the total cost would be determined in a few seconds.

The first UPC-marked item to ever be scanned at a retail checkout was a 10-pack of Wrigley's Juicy Fruit chewing gum. This occurred in June 1974 in Troy, Ohio using a NCR scanner. The gum pack was subsequently placed on display at the Smithsonian Museum. Most of the team was present to observe the event.

Implications for nuclear power industry modernization: **A major message in this case study is that one or more technology advances introduced into an organization (such as a nuclear plant) can have a major impact on how the operations are changed and that costs, productivity, and efficiency can be greatly improved. One of the possible major causes of the improvements may be the database that is created with the new technology and their use.**

Case Study 5 – Design of a revised corporate ergonomics plan

The following project was carried out by the behavioral sciences unit of a corporate research laboratory. The company had a corporate-wide ergonomics program in which practical ergonomics guidance to individual employees was the responsibility of individual managers with the support of a designated ergonomics specialist in each unit. Given indications that the program was not as effective as it should be, the behavioral sciences unit proposed a coordinated approach to investigate alternative solutions with the Corporate Health and Safety Department. The proposal was accepted, and the Intervention Design and Analysis Scorecard (IDEAS) approach was utilized to establish a cross-functional design process. The process involved the establishment of two teams: the Steering Committee (high-level members from the Corporate Health and Safety Department) and the Design Team (safety officers, line employees, supervisors, ergonomics professionals, and a quality specialist).

A formal, seven step process was established. Step 1, which was carried out by the Design Team under guidance of the Steering Committee, consisted of identifying contributing factors. This process involved knowledge elicitation from team members with mediation by the ergonomic professionals from the behavioral sciences unit. Steps 2–4 were carried out by the Design Team. In Step 2, the team developed activities and objectives, which could be grouped into a set of alternative solutions (potential interventions). In Step 3, selection criteria were developed. These included cost/benefit analyses related to the overall mission of the organization. In Step 4, each of the proposed alternative interventions were described in terms of the selection criteria. Seven possible alternatives to the existing manager-ergonomic specialist system were proposed. The knowledge representation of the proposed alternatives was characterized by utilizing the Safety Control Structure attribute of STAMP/STPA.

The remaining steps (5–7) reflected concern with implementation and sustainability. These steps were supposed to be directed by the Steering Committee in coordination with the Design Team. Step 5 consists of a formal vote in which each alternative is rated in terms of each criterion. Step 6 consists of the logistics and planning of the intervention(s) that emerged from Step 5. Step 7 consists of the evaluation of the effectiveness of the intervention. Unfortunately, at the point at which Step 5 was to occur, the research laboratory was closed by top management. Thus, it is not known how or if these steps were completed. However, the process itself was considered effective. One member of the Design Team, who was a senior instructor in the corporate quality management program, commented that the IDEAS process was as effective as, but more efficient than, the quality program he was teaching.

Implication for nuclear industry modernization: **This is an established method for simultaneously accomplishing knowledge elicitation, knowledge representation, and cross-functional integration. The method can be easily modified to meet local needs, such as adding the NGT.**

Case Study 6 – Redesign of a major software package

This case study describes the collaboration between an academic human factors researcher and a software company. The software package is a project management database allowing individual users within a corporate environment to keep track of components of long-term projects. In 2004, the software had over 200 corporate clients. The software was originally designed for use on a mainframe computer, and the format of the audit reports was a printout with static lines of text. In the late 1990s, the software migrated to a web-based format, but the format of the reports maintained its printout-like structure. At the same time, more modern competitive products were coming on the market, and the database was in danger of losing its market share.

The academic human factors researchers were approached by the head systems programmer at the software company for advice. Fortunately, at the time, the researcher was teaching a graduate seminar on Cognitive Work Analysis. The researcher invited the systems programmer to sit in and see if CWA might be helpful in structuring his redesign. The outcome was an agreement to collaborate. The software redesign would be conducted as a MA thesis using CWA, which the academic researcher would supervise. The design process systematically employed all five components of CWA: Work Domain Analysis, Control Task Analysis, Strategies Analysis, Social Organization and Cooperation Analysis, and Workers Competencies Analysis.

The final product involved a web-based graphic user interface in which the audit record was transformed from pages of static text to dynamic graphics. The software was launched and started to regain market share for the university.

The following comments are from the system designer's thesis.

> *An informal review of available literature was performed. Although many books are available in the area of computer interface and web design, nearly all are a collection of dos and don'ts gathered from the writer's experience. A few of these collections are excellent, offering valuable insight into what works and what does not work with user interfaces. The best selections also provide usability advice and guidelines for testing once a product has been developed. But none were found to offer a process for building an interface from the ground up. In many respects, CWA was chosen because it was the only available process that met the defined needs of the project*
>
> *Cognitive Work Analysis is the foundation on which the [core analytic engine of the data base] is built. CWA was not viewed as a replacement for more traditional human-computer interaction design or systems design. Rather, it provided the team with distinct goals, focused scope, and a clear understanding of the project environment that was carried forward into these important tasks.*

Implications for nuclear industry modernization: **Cognitive Work Analysis is a cross-functional team analytic activity that has been used in the development of numerous complex systems. Its principal advantages lay in clearly delineating the nature of the design problem under examination and identifying specific work scope required to address it.**

Appendix B: Additional HFE Tools and Methods

The socio-technical methods described in the main body of this report may not be sufficient to analyze all of the conditions related to HFE during the analysis. This table identifies some additional methods, many of which have been applied in nuclear plant modernization efforts, that may be applicable. Descriptions of when and how to apply these methods may be found in the references.

Tool	Application	References
Hierarchical Task Analysis	Task Analysis	Annett 2005; Phipps et al. 2011; Shepherd 2002; Stanton 2006
Verbal Protocol Analysis	Task Analysis	Ericsson & Simon 1993; Trickelt & Trafton 2009; Walker 2004
Goals, Operators, Methods, and Selection Rules	Task Analysis	Card, Moran, & Newell 1983; Kieras 2003; Kirwan & Ainsworth 1992
Task Decomposition	Task Analysis	Kirwan & Ainsworth, 1992; MacKenzie et al., 2001
Sub-Goal Template Method	Task Analysis	Ormerod & Shepherd 2004; Ormerod et al. 1998
Tabular Task Analysis	Task Analysis	Shepherd 1976, 2002
Applied Cognitive Task Analysis	Task Analysis	Militello & Hutton 2000; Seamster & Redding 2017
Critical Decision Method	Task Analysis	Hoffman et al. 1998; Klein et al. 1989
Cognitive Walkthrough	Task Analysis and Prototype Design	Blackmon et al. 2002; Mahatody et al. 2010; Rieman et al. 1995
Critical Incident Technique	Task Analysis and Prototype Design	Butterfield et al. 2005; Chell 1998; Flanagan,1954
Operational Sequence Diagrams	Process and Network Model	Harris et al. 2015; Huddlestone et al. 2017
Event Tree Analysis	Process and Network Model	Alileche et al. 2017; Metzroth et al. 2010; Sotiralis et al. 2016
Fault Tree Analysis	Process and Accident Model	Hauptmanns 1988; Kaibar 2017; Volkanovski et al. 2009
Human Error HAZOP	Human Error Identification	Kirwan 1992: Salmon et al. 2002
Systematic Human Error Reduction and Prediction Approach	Human Error Identification	Babaei et al. 2017; Hughes et al. 2015; Phipps et al. 2008
Situation Awareness Global Assessment Technique	Situation Awareness Assessment	Endsley 1995; Endsley et al. 1998
Situation Awareness Rating Technique	Situation Awareness Assessment	Selcon & Taylor 1990; Selcon et al. 1991; Taylor 1990
NASA Task Load Index	Workload Assessment	Grier 2015; Hart & Staveland 1988; Lowndes 2020
Subjective Workload Assessment Technique	Workload Assessment	Luximon & Goonetilleke 2001; Reid & Nygren 1988; Vidulich & Tsang 1986
Cognitive Task Load Analysis	Workload Assessment	Neerincx 2003; Stanton et al. 2005
Comms Usage Diagram	Team Communication and Performance	Monk & Watts 1997; Watts & Monk 1998

Tool	Application	References
Team Cognitive Task Analysis	Team Workload	Ashoori & Burns 2013; Ashoori et al. 2014
Team Task Analysis	Team Workload	Arthur et al. 2005, 2012; Lorenzet et al. 2003
Task and Training Requirements Analysis Methodology	Team Training Requirements	Stanton et al. 2005; Swezey et al. 1998
System Usability Scale	HSI Analysis	Stanton et al. 2005; Stanton & Young 1998
Software Usability Measurement Inventory	HSI Analysis	Kirakowski 1996; Mansor et al. 2012
Timeline Analysis	Performance Time Prediction	Kirwan & Ainsworth 1992; Schlieirf et al. 2011
Keystroke Level Model	Performance Time Prediction	Al-Megren et al. 2018; Lane et al. 1993; Luo & John 2005