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Light Water Reactor Sustainability Program

Development of Human and Technology Integration Guidance for Work Optimization and Effective Use of Information

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Development of Human and Technology Integration Guidance for Work Optimization and Effective Use of Information

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SUMMARY

Context of Research

Existing nuclear power contributes to roughly 20% of the total electricity generation and consistently provides the highest capacity factor of any other electricity generating resource in the United States. Despite these advantages, the existing nuclear power plant fleet in the United States has been enduring significant challenges in providing electricity in a cost-competitive manner, which has ultimately threatened the long-term economic viability of these plants.

A major contributor to these increased operating and maintenance costs has been the continued reliance on a large workforce who perform their work under an operating model that has largely remained unchanged since the commissioning of these nuclear power plants. Unfortunately, while this operating model has provided safe and reliable electricity, other industries have already began transforming their workforce through the use of advanced digital technology and automation that has reduced their operating and maintenance costs significantly.

In order for the U.S. nuclear industry to remain economically viable, a similar transformation must be considered in which digital technologies and automation capabilities are brought in to support key plant functions across all work functions across plant operation, maintenance, and support. To effectively integrate digital technology and automation in the existing nuclear power plant operating model, the technology being implemented must have a mature technology readiness level, as well as human readiness level. To enable an effective implementation of digital technologies, a multidisciplinary approach is thus needed that addresses technical and sociotechnical considerations for continued safe, reliable, and efficient use of these new technologies in existing nuclear power plants.

Summary of Research

This report describes the development of an extension of the human and technology integration methodology, herein referred to as the Human Integration and Technology Task Force for Work Management Optimization (HITT), to support the safe, reliable, and efficient use of proposed innovations with the intended users in their intended environment to perform their intended tasks. The intent of this work is to provide practical guidance for industry to follow to ensure that the proposed digital technologies are implemented in a way that are usable to the intended users in the intended environment.

Results

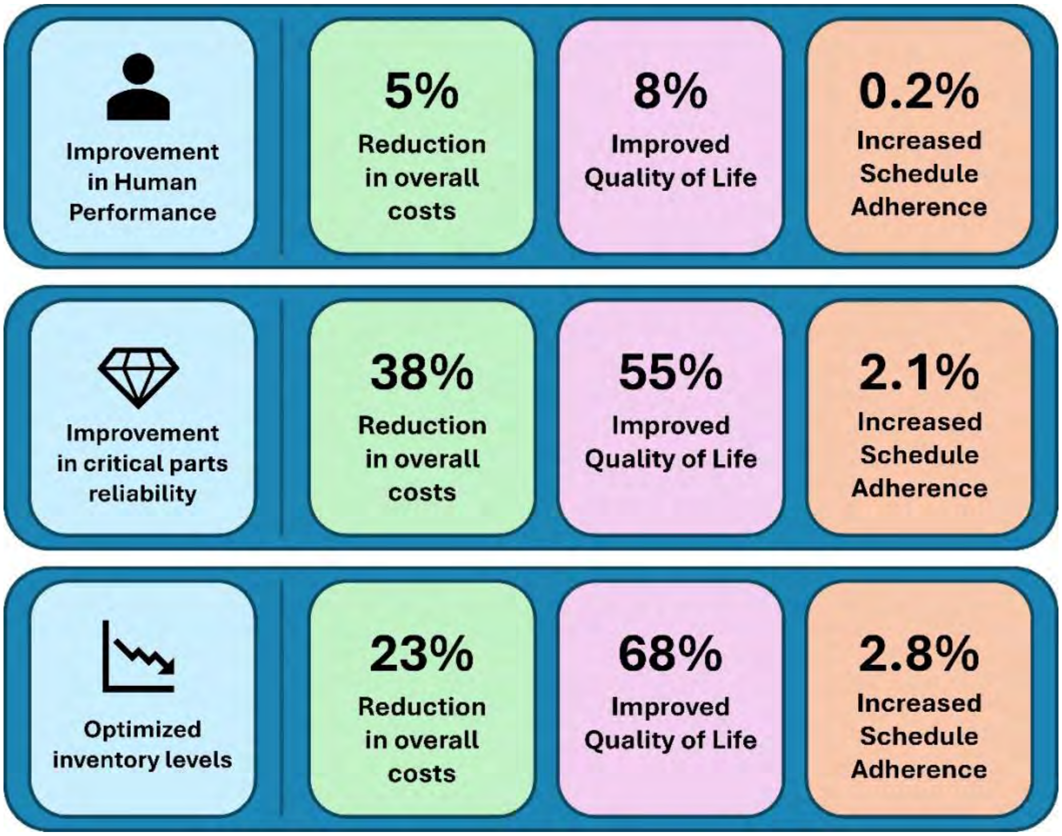
HITT supports the human readiness of advanced technologies through a 10-step process illustrated in Table 1. This process enables the implementation team to gain a deep understanding of the work being performed and opportunities to effectively integrate improvements that support both the users' needs and business needs.

Table 1. Simplified HITT process overview.

1	Perform an initial screening of work reduction opportunities.	Section 4.3.1
2	Create a visual representation of the current processes to identify inefficiencies, redundancies, and bottlenecks.	Section 4.3.2
3	Form a multidisciplinary, cross-functional team to support the execution of the remaining HITT steps.	Section 4.3.3
4	Elicit knowledge of the work domain using the DERIVE deep dive process.	Section 4.3.4
5	Update the process map outputs with the newfound insights and data after conducting the DERIVE process.	Section 4.3.5
6	Select systems thinking impact assessment methods.	Section 4.3.6
7	Perform the impact assessment on existing work system.	Section 4.3.7
8	Identify HTI improvements using the results of the impact assessment in Step 7.	Section 4.3.8
9	Develop a process map outputs for the new state of the system after the identified HTI improvements have been conceptually integrated.	Section 4.3.9
10	Perform a comparative assessment of the existing work system to the redesigned work system.	Section 4.3.10

Impact

The HITT methodology is expected to provide significant improvements in plant performance, resulting from a number of contributing improvements such as quality of life for plant workers, improved safety system performance and availability, improved plant reliability, reduced backlogs, and reduced operating and maintenance costs. Figure 1 shows the key benefits of HITT for improvements of a single process.[1]



Improvement in Human Performance	5% Reduction in overall costs	8% Improved Quality of Life	0.2% Increased Schedule Adherence
Improvement in critical parts reliability	38% Reduction in overall costs	55% Improved Quality of Life	2.1% Increased Schedule Adherence
Optimized inventory levels	23% Reduction in overall costs	68% Improved Quality of Life	2.8% Increased Schedule Adherence

Figure 1. Key benefits of the HITT process.

Next Steps

The next step in this research is to demonstrate the application of HITT with an industry collaborator to support a major digital modification. In this collaboration, the HITT results will be used by the collaborator to support their modernization efforts. With this, lessons learned in applying HITT will be documented in a technical report to support HITT use for the industry at large.

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[1] These benefits are not based on any specific nuclear power plant site but are from modeling results from representative dataset.

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ACKNOWLEDGEMENTS

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ACRONYMS

3D	Three-Dimensional
ACC	Adaptive Cruise Control
AcciNet	Accident Network Method
AH	Abstraction Hierarchy
AI	Artificial Intelligence
ANSI	American National Standards Institute
CAPEX	Capital Expenditures
CAST	Casual Analysis based on Systems Theory
CFM	Crew Failure Mode
ConTA	Control Task Analysis
DCF	Discounted Cash Flow
DCS	Distributed Control System
DEG	Digital Engineering Guide
DERIVE	Define new state vision for work management, Evaluate Department Performance Factors, Review Relevant Performance Information, Interviews of Stakeholders, Valuate Current Organization Digitalization Level, End-State Gap Analysis
DOE	Department of Energy
EAM	Enterprise Asset Management
EPRI	Electrical Power Research Institute
FA&A	Function Analysis and Allocation
GOMS	Goals, Operators, Methods, and Selection Rules
HED	Human Engineering Discrepancy
HFE	Human Factors Engineering
HFES	Human Factors and Ergonomics Society
HITT	Human Integration and Technology Task Force for Work Optimization
HRA	Human Reliability Analysis
HRL	Human Readiness Level
HSI	Human-System Interface
HSSL	Human-Systems Simulation Laboratory
HTA	Hierarchical Task Analysis
HTI	Human and Technology Integration
HUNTER	Human Unimodel for Nuclear Technology to Enhance Reliability
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency

ICA	Ineffective Control Action
IDHEAS	Integrated Decision-tree Human Event Analysis System
IEC	International Electrotechnical Commission
IEEE	Institute for Electrical and Electronics Engineers
INL	Idaho National Laboratory
ION	Integrated Operations for Nuclear
IRR	Internal Rate of Return
ISG	Interim Staff Guidance
ISV	Integrated System Validation
KLM	Keystroke-Level Model
KPI	Key Performance Indicator
LWRS	Light-Water Reactor Sustainability
MCAS	Maneuvering Characteristics Augmentation System
ML	Machine Learning
Net-HARMS	The Networked Hazard Analysis and Risk Management System
NPV	Net Present Value
NRC	Nuclear Regulatory Commission
O&M	Operating and Maintenance
OE	Operating Experience
OER	Operating Experience Review
OPEX	Operating Expenses
ORL	Organizational Readiness Level
OSA	Operational Sequence Analysis
OSD	Operational Sequence Diagram
PTPG	People, Technology, Process, and Governance
R&D	Research and Development
RAG	Resilience Assessment Grid
RCA	Root Cause Analysis
ROI	Return on Investment
SHERPA	Systematic Human Error Reduction and Prediction Approach
SIPOC	Suppliers, Inputs, Process, Outputs, and Consumers
SME	Subject Matter Expert
SOCA	Social Organization and Cooperation Analysis
SOI	System of Interest
SRK	Skills, Rules, and Knowledge

STAMP	System-Theoretic Accident Model and Processes
STPA	System-Theoretic Process Analysis
StrA	Strategies Analysis
TERA	Technology, Economic, and Risk Assessment
TRL	Technology Readiness Level
TTA	Tabular Task Analysis
V&V	Verification and Validation
VDU	Video Display Unit
WAD	Work as Done
WAI	Work as Imagined
WCA	Worker Competencies Analysis
WDA	Work Domain Analysis
WRO	Work Reduction Opportunity

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DEVELOPMENT OF HUMAN AND TECHNOLOGY INTEGRATION GUIDANCE FOR WORK OPTIMIZATION AND EFFECTIVE USE OF INFORMATION

1. INTRODUCTION

In the United States, existing nuclear power contributes to roughly 20% of the total electricity generation and consistently provides the highest capacity factor of any other electricity generating resource. Despite these advantages, the existing U.S. nuclear power plant fleet has been enduring significant challenges in providing electricity in a cost-competitive manner, which has ultimately threatened the long-term economic viability of these plants (Remer et al. 2023; Remer et al. 2021). A major contributor to these increased operating and maintenance (O&M) costs has been the continued reliance on an operating model that has largely remained unchanged since the commissioning of these nuclear power plants.

Unfortunately, while this operating model has provided safe and reliable electricity, other industries have already begun transforming their workforce through the use of advanced digital technology and automation that has significantly reduced their O&M costs. In order for the U.S. nuclear industry to remain economically viable, a similar transformation must be considered in which digital technologies and automation capabilities are brought in to support key plant functions across all work functions for plant operation, maintenance, and support.

To support the continued operation of the existing nuclear power plant fleet in the United States, the Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program Plant Modernization Pathway is conducting targeted research and development (R&D) in two key mission areas:

- To deliver a sustainable business model that enables a cost-competitive U.S. nuclear industry.
- To develop technology modernization solutions that address aging and obsolescence challenges.

These mission areas are being accomplished through a multidisciplinary R&D approach. Figure 1 illustrates the primary research areas of the LWRS Program Plant Modernization Pathway.

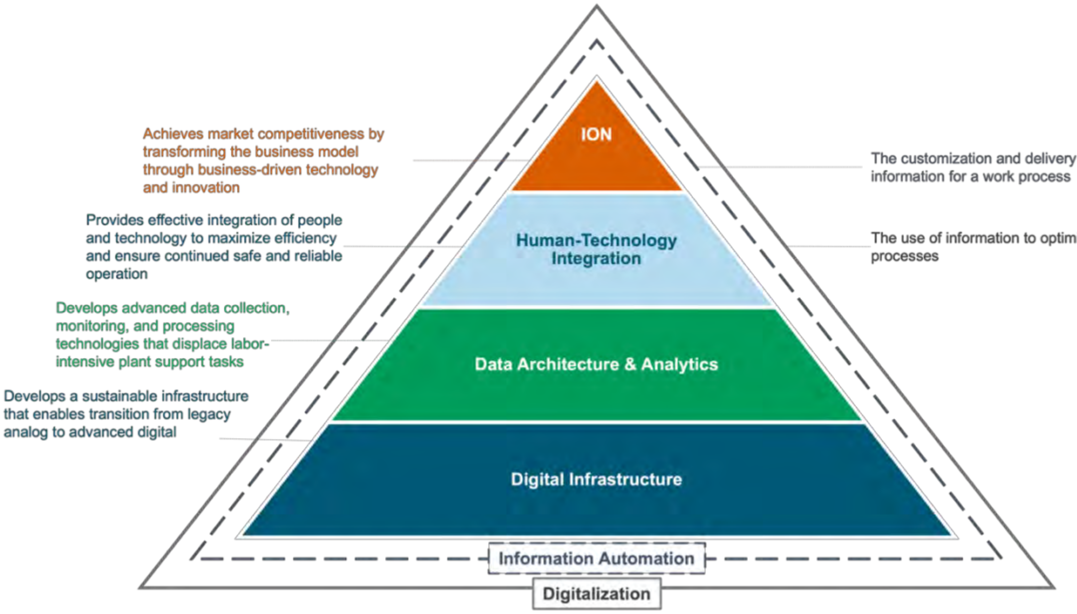

Figure 1. R&D areas of the U.S. DOE LWRS Program Plant Modernization Pathway.

Supporting the LWRS Program Plant Modernization Pathway mission, the scope of this technical report presents an extension to the human and technology integration (HTI) methodology. This extension to the methodology is referred to as the Human Integration and Technology Task Force for Work Optimization (HITT). Specifically, HITT ensures that proposed modernization solutions for different work functions across the plant are safe, reliable, and efficient for the intended users in their operational environment when performing their tasks.

The value of applying HITT to any large modernization project is significantly reduced O&M costs and improvements in work performance. Because HITT follows a human-centered approach, additional benefits include an improved quality of life for all plant workers, improved safety system performance and availability, improved plant reliability, reduced unplanned corrective work orders, and reduced backlogs. Figure 2 shows the key benefits of HITT for improvements of a single process.[2]

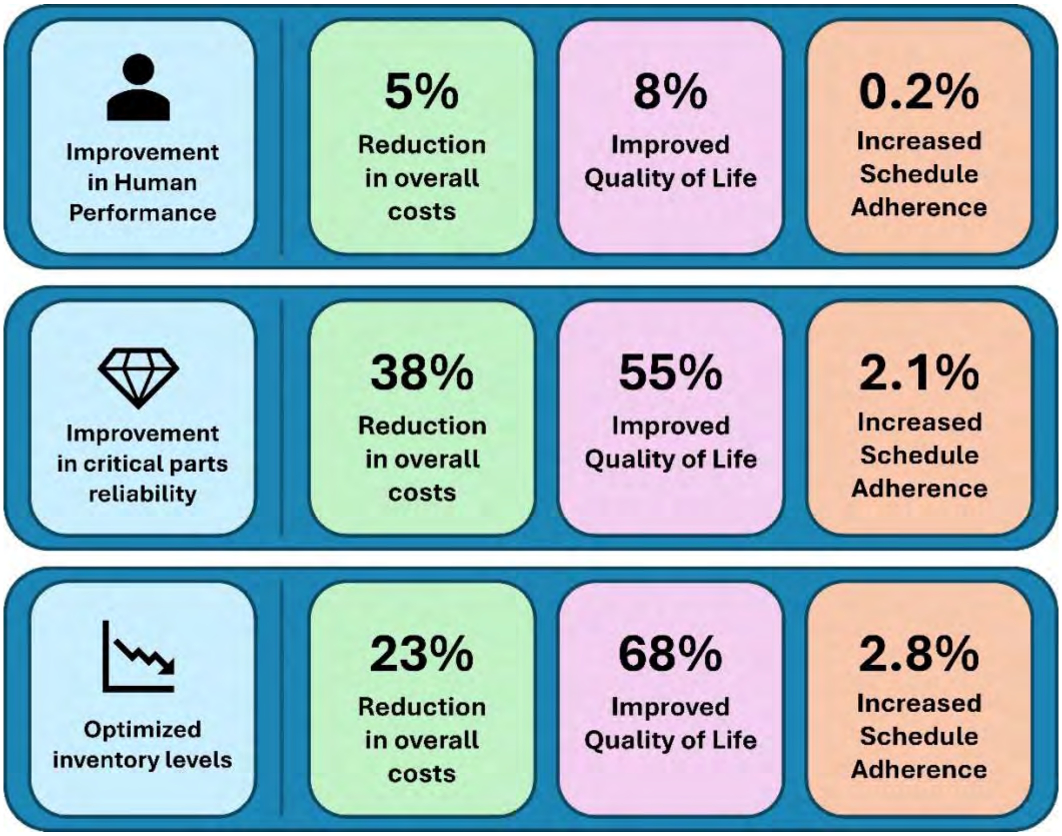

Figure 2. Key benefits of the HITT process.

Table 1 presents a simplified overview of HITT. The intent of table is to be a practitioner's guide in executing HITT. The listed section numbers on the right provide a way to navigate to detailed guidance on each step. Section 1.1 presents the objectives of this technical report and a summary of its key sections.

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[2] These benefits are not based on any specific nuclear power plant site but are from modeling results from representative dataset.

Table 1. Simplified HITT process overview.

1	Perform an initial screening of work reduction opportunities.	Section 4.3.1
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1.1 Report Objective

This report describes an extension to the HTI methodology described in INL/EXT-21-64320 (i.e., herein referred to as HITT) to support work reduction opportunities (WROs) that go beyond main control room modernization and digital instrumentation and control (I&C) upgrades. Specifically, this extension is intended to support the safe, reliable, and efficient use of proposed innovations identified through integrated operations for nuclear (ION) with the intended users in their intended environment to perform their intended tasks. As such, this report is broken up into the following sections:

- **Section 1.2 presents the multidisciplinary approach to plant modernization.**

  Plant modernization requires a multidisciplinary R&D approach. As such, the DOE LWRS Program Plant Modernization Pathway is performing crosscutting R&D across multiple research areas. Each research area has a unique focus, but the research outcomes coming out of these areas are tightly integrated. As a result, this section provides an overview of these other areas as they interrelate to HTI.

- **Section 2 discusses the role of HTI for plant modernization.**

  This section provides the fundamental objectives of HTI and gives an overview of the HTI methodology described in INL/EXT-21-64320 and demonstrated in several key industry collaborations to support main control room modernization and digital I&C upgrades. This overview shares updates to the methodology based on lessons learned from these industry collaborations. Finally, key lessons learned are provided that can be scaled to other WROs beyond the main control room.

- **Section 3 builds on the discussion in Section 2 to describe the development of HTI guidance for WROs that are beyond the main control room.**

  This section describes the role of HTI across plant modernization activities (i.e., referred to as work optimization) to enable joint optimization between people and technology. Leveraging parallel LWRS Program efforts in developing the Technology, Economic, and Risk Assessment (TERA) framework, Section 3 introduces TERA and describes the value of HTI in this framework. Further, it gives the need for addressing work optimization through the lens of systems thinking and provides specific emerging methods in this area. This section finally advocates for a strategic use of multiple systems thinking methods to address work optimization. These topics are fundamental to the extended HTI guidance described in Section 3 of this technical report.

- **Section 4 builds on Section 3 and presents the extension to the HTI methodology to support work optimization.**

  This section gives an overview within the context of how it addresses HTI considerations as part of a broader solution readiness perspective. Next, it presents key elements of the extended methodology, including the use of knowledge elicitation techniques and systems thinking methods described in Section 4. A mapping of the methodology to a broader systems engineering lifecycle is also given to illustrate how the approach can be applied within a project lifecycle. Finally, detailed steps of the methodology are described, providing both practical ("how to") guidance and detailed supplemental information for each step. Working examples using realistic examples are provided to illustrate key points in the methodology.

- **Finally, Section 5 concludes with final remarks and next steps with this research area.**

1.2 Plant Modernization Research Areas

The LWRS Program Plant Modernization Pathway research areas can be characterized into core areas and cross-disciplinary areas. The core areas are illustrated as the solid fill regions of the pyramid in Figure 1 and include ION, HTI, data architecture and analytics, and digital infrastructure. Across these four areas, the Plant Modernization Pathway has recently developed cross-disciplinary research areas that leverage the capabilities of these core areas under the topics of information automation and digitalization.

1.2.1 Core Research Areas

The following subsections provide a summary of the Plant Modernization Pathway core research areas.

1.2.1.1 Integrated Operations for Nuclear

The primary goal of ION is to deliver a sustainable business model that enables a cost-competitive U.S. nuclear industry. A key element of ION is its business-driven top-down analysis, which starts by setting a target price point for cost-competitive electricity generation. From this target price point, ION evaluates innovation opportunities (i.e., referred to as WROs) that, when implemented, will strategically meet the target cost reduction originally defined through market assessment. Evaluating WROs follows a holistic approach to innovating and utilizes a framework from integrated operations in the North Sea oil and gas industry, denoted as people, technology, processes, and governance (PTPG; Thomas et al., 2020).

Recently, ION developed a target price point cost reduction of one-third for existing plants to remain cost-competitive (Remer et al., 2023). This effort largely considered utilizing commercially available digital technologies that could be implemented within the next 3–5 years. The effort has been defined as ION Generation 1 (Remer et al., 2021). ION Generation 1 consists of a number of WROs grouped into 10 critical work domains (Figure 3). These critical work domains provide a basis for targeted R&D across the other LWRS Program research areas through technology demonstration and integration.

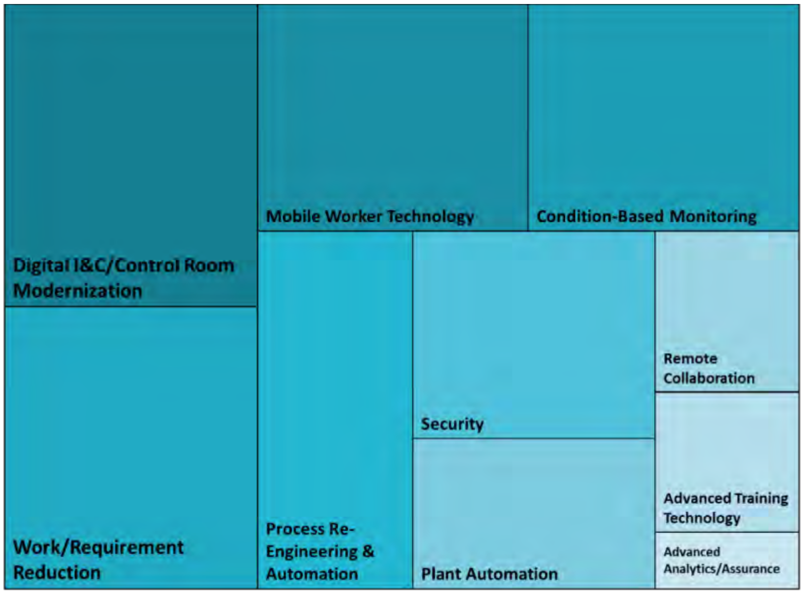

Figure 3. Critical work domains of ION Generation 1 (adapted from INL/RPT-22-68671).

1.2.1.2 Digital Infrastructure

Digital infrastructure establishes a comprehensive physical and logical foundation to support ION-informed advanced capabilities, including those developed in data architecture and analytics. While existing nuclear power plants have performed safely and with the highest capacity factors in the world for decades, this current way of operating is being challenged economically by other industries leveraging new data integration and automation capabilities.

Conversely, the new state of an ION-informed modernized plant leverages digital technology in a way that fundamentally transforms the roles and responsibilities of staff such that the same plant operating, maintenance, and support functions can be accomplished using fewer manual tasks by enabling greater access to plant data. These technologies are situated strategically onto the digital infrastructure such that the native capabilities of these advanced technologies (e.g., electronic work package or distributed control system [DCS]) can be leveraged in a way that minimizes regulatory and cyber risks. The digital infrastructure is shown in Figure 4. Essentially, the diagram represents the placement of I&C and applications across different infrastructure levels.

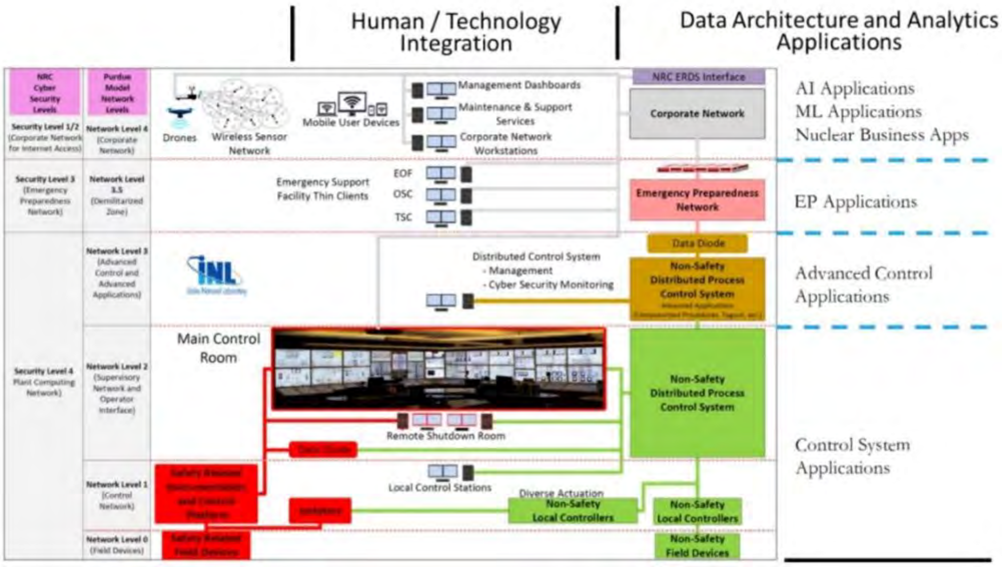

Figure 4. Simplified digital infrastructure (adapted from INL/RPT-23-74671).

Figure 4 uses the Purdue Model network levels (i.e., ranging from Levels 0 to 4, from bottom to top, respectively), which are characterized by the functions performed and associated requirements. Inversely, the U.S. Nuclear Regulatory Commission (NRC) cybersecurity levels that address governing requirements of 10 Code of Federal Regulation (CFR) Part 73.54 are depicted in the inverse order of the Purdue Model network levels (i.e., ranging from Levels 4 to 1). A salient feature of the digital infrastructure is that data from lower levels of the Purdue Model network can be shared through a one-way data diode to the levels above, such as the corporate business network. As such, data integration is achieved such that the organization has greater access to plant data for more informed decision-making and greater organizational situation awareness of the plant.

1.2.1.3 Data Architecture and Analytics

Data architecture and analytics develops and demonstrates advanced monitoring and data processing capabilities to replace labor-intensive plant support tasks. These capabilities leverage machine learning (ML) and artificial intelligence (AI) techniques to automate highly manual tasks so that efficiencies can be realized (Agarwal et al., 2022). The research done in this area is diverse. There have been a number of use cases under data architecture and analytics, including:

- Condition-based monitoring (Agarwal et al., 2022)
- Automated outage risk and technical specification compliance (St Germain, Masterlark, Priddy, and Beck, 2019)

- Automated work packages (Al Rashdan, Oxstrand, and Agarwal, 2016)
- Computer-based procedures for field workers (Oxstrand, Le Blanc, and Bly, 2016)
- Automated fire watch (Al Rashdan, Griffel, and Powell, 2019).

1.2.1.4 Human and Technology Integration

The objective of HTI is to provide an effective integration of people and technology to maximize efficiency and ensure continued safe and reliable operation. Section 2 describes HTI in detail, but it is important to highlight here that any large-scale plant transformation effort is both a technical and *sociotechnical* endeavor. HTI addresses the sociotechnical considerations of nuclear power plant modernization. The scope of HTI therefore spans:

- The design of human-system interfaces (HSIs), procedures, and training
- The design of information to support organizational decision-making and situation awareness (see Section 1.2.2.1)
- The design of the workstation and workplace
- The design and application of AI/ML and implications associated with trust and transparency
- Technology acceptance, impacting worker quality of life, attraction, and retention, when using emerging technologies
- Considerations of digital technologies and automation on organizational effectiveness and teamwork.

1.2.2 Cross-Disciplinary Areas

Two recent cross-disciplinary plant modernization research areas include information automation and digitalization.

1.2.2.1 Information Automation

Information automation pertains to the customization and delivery of information to support work processes within the plant. Research performed in this cross-disciplinary area has focused on the development of information automation to support performance improvement at nuclear power plants (Joe et al., 2023). This research area is developing an issue resolution process that leverages information automation and AI/ML to identify performance improvement opportunities in a timelier and more proactive manner when compared to current work processes. A sociotechnical approach, leveraging methods such as cognitive work analysis (e.g., Dainoff, Hettinger, and Joe, 2022) and system-theoretic process analysis (STPA; Leveson and Thomas, 2018), identifies weak control structures. These approaches are also leveraged in HTI and hence create natural synergies between research areas regarding their scope and approach.

1.2.2.2 Digitalization

Digitalization focuses on using information to optimize work processes by leveraging capabilities of digitalized tools, such as electronic work packages, smart planning and scheduling technologies, dynamic instructions, and data analytics like information automation to improve plant performance, reliability, and safety. Most recently, this research has developed digitalization guiding principles, which are documented in INL/RPT-23-74429. These principles provide the guidance needed to effectively digitalize and optimize nuclear power plant work processes.

2. THE ROLE OF HUMAN AND TECHNOLOGY INTEGRATION FOR PLANT MODERNIZATION

HTI is a research area within the LWRS Program Plant Modernization Pathway that uses systematic human factors engineering (HFE) methods and tools to ensure the human readiness of proposed technology and innovation solutions so that safety and reliability are maintained and efficiencies are realized. The specific objectives and scope of HTI are described next, followed by a summary of key HTI activities described from original work in INL/EXT-21-64320. Section 2 closes with a summary of key lessons learned over the past several years in enabling large-scale digital I&C upgrades and control room modernization.

2.1 Objectives and Scope

This section presents the objectives and scope of HTI.

2.1.1 Objective 1. Ensure Safety and Reliability

A central goal for HTI is to ensure the safe and reliable operation of the nuclear power plant using new digital technologies while also providing an effective integration to enable efficiency. Safety and reliability are achieved through a systematic use of HFE methods across the project lifecycle to:

- Analyze and understand the impact of the new technologies on the concept of operations
- Develop HTI requirements that account for the capabilities of the personnel, the tasks performed, and use environment
- Synthesize the HTI requirements into design specifications and perform subsequent refinements of these designs through iterative prototypes and design tests
- Verify and validate the designs against the requirements by applying industry-recognized standards and performance-based tests
- Perform human performance monitoring of the as-implemented new technologies.

One common approach recognized by industry in the United States is the *Human Factors Engineering Review Model*, NUREG-0711 (2012; Figure 5). While NUREG-0711 comprises a framework for regulatory review, it has been considered a useful engineering process for addressing HFE considerations in large-scale digital modifications (Kovesdi et al., 2021).

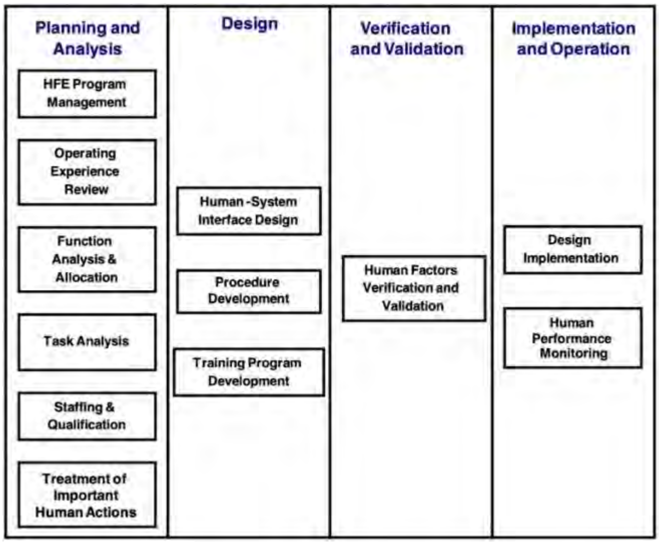

Figure 5. Twelve elements of NUREG-0711 (adapted from NUREG-0711 2012).

Similarly, another common industry approach is described in Institute for Electrical and Electronics Engineers (IEEE) Standard 1023 (2020) as the Star Model. Figure 6 illustrates the primary activities from the IEEE Standard 1023 Star Model.

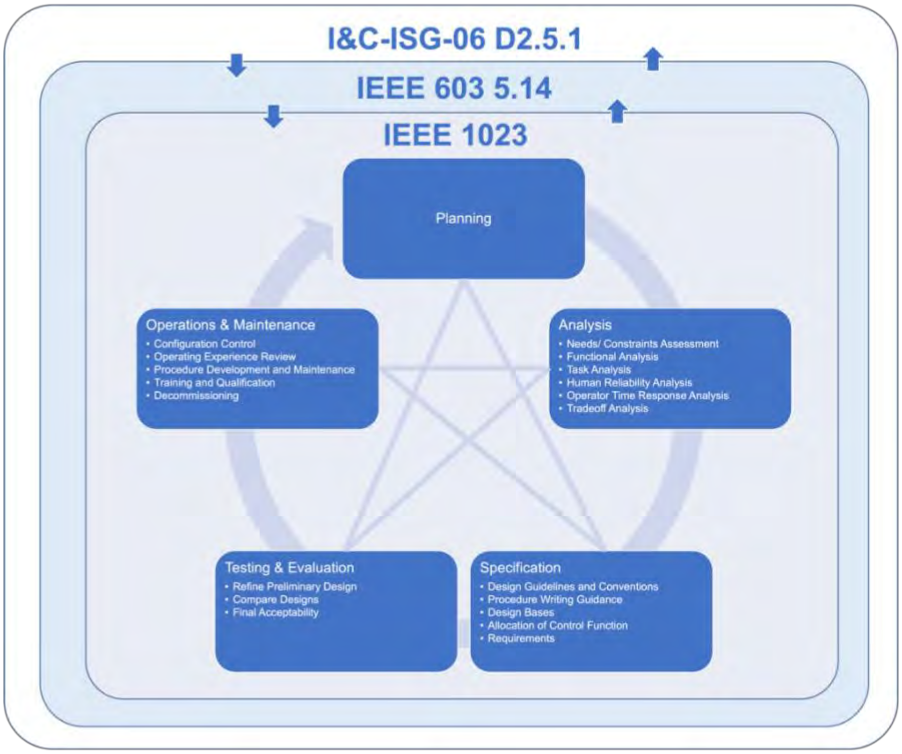

Figure 6. Star Model depicted in IEEE Standard 1023 (2020).

The Star Model depicts a series of primary HFE activities performed across the lifecycle of systems and equipment that have significant human interfaces[3]. These activities begin with *Planning* and end at *Operations and Maintenance*. HFE activities are intended to be performed in a clockwise manner (see the thick circular arrow in Figure 6), but a diversity of approaches must be considered, so each of the five activities are all connected with each other. In any case, like NUREG-0711, the Star Model presents a framework of applying HFE early and throughout the project lifecycle that accounts for the tasks, work environments, equipment, personnel, and organizations to ensure the safe and reliable use of HSIs that are important for safe and reliable operation. Both frameworks are referenced in key guidance and standards like Digital I&C Interim Staff Guidance (ISG) 06 (DI&C-ISG-06; 2018) and IEEE Standard 603 (2018) for modifying safety systems.

2.1.2 Objective 2. Address Hybrid Issues and Considerations

The implementation of new digital HSIs into legacy nuclear power plants presents the following unique challenges.

Function Allocation. One challenge concerns addressing function allocation considerations in existing nuclear power plants. Existing guidance for performing function analysis and allocation (FA&A) is rooted in NUREG/CR-3331 (1983), which describes a very detailed deductive function allocation framework that has been criticized as being "impractical, inappropriate, and unproven with no definitive results" (Fuld, 2000). Furthermore, the approach described in NUREG/CR-3331 focuses on "blank slate" function allocation design decisions that may be particularly useful for control room modernization (Kovesdi, 2022). Digital upgrades at existing nuclear power plants use commercially available qualified vendor digital technologies like a commercial off-the-shelf DCS platform. The high-level safety functions of the existing

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[3] IEEE Standard 1023 (2020) defines *significant human interface* as a point of interaction between users and equipment, facilities, software, or documentation, where the resulting human performance is necessary for acceptable system performance and the probability of human error contributes significantly to facility risk.

nuclear power plant (e.g., reactor heat removal) are established during the plant's licensing. The DCS capabilities are generally bounded. Hence, the function allocation challenge is really about managing the configuration of the DCS capabilities such that the high-level plant functions are met in a way that harmonizes with plant's existing concept of operations (see Figure 7). This is particularly important when new digital I&C is being introduced with existing legacy I&C in hybrid migration configurations of the main control room (e.g., interim states).

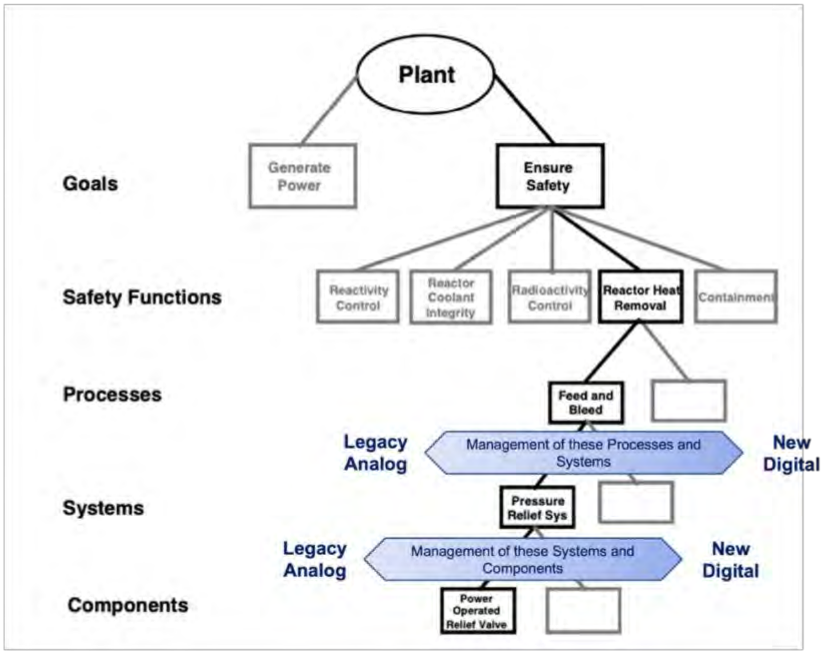


Figure 7. Vertical slide through a plant's functional hierarchy for ensuring safety (adapted and enhanced from NUREG-0711 2012).

HSI Placement. A second hybrid challenge concerns the placement of new digital HSI visual display units (VDUs) in an existing main control room. In cases of interim states of the main control room, the VDU placement must always enable safe and reliable operation. Hybrid states should also be configured in a manner that enables a smooth transition to a new state vision such that training demands are minimized and control board migration "rework" is minimized. In hybrid main control room configurations, the placement of the new digital HSIs must meet human factors design guidance related to accessibility and viewability. The placement of the new digital HSIs must also meet other, often conflicting, requirements associated with other engineering considerations like seismic requirements related to the placement of VDUs on the control boards.

2.1.3 Objective 3. Maximize the Benefits of People and Technology

A third objective of HTI is to maximize the benefits of people and technology (i.e., herein referred to as *joint optimization*) that ensures safe and economical operation. This goal is accomplished through close coordination of HTI with other LWRS Program research areas like ION, digitalization and information automation, digital infrastructure, and data analytics and architecture. While ION provides a business model that enables a cost-competitive nuclear industry by identifying key WROs, HTI is systematically applied to the implementation of digital technologies that enable joint optimization, increase work attraction and retention, and improve overall quality of life.

2.1.4 Objective 4. Ensure Human Readiness

The construct of ensuring the human readiness of newly proposed technologies is the fourth goal of HTI. The term *human readiness* was developed in a recently published standard from the American

National Standards Institute (ANSI) and Human Factors and Ergonomics Society (HFES) 400 (2021), which refers to:

> …the readiness of a technology for use by the intended human users in the specified intended operational environment.

The motivation of this standard, ANSI/HFES-400:2021, was to develop a standard set of *human readiness levels* (HRLs) that can be used to evaluate, track, and communicate the readiness of a technology or system for safe and effective human use. There are nine levels of HRLs; a description of the nine levels is provided in Appendix A. The HRLs are meant to map directly to already established technology readiness levels (TRLs).

Essentially, ANSI/HFES-400:2021 was designed to provide a common framework for assessing a technology throughout the lifespan of a project, emphasizing early and continuous HFE involvement. To support this objective, the standard presents the case that, across different industries, the notion of *human error* accounts for roughly 60%–90% of all accidents and incidents. The cost attributed to human readiness in terms of system training, operations, and maintenance accounts for roughly 35%–70% of overall system cost. Furthermore, the cost for performing a system modification (i.e., to address a human factors design deficiency) once the system design is finalized can cost between 60× and 100× more than if the same deficiency was caught early in the project lifecycle, such as in the conceptual design.

Therefore, the HRLs are meant as a way to assess a technology's maturity in terms of its human readiness and to apply the appropriate HFE methods at appropriate times within the project to ensure suitability for human use of the newly designed or modified system in its intended use environment. This objective is foundational for HTI and is accomplished through a methodology, described next in Section 2.2, that systematically addresses HFE through the use of established human factors methods early and throughout the lifespan of a major plant modification.

2.2 Human and Technology Integration Technical Phases

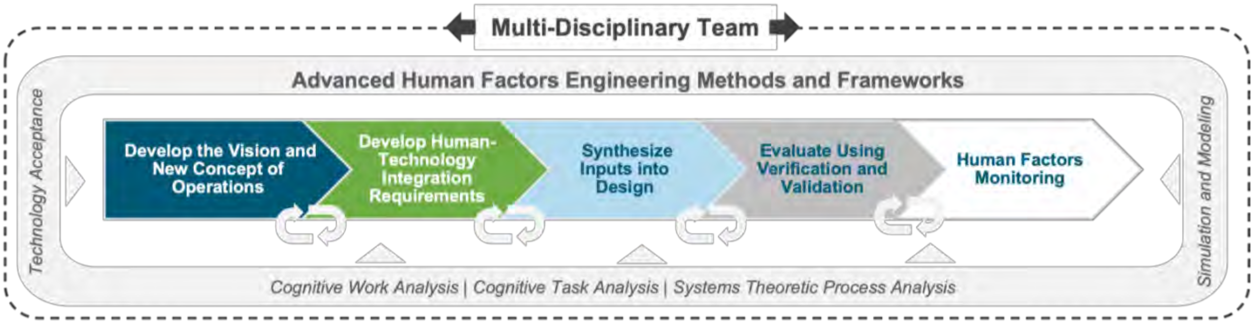


Figure 8. HTI methodology (adapted from INL/EXT-21-64320).

The HTI methodology was developed by the LWRS Program and was first referenced in INL/EXT-21-64320 (2021). Figure 8 presents the HTI methodology, which represents a series of five phases that enable the planning and execution of HFE across the lifecycle of a major digital modification. While the figure indicates a left-to-right progression, it is assumed that iteration is performed between phases, which is indicated by the iterative loops between each phase. The HTI methodology is applied by a multidisciplinary team throughout the project lifecycle. It leverages advanced HFE methods and frameworks, including cognitive work analysis approaches, cognitive task analysis approaches, as well as simulation and modeling techniques.

The HTI methodology was developed based on the review and synthesis of existing industry standards and guidelines, as well as lessons learned from prior control room modernization research performed by the LWRS Program. Further, the HTI methodology follows a systems engineering framework, such as those in the Electric Power Research Institute (EPRI) Digital Engineering Guide (DEG; 2021) and in the International Council on Systems Engineering (INCOSE) guidance for systems engineering (2015).

The following U.S. and international standards and guidelines were therefore considered in developing the HTI methodology:

- U.S. NRC guidance:
    - **NUREG-0800 Chapter 18**, Standard Review Plan (SRP) for the Review of Safety Analysis Reports for Nuclear Power Plants: Human Factors Engineering, Revision 3 (2016)
    - **NUREG-0711**, Human Factors Engineering Review Model, Revision 3 (2012)
    - **NUREG-0700**, Human-System Interface Design Review Guidelines, Revisions 2 and 3 (2002; 2020)
    - **NUREG/CR-3331**, Methodology for Allocating Nuclear Power Plant Control Functions to Human or Automatic Control (1983)
- EPRI guidance:
    - **EPRI 3002011816**, Digital Engineering Guide (DEG): Decision Making Using Systems Engineering (2021)
    - **EPRI 3002015797**, Digital Systems Engineering: Modernization Guide for Practitioners (2020)
    - **EPRI 3002004310**, Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification Guidelines for Planning, Specification, Design, Licensing, Implementation, Training, Operation, and Maintenance for Operating Plants and New Builds (2015)
    - **EPRI 3002018392**, HFAM - Human Factors Analysis Methodology for Digital Systems: A Risk-Informed Approach to Human Factors Engineering (2021)
- IEEE guidance:
    - **IEEE 1023**, IEEE Recommended Practice for the Application of Human Factors Engineering to Systems, Equipment, and Facilities of Nuclear Power Generating Stations and Other Nuclear Facilities (2020)
    - **IEEE 845**, IEEE Guide for the Evaluation of Human-System Performance in Nuclear Power Generating Stations (1999)
    - **IEEE 2411**, IEEE Guide for Human Factors Engineering for the Validation of System Designs and Integrated Systems Operations at Nuclear Facilities (2021)
- International Atomic Energy Agency (IAEA) guidance:
    - **IAEA No. NR-T-2.12**, Human Factors Engineering Aspects of Instrumentation and Control System Design (2021)
- International Electrotechnical Commission (IEC) guidance:
    - **IEC 61839**, Nuclear Power Plants – Design of Control Rooms – Functional Analysis and Assignment (2000).

The next subsections summarize the phases of the HTI methodology, depicted as the five phases in Figure 8. Following the format taken from the INL/EXT-21-64320 technical report in describing the primary HTI technical phases and activities, the standards and guidelines shown above are highlighted in a summary figure for each phase in the following manner (see Figure 9).

Figure 9. HTI methodology technical phase summary.

It should be emphasized that additional resources have been added in this technical report beyond what are presented in the original INL/EXT-21-64320 technical report. These additions are based on demonstrating the methodology through industry collaborations. For each phase, a summary of key stakeholders needed to execute each phase is highlighted by the dark blue banner. Key technical activities and resources needed are highlighted in the green banner. Finally, applicable references (i.e., including standards and guidelines) are highlighted in light blue. It should also be emphasized that, while the HTI methodology described in this section was developed from main control room modernization activities, it is foundational to the approach described in Section 3 and Section 4 that expands HTI to address work optimization across the entire plant infrastructure and organization.

2.2.1 Phase 1: Develop the Vision and New Concept of Operations

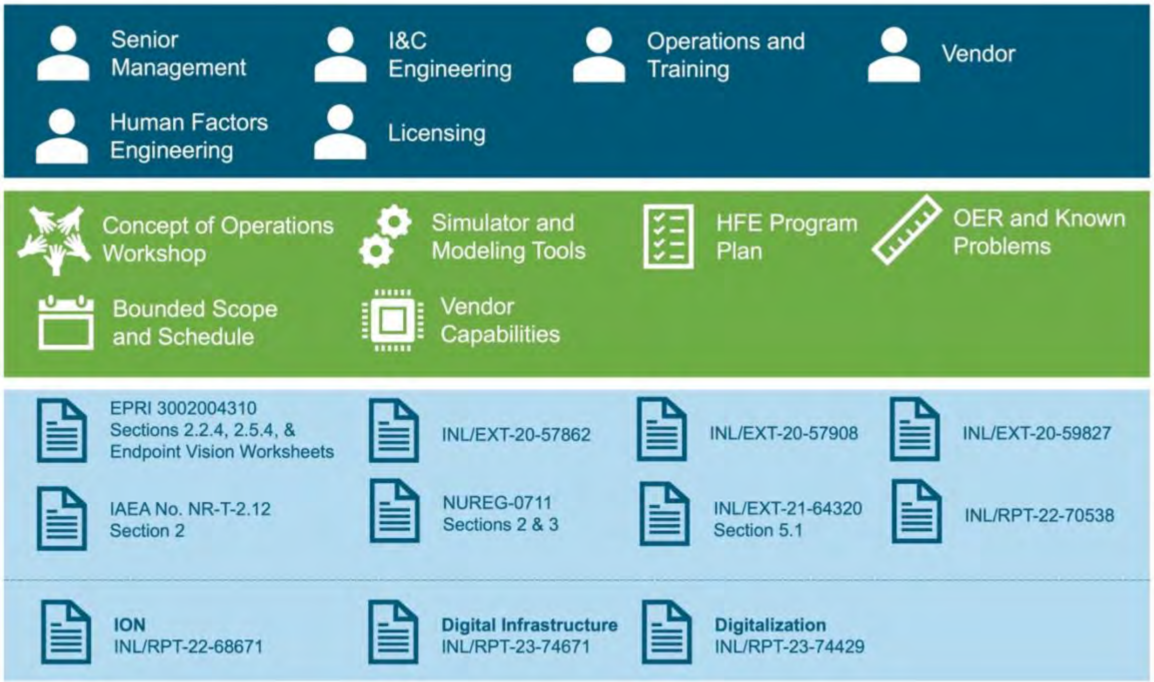


Figure 10. Summary of Phase 1 of the HTI methodology.

Major digital modifications are driven by the necessity to address obsolescence management challenges and to reduce O&M costs (Hunton and England, 2021). Such projects are bounded by scope, budget, and schedule to ensure timely and economical completion. Ironically, these bounding constraints can present their own set of challenges to the project that must be addressed early in the project to reduce the risk of project scope creep. The following HFE technical activities are key elements in ensuring that potential engineering tradeoffs are identified and addressed early in the project when the cost of addressing changes is considerably less than later in the project lifecycle.

2.2.1.1 Define the Vision

Foundational to the success of any major digital modification is defining the *vision* of the new state. The vision should define the overarching I&C architecture (e.g., Section 1.2.1.2) and associated HSIs, including key functionality, for the new modernized state. The new state offers a realistic target to be reached in subsequent digital I&C modification migration phases (described in Section 2.2.1.4) that provides a cohesive operating philosophy for the new digital equipment.

The use of three dimensional (3D) modeling and simulator demonstrations are enabling HFE tools that can support developing a clear new state vision (e.g., Mohon and Kovesdi, 2022). Figure 11 presents an example of the 3D model depiction of a major U.S. utility's new state vision. The development of the model provides a means for communicating the physical characteristics of the new vision to key stakeholders, including personnel from operations, training, and engineering for design feedback and buy-in. Design tradeoffs can be readily identified and addressed when presented to a diverse range of stakeholders, avoiding potential costly rework later in the project. With this, the use of digital human models can be applied inside the 3D modeling environment to perform early ergonomic and anthropometric evaluations of the VDU and workstation placements. The reader is referred to Mohon and colleagues (2023) for details on lessons learned applying 3D modeling for early HFE evaluations.

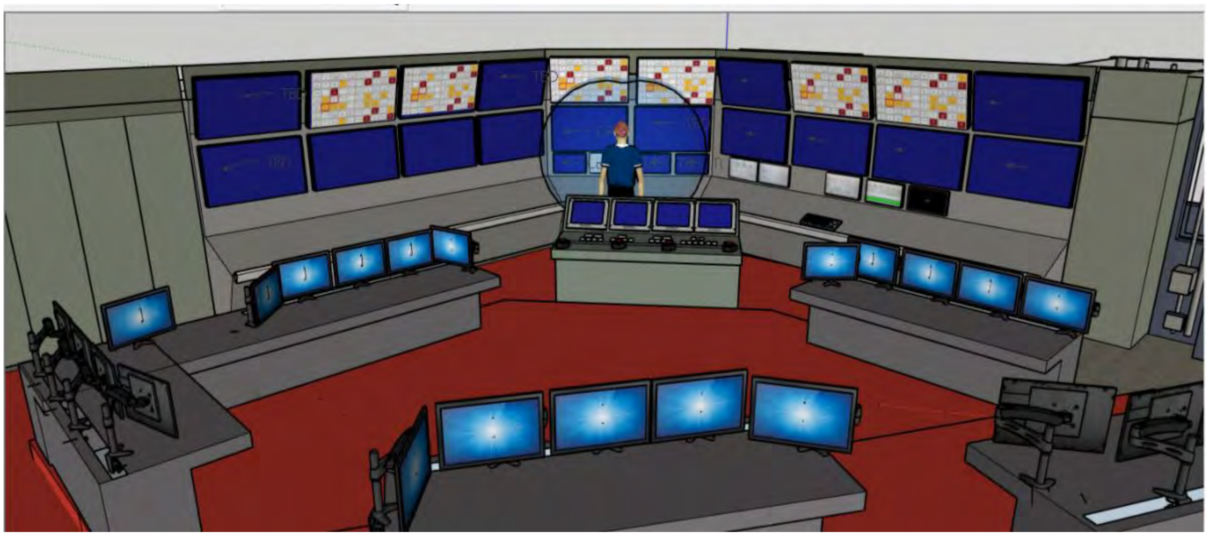


Figure 11. Use of 3D modeling to present a concept of a new state vision.

A second enabling tool used to support a new state vision definition uses glass top simulator test beds to support technology demonstrations and early conceptual design tests that evaluate the key functionality of the proposed vision, including the arrangement of information, navigation strategy of the HSIs, use of advanced features like computerized procedures or task-based displays, and advanced alarm systems. Figure 12 presents Idaho National Laboratory's Human System Simulation Laboratory (HSSL) being used for an early conceptual design workshop with a major U.S. utility. Used in conjunction with the 3D model of the new state vision, LWRS Program researchers have been able to use the HSSL to develop early functional prototypes of the envisioned HSIs that integrate with the utility's site training simulator software for early design tests. While the prototypes are of limited scope and fidelity at this stage (e.g., certain features are not programmed), their application has been instrumental in allowing end users (i.e., licensed operators) to perform walkthroughs with select scenarios to evaluate the usefulness and usability of the proposed vision. An example of an advanced HSI concept developed using rapid prototyping software is presented in Figure 13. Further details of the use of 3D modeling and simulation are shared in INL/RPT-22-70538, INL/RPT-23-71395, and INL/RPT-23-74346.

Figure 12. Photograph of the HSSL in an early new state vision workshop.

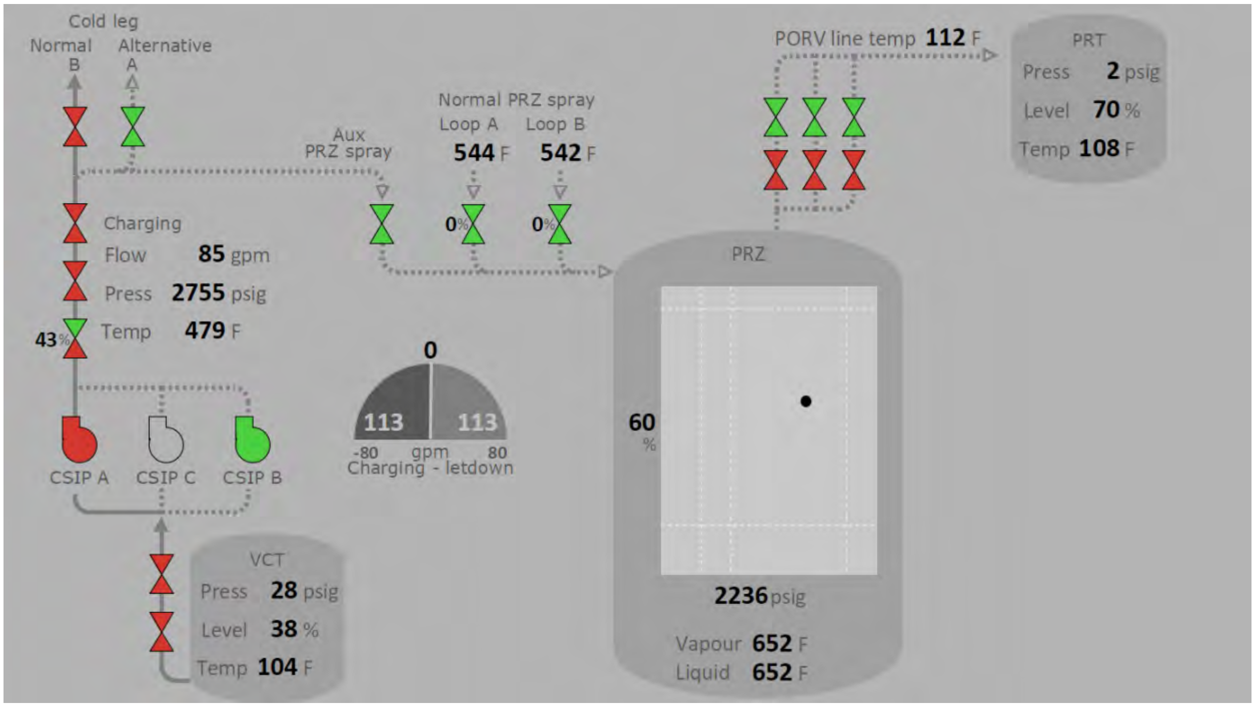


Figure 13. Advanced main control room HSI display concept (credit to Institute of Energy Technology).

2.2.1.2 Evaluate Impacts to the Concept of Operation

The new state vision will fundamentally change the way in which operators perform their tasks to support safe and reliable operation of the nuclear power plant. Therefore, HFE must evaluate the impacts of proposed technologies on the concept of operations. The concept of operations describes the vision, goals, and expectations for the new system from the lens of the users (NUREG-0711, 2012). As illustrated in Figure 7, HFE plays a critical role in evaluating the impacts of the proposed automation enhancements, digital HSIs, and other advanced features that manage the high-level plant functions. This evaluation ensures these modifications do not negatively impact the ability of operators to perform their tasks important to public safety, personnel safety, or plant economic efficiency. Impacts on the plant's concept of operation can be evaluated using early conceptual design tests with the 3D modeling and simulation capabilities discussed in Section 2.2.1.1. In addition to these capabilities, a useful tool in documenting key differences between the existing state compared to the new state, in terms of concept of operations, is the EPRI 3002004310 concept of operation and concept of HSI worksheets (2015). An example of these worksheets is shown in Table 2, and their use is described further in INL/RPT-22-70538.

Table 2. Example of a topic from the EPRI 3002004310 concept of operation worksheet.

Normal Operations Topic	Existing Control Room	Endpoint Vision	Human Factors Impacts
Monitors the plant process, systems, and equipment, including performance monitoring	Captures how operations currently manages the topic column based on the formal conduct of operations and operating experience (OE)	Captures the technology and changes the endpoint vision, which may impact how current operations manage the topic column	Captures the specific expected impacts on operations based on the endpoint vision column content that has been or will be addressed

2.2.1.3 Align the Vision and Concept of Operations with Digital Infrastructure

Functionality of the new state vision requires careful examination of the envisioned I&C architecture. The I&C architecture can be conceived as the "central nervous system" of the nuclear power plant, in which its characteristics and structure enable the functionality of the control systems and applications in a manner that supports safe and reliable operation while also addresses technical requirements (Hunton and England, 2021). The LWRS Program has performed significant research in providing technical guidance in deploying an I&C architecture that enables a technology-centric concept of operations (i.e., as opposed to labor-centric) that will lower the total cost of ownership for utilities while addressing obsolescence and cybersecurity concerns associated with digital I&C systems. The technical report INL/RPT-23-74671 describes the digital infrastructure framework in detail.

It is worth highlighting here that a generic framework is used to communicate key features of the digital infrastructure framework (refer to Figure 4). As previously highlighted, the digital infrastructure in Figure 4 is simplified to show general classes of plant applications located across different levels of the infrastructure. These levels are described by the NRC Cybersecurity Levels and Purdue Model Network Levels. Plant data is generated by the safety-related I&C platform and non-safety related DCS through a data diode up to the corporate network to enable enhanced access to plant information for improved organizational situation awareness and decision-making, while inhibiting the bidirectional flow of control signals down the infrastructure. This architecture ensures extending the operating lifetime of existing light-water reactors to over 80 years while minimizing the economic and technical burden throughout their entire lifespan.

An obvious intersection between HTI and digital infrastructure is the need for ensuring that the HSIs at all infrastructure levels are designed to support the personnel's tasks and in a consistent manner. Likewise, the role of automation offered from commercially available vendor capabilities within the infrastructure must be evaluated from an HFE perspective, such as through the activities described in Sections 2.2.1.1 and 2.2.1.2. Furthermore, we must emphasize that the placement of specific applications in the infrastructure will determine what scope and breadth of bounding technical requirements may influence the way that personnel use the technology. For example, an ML application for preventative maintenance may be used for such maintenance functions, but the data processed from it may only serve as an aid for operations that licensed operators must verify from the HSIs of the safety-related platform or non-safety DCS, via policy and procedure. The manner of how the digital infrastructure influences technology use must be understood and accounted for synergistically in all HTI activities.

2.2.1.4 Develop a Migration Strategy

A general strategy observed by industry is to perform digital modifications in a stepwise manner, in which the new state vision is reached through a series of planned systematic smaller scoped modifications between plant outages. This approach has economical merit by minimizing plant downtime through a more manageable scope that can be performed in an extended outage thereby maximizing plant availability. Another advantage of a stepwise approach is that it provides incremental change in terms of impacts to the concept of operations, allowing for gradual familiarization to new digital technology, which can reduce peak demands on training.

An important part of developing a migration strategy is to provide clarity into the specific plant systems encompassed and associated impacts of the expected modifications at each phase. Ideally, each migration phase should complement each previous migration phase. For instance, a VDU should be placed in a given phase with careful thought toward avoiding needing to relocate the VDU in later phases. Likewise, the plant systems may be selected based on their operational similarities such that a given modification does not introduce a new error trap, such as requiring an operator to have to perform plant control by "ping ponging" between a seated workstation and standing control board.

The introduction of the new state vision through targeted HTI activities, like a conceptual workshop (e.g., Section 2.2.1.1), should therefore also consider how the migration from the existing plant state to new state will be accomplished and identify human factors impacts across these migration phases. One such tool in documenting key changes is presented in Table 3. This table represents a template for documenting key changes across each migration phase.

Table 3. Template for recording human factors impacts by migration strategy.

Phase	Systems Impacted	Modernization Path	Summary of HSI Changes	Human Factors Impacts
Upgrade Phase Sequence	Enter system(s) impacted by phase	License amendment request or 10 CFR 50.59	Summary of HSI changes	Identify HFE considerations

2.2.1.5 Develop a Human Factors Engineering Program Plan

The HFE Program Plan is a key HTI element and is described in NUREG-0711 (2012). Key characteristics of an HFE Program Plan, as described by NUREG-0711, include:

- HFE Program Plan goals and scope
- Team composition
- HFE processes, procedures, and elements
- HFE issue tracking.

These topics are further described in NUREG-0711 (2012), under Section 2. Though, it is worth noting here that the HFE Program Plan should enable a *graded approach* to applying HFE to which particular focus is on important human factors (e.g., credited operator actions in the plant's licensing basis) impacted by the modification. Grading HFE technical activities is generally done by examining the risk to plant safety, personnel safety, and economic impact, as well as the degree of modification complexity (see Figure 14).

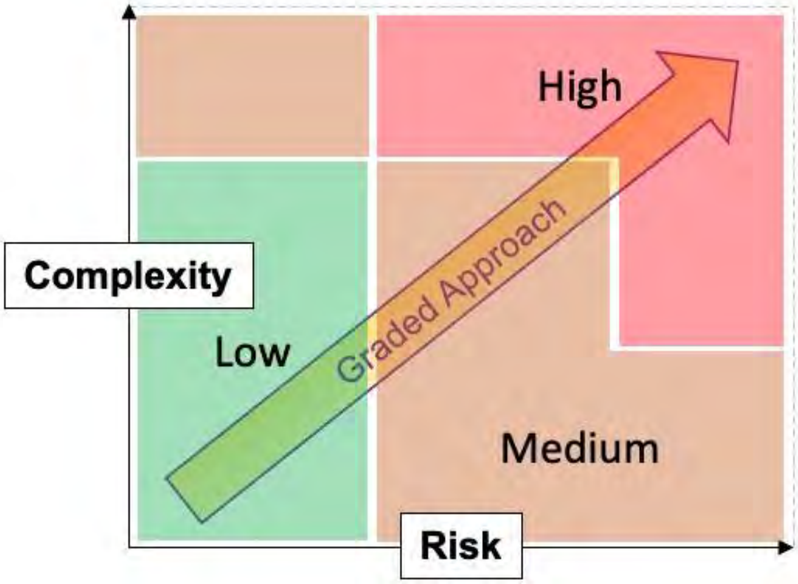
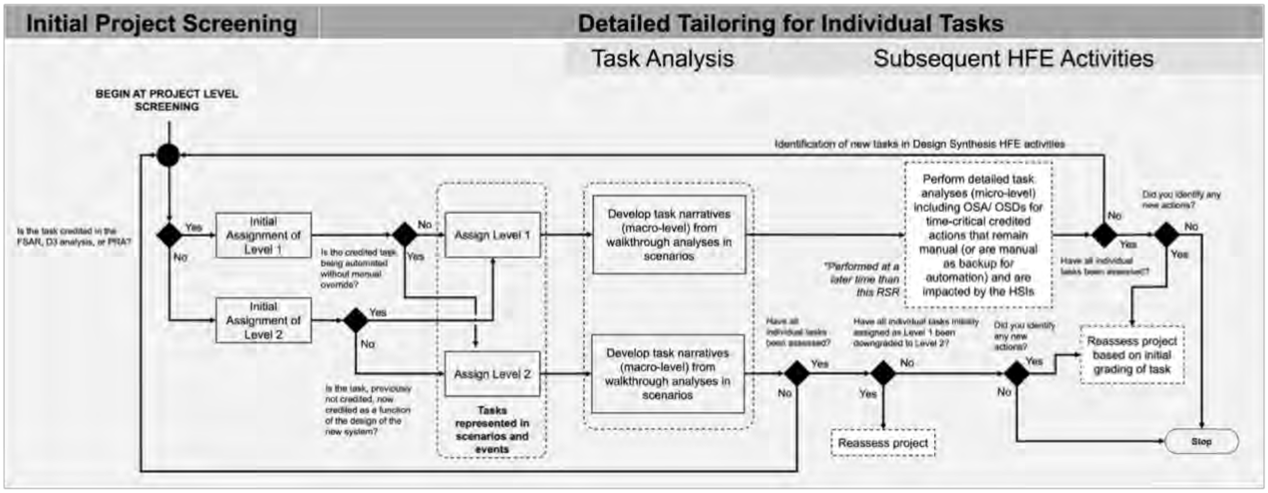


Figure 14. Grading HFE by complexity and risk (adapted from INL/RPT-22-70538).

This grading ensures that greatest priority is on impacted tasks that have the greatest significance to safety and plant efficiency and that key HFE technical activities described in NUREG-0711 are performed appropriately for the scope of the modification. For instance, if the modification has little to no impact on staffing and qualifications, the HFE Program Plan should provide a way to refocus on other HFE elements that require greater attention.

As each migration phase is graded, the HFE Program Plan should also describe how specific tasks are tailored using a similar grading. Recent collaborations with a major U.S. utility in supporting their safety-related digital I&C upgrades applied a tailoring approach, as seen in Figure 15.



Note. Tasks not impacted by the upgrade were noted as a Level 3 (little to no impact) and were not considered for subsequent HFE analysis.

Figure 15. Tailoring HFE by task risk level (adapted from INL/RPT-22-68472).

The objective of tailoring in this context to ensure that the impacted manual actions of significance (i.e., such as credited operator actions documented in the final safety analysis report) was twofold. First it ensured that the tasks of greater significance were analyzed in greater detail. Second it allowed the HFE team to analyze additional impacted tasks at an appropriate level to ensure the HSIs provided operators with adequate control and information to perform their tasks through a wide envelope of use cases beyond what is required of the operators for the important human actions. An example of a HFE Program Plan is provided in INL/RPT-22-68693 from a safety-related upgrade pilot project. This report is accessible from:

- https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML23255A095 (Page 780)

2.2.1.6 Perform Operating Experience Review

The main objective of an operating experience review (OER) is to identify HFE-related safety and availability issues and lessons learned that can be applied in designing, analyzing, and evaluating the modification in question (NUREG-0711, 2012). An OER therefore provides information on the performance of predecessor technologies (earlier technologies that the modification is based on). The issues and lessons learned from operating experience (OE) collected during an OER provide a basis for improvement. Inputs into the OER come from multiple sources, including database searches across multiple sources and interviews with plant staff (Figure 16).

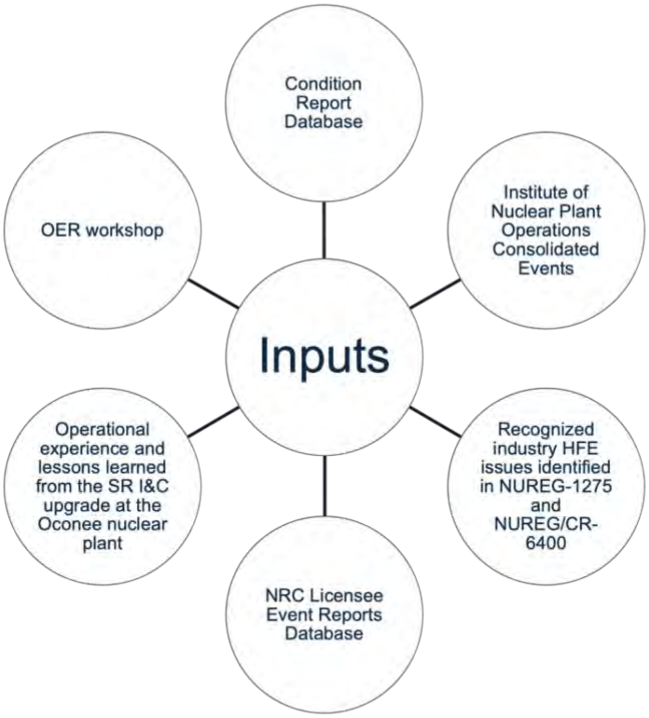
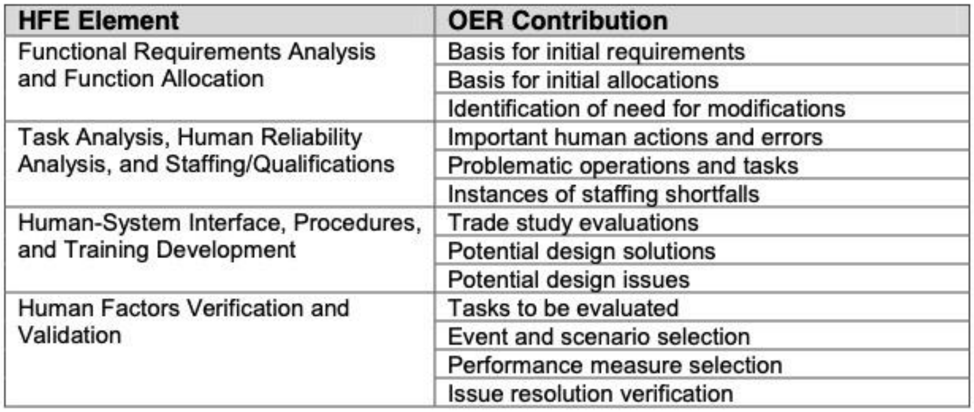


Figure 16. Data input for performing an OER.

The OE collected in an OER (i.e., the output of this activity) serves as *input* into all subsequent HFE technical implementation activities. The nature of input that the OER contributes is summarized in Figure 17. The OER provides insights into the design and identification of important human actions, as well as scenarios for verification and validation (V&V).



HFE Element	OER Contribution
Functional Requirements Analysis and Function Allocation	Basis for initial requirements
	Basis for initial allocations
	Identification of need for modifications
Task Analysis, Human Reliability Analysis, and Staffing/Qualifications	Important human actions and errors
	Problematic operations and tasks
	Instances of staffing shortfalls
Human-System Interface, Procedures, and Training Development	Trade study evaluations
	Potential design solutions
	Potential design issues
Human Factors Verification and Validation	Tasks to be evaluated
	Event and scenario selection
	Performance measure selection
	Issue resolution verification

Figure 17. The role of OER in the HFE Program (adapted from NUREG-0711).

2.2.2 Phase 2: Develop Human-Technology Integration Requirements

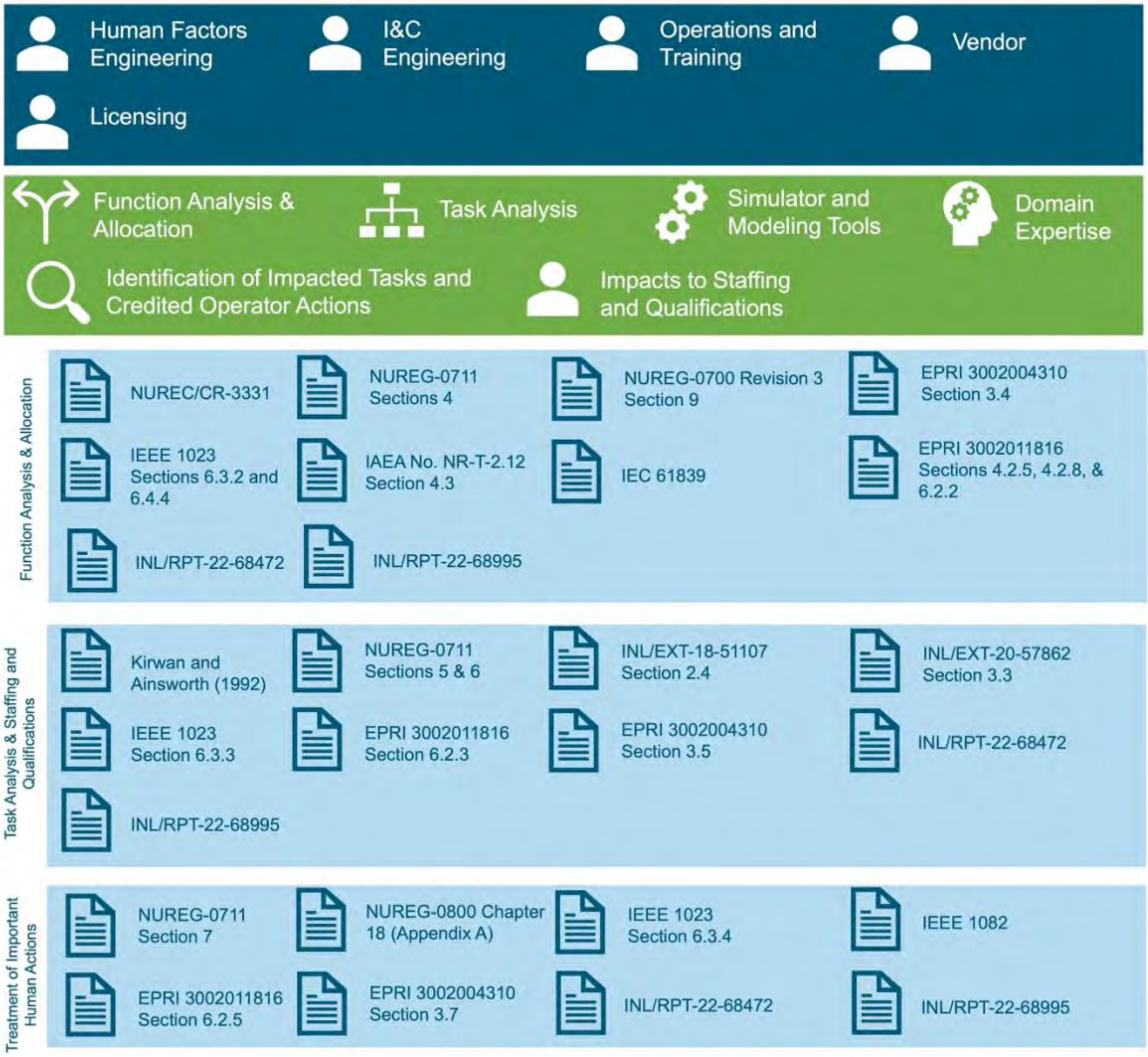


Figure 18. Summary of Phase 2 of the HTI methodology.

The next major phase is to translate the new state vision into the functional, information, and task requirements that drive the design of the new HSIs, impacted procedures, and training. These activities typically begin during the conceptual design phase of the project. The key activities in achieving this new vision include function analysis, function allocation, and task analysis that follow a graded approach based on an integration of risk analyses. This phase also includes a review of impacts to staffing and qualifications, following the complete set of planning and analysis elements of NUREG-0711. These activities are described next.

2.2.2.1 Function Analysis and Function Allocation

FA&A[4] consists of two technical activities. First, *function analysis* identifies the functions that must be performed by the plant systems to ensure safety and generate power (NUREG-0711, 2012). These functions are then decomposed into more detailed system-level functions needed to achieve the higher level functions. Figure 7 provides an example of a function decomposition. When the functions have been sufficiently defined, functions can be assigned by determining whether these functions are performed automatically, manually, or both (shared assignment). This step is denoted as *function allocation*.

As previously highlighted in Section 2.1.2, the FA&A element for performing modifications to existing light-water reactors is inherently different from developing a new reactor. For existing plants, the high-level functions have already been defined and are licensed and operable. The primary focus of FA&A in this context is therefore to focus on how the new digital control system, including proposed automation enhancements and associated HSIs, will impact the plant's existing concept of operations and how these features will affect the crew's abilities to safely and reliably operate the plant.

While FA&A elements may be addressed earlier in the project lifecycle (e.g., Section 2.2.1.2), the clarity of specific changes in personnel tasks may not be completely understood at that time. Furthermore, specific technologies may not even be procured. Therefore, when the vendor has been chosen and there is a clear understanding of the available features and functions of the selected platform, further evaluating the impacts of these automation features within the conceptual design is warranted. For example, in a recent industry collaboration for a major safety-related digital I&C upgrade, LWRS Program researchers performed FA&A through a focused workshop at the site's training simulator to gain a baseline understanding of the current concept of operations (Figure 19). Impacts of the new features were then evaluated in subsequent HFE activities.

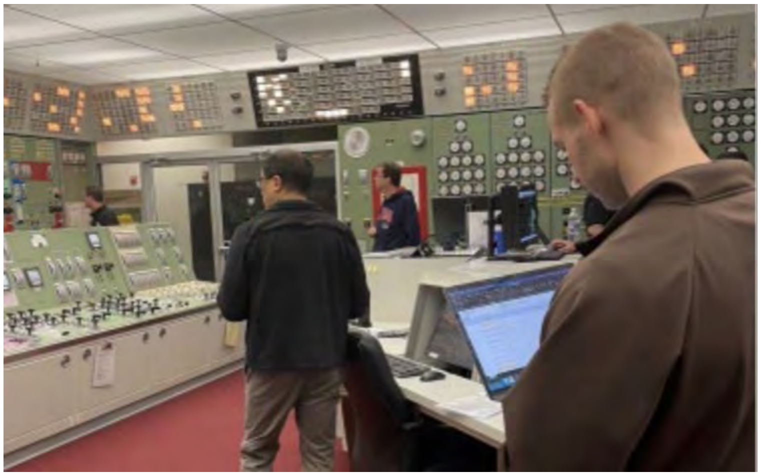


Figure 19. LWRS Program researchers performing FA&A.

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[4] Oftentimes referred to as **functional requirements analysis and function allocation**.

A key outcome of the baseline FA&A activity was that the LWRS Program researchers (i.e., defined as the human factors process team) were able to develop a baseline understand of the plant's existing concept of operations, including:

- The way in which operators perform their tasks
- The coordination between crew members in mitigating plant casualties requiring the use of emergency operating procedures
- The task flow between different control boards to perform tasks related to mitigating plant casualties
- The identification of key scenarios to use in subsequent HFE activities
- The existing pain points and error traps the proposed system should address.

2.2.2.2 Task Analysis

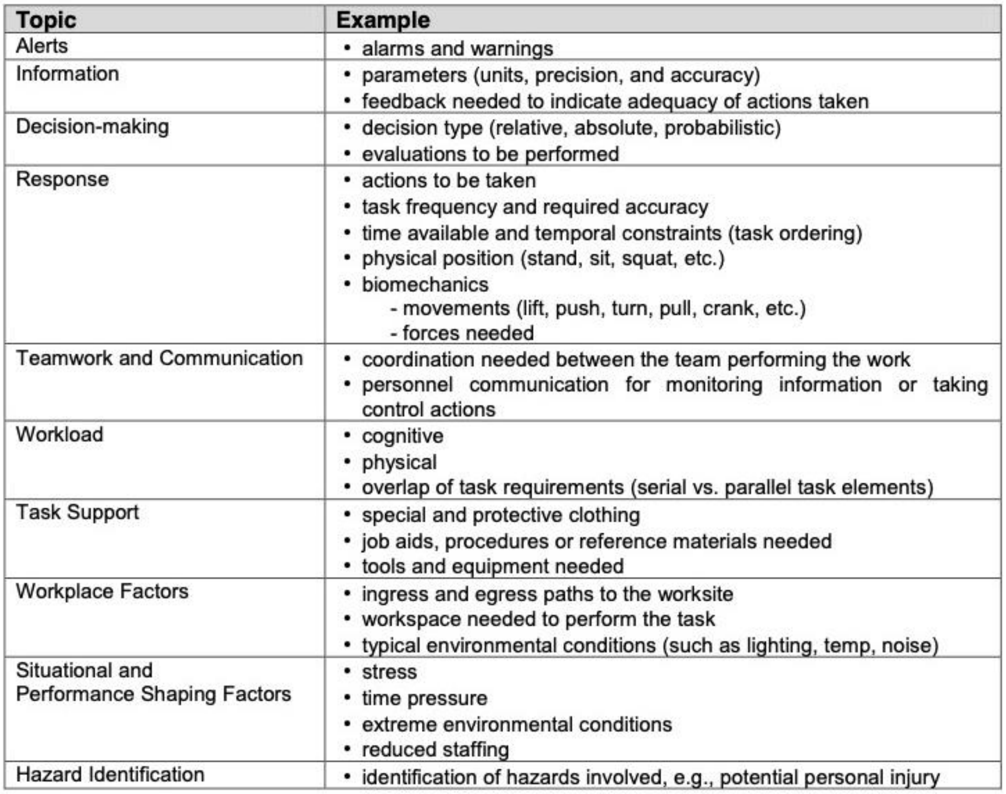
The purpose of task analysis is to identify the specific tasks needed to accomplish functions assigned to personnel and to further identify the information, controls, and task support required to complete the tasks. The output of task analysis serves as a basis for the design of HSIs, procedures, and training (covered in Section 2.2.3). Task analysis covers a range of specific task data collection and representation methods (Kirwan and Ainsworth, 1993; Stanton et al., 2013). Notable approaches used for nuclear power plant control room modernization include:

- Hierarchical task analysis (HTA) and tabular task analysis (TTA)
- Operational sequence analysis (OSA) and operational sequence diagrams (OSDs)
- Walk-through analysis and talk-through analysis
- Cognitive task analysis techniques
- Process charting techniques.

Specific methods that have been used in control room modernization can be found in NUREG-0711 (2012) Section 5, EPRI 3002018392 Section 3.5 (2021), EPRI 3002004310 Section 3.5 (2015), IEEE 1023 (2020), INL/EXT-21-64320 (2021), and INL/RPT-22-68472 (2022). To illustrate the use of task analysis, LWRS Program researchers applied a combination of techniques to support the safety-related digital upgrade with a major U.S. utility. Using the scenarios identified by the site's operations subject matter experts (SMEs), a task analysis workshop was executed at Idaho National Laboratory's HSSL in which a subset of conceptual HSIs were rendered and presented in tandem with digital representations of the existing analog control boards to enable a subset of the site's licensed operators to "walk through" the scenarios with their procedures (Figure 20). The operators were able to readily refer to the existing boards when walking through the scenarios and then reference the new HSI concepts to determine the necessary information and controls needed on each display to support their tasks.

Figure 20. Photograph of a task analysis workshop in the HSSL.

During this workshop, the scenarios exercised a range of tasks impacted by the modification and global information requirements were identified to support the design of the new HSIs and modifications to the procedures and training, leveraging the guidance in NUREG-0711 (see Figure 21).



Topic	Example
Alerts	• alarms and warnings
Information	• parameters (units, precision, and accuracy) • feedback needed to indicate adequacy of actions taken
Decision-making	• decision type (relative, absolute, probabilistic) • evaluations to be performed
Response	• actions to be taken • task frequency and required accuracy • time available and temporal constraints (task ordering) • physical position (stand, sit, squat, etc.) • biomechanics - movements (lift, push, turn, pull, crank, etc.) - forces needed
Teamwork and Communication	• coordination needed between the team performing the work • personnel communication for monitoring information or taking control actions
Workload	• cognitive • physical • overlap of task requirements (serial vs. parallel task elements)
Task Support	• special and protective clothing • job aids, procedures or reference materials needed • tools and equipment needed
Workplace Factors	• ingress and egress paths to the worksite • workspace needed to perform the task • typical environmental conditions (such as lighting, temp, noise)
Situational and Performance Shaping Factors	• stress • time pressure • extreme environmental conditions • reduced staffing
Hazard Identification	• identification of hazards involved, e.g., potential personal injury

Figure 21. Information requirements and task considerations (adapted from NUREG-0711).

Specific credited manual operator actions from the site’s final safety analysis report, defense-in-depth analysis, and plant probabilistic risk assessment were also identified, for which a detailed task analysis using OSAs and OSDs was performed in later HFE activities, as described in Section 2.2.3.2. Staffing and qualifications were also examined following the task analysis. The task analysis results determined that the digital upgrade would not fundamentally impact staffing and qualification requirements for plant personnel.

2.2.3 Phase 3: Synthesize Inputs into Design

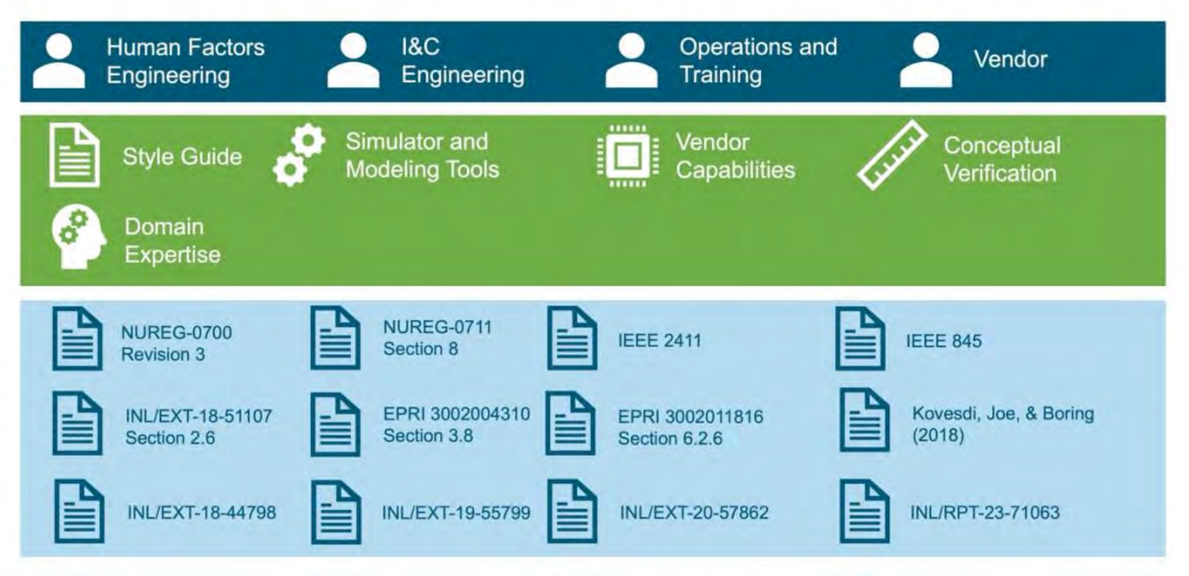


Figure 22. Summary of Phase 3 of the HTI methodology.

The design synthesis translates the results from Phase 1 activities (Section 2.2.1) and Phase 2 activities (Section 2.2.2) into HSIs that will be used by personnel. Key activities for this phase include developing a style guide and completing tests and evaluations to refine the style guide and associated HSI designs. These activities are discussed next.

2.2.3.1 Human-System Interface Style Guide

The HSI style guide provides the set of rules that guide HSI design to ensure consistency across displays and to ensure that HFE principles and operational input are applied to the design (EPRI 3002004310 2015). The style guide addresses pertinent design topics, including:

- The organization and presentation of information on individual display pages to be presented on VDUs
- The organization and navigation between display pages
- The design of display fonts and symbols and use of color coding and labeling
- The design of touch panels to provide for operator input of decisions.

For demonstration, LWRS Program researchers led the development of the HSI style guide for the safety-related and non-safety related HSIs, as part of the participating utility’s safety-related digital I&C upgrade. The HSI style guide was intended to guide the design of the HSIs for the upgrade, as well as provide support for the design of future additional main control room upgrades by the utility. The process through which the HSI style guide was developed is illustrated in Figure 23.

The top of the figure shows the inputs that informed the style guide (light blue). These included industry standards and guidelines such as the NRC *Human-System Interface Design Review Guidelines* (NUREG-

0700, 2002), the new state vision (Section 2.2.1), the selected vendor design conventions and resulting design documentation, the results from HFE planning and analysis activities (Section 2.2.2), and the existing design conventions of the utility documented in a design baseline document.

The HSI style guide provided general guidance for the design of the safety-related and non-safety related HSIs (green), such as by providing general design bases for the specifications made by these platforms. Moreover, the style guide is considered a "living document" where subsequent HFE design activities may further inform its guidance, particularly when certain tradeoffs are identified (i.e., in the synthesis of multiple inputs). Key activities including task analysis (Section 2.2.2.2) and conceptual verification (Section 2.2.3.2) served as subsequent inputs into revisions to the HSI style guide for addressing particular tradeoffs identified by the design team. A final point worth mentioning is that the style guide also supports V&V activities (Section 2.2.4), particularly with design verification.

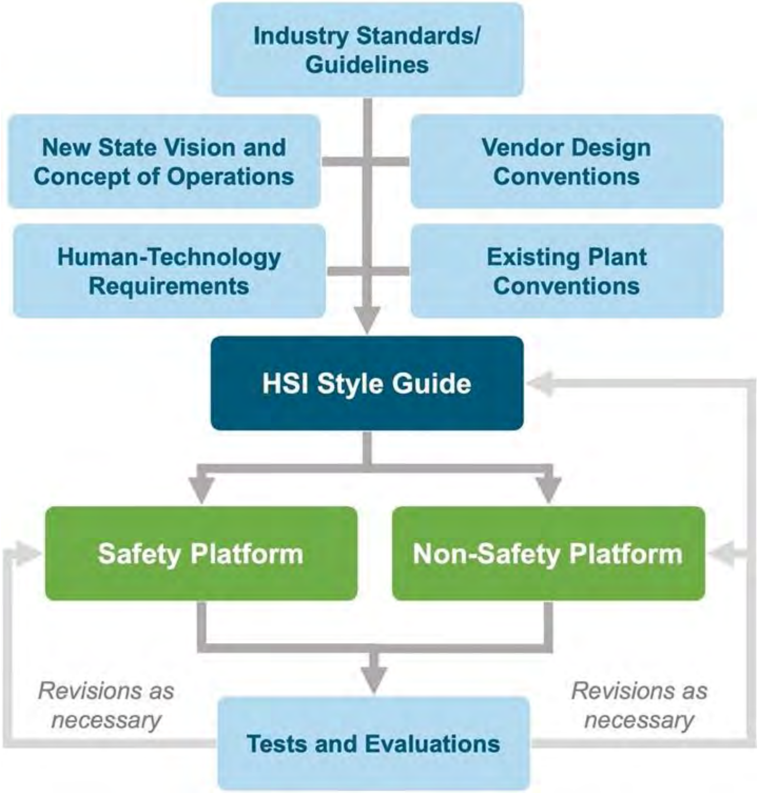


Figure 23. HSI style guide development process.

2.2.3.2 Design Tests and Evaluations

The style guide is a "living document." This is well recognized across various standards and guidance documents, including EPRI 3002004310 (2015), ANSI/ International Society of Automation (ISA)-101.01-2015, and INL/EXT-21-64320 (2021). As seen in Figure 23, there is an iterative feedback loop between tests and evaluations (i.e., also referred to as *design testing* or *formative usability testing*) for revisions to the style guide. The purpose of design testing is to elicit information that can be used by the design team to make design decisions (IEEE 2411, 2021). The nature of what design decisions are to be made will determine the scope and type of design tests in question. As described in IEEE 2411 (2021), the cases for which design tests are used range from evaluating conceptual designs (e.g., Section 2.2.1) to evaluating different design options or tradeoffs to refining the design for detailed specification.

Design tests differ from validation activities, as in V&V, based on their scope and objectives. For further elaboration, validation is more limited in terms of its objectives; it focuses on assessing whether the design meets its intended purpose. This is accomplished using acceptance criteria. Similarly, because design tests are intended to support design decisions, refinement will be made to the design using the produced results. With this, IEEE 2411 (2021) further differentiates design tests from validation in terms of the degree of configuration control of the design, in which validation applies a high degree of configuration control whereas design testing may be less formal in this nature. This is also the case with formality in documentation.

The treatment of "deficiencies" in the design differ between design tests and validation. With design tests, identified design issues will be documented, prioritized, and addressed in the design process. This process ensures validation is performed successfully. Through iterative design, the number of design issues and recommendations will diminish through each subsequent design test. This pattern demonstrates a degree of convergence that the design will adequately support the intended users' task needs.

The specific measures used for design tests may differ from what is selected for validation. Kovesdi, Joe, and Boring (2018) provide a framework for characterizing human-system performance measures, as seen in Figure 24.

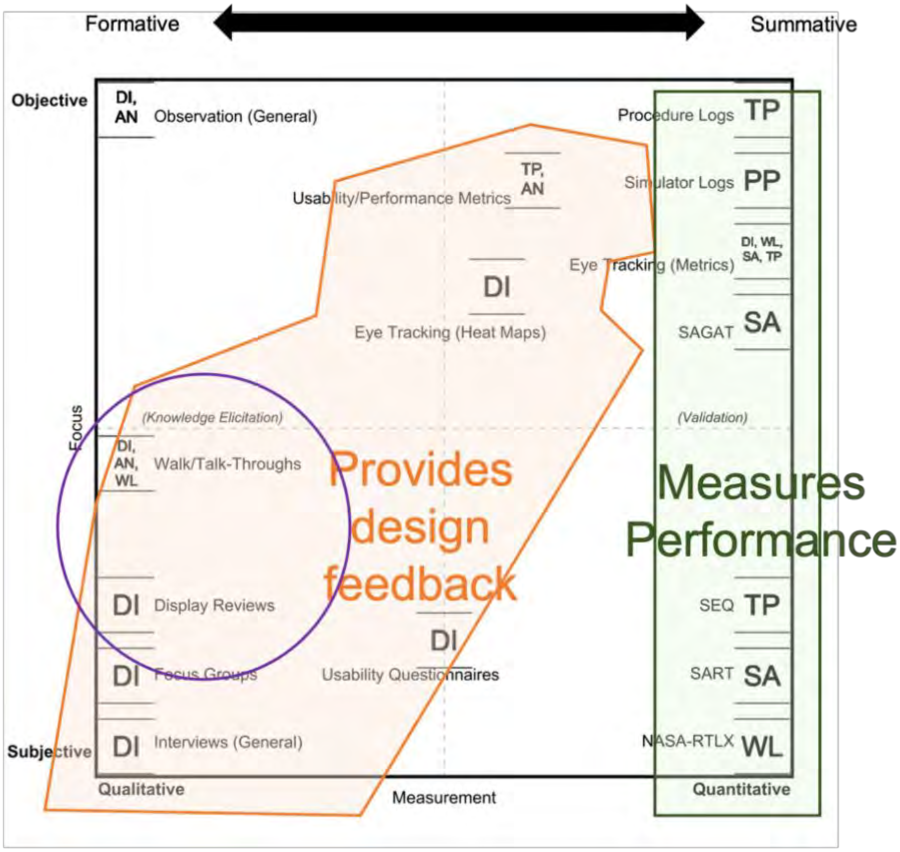


Figure 24. Landscape of HFE methods and measures for nuclear power plant modernization (adapted and enhanced from Kovesdi, Joe, and Boring, 2018).

Figure 24 presents common HFE methods and measures across two dimensions: the extent to which a method or measure is objective or subjective (y-axis) and the extent to which the method or measure is qualitative or quantitative (x-axis). Since the focus of design tests is to support design decisions, which commonly implies identifying and prioritizing design issues, the specific methods and measures selected tend to favor more qualitative approaches. In this context, a diverse set of qualitative methods and measures that includes a combination of subjective and objective measures is beneficial. For instance, observations of the user performing tasks in their existing environment or walking through their tasks with a conceptual prototype of the new design provides behavioral data of what the user needs to accomplish and how they are performing their tasks (i.e., objective data). In combination with observation, the human factors engineer may ask the user to verbalize their thoughts and decision processes in performing their tasks to understand the rationale and decision-making characteristics of the task (i.e., subjective data). The combination of the two approaches provides a rich dataset to support design decisions.

Performance-based measures that are quantitative in nature are generally used for validation. These measures too can range from objective to subjective. Objective quantitative measures may include operator task performance times recorded by the simulator or a data recording device. Validation may include dispositive (i.e., pass/fail) acceptance criteria for performance times, such as defined by the plant's final safety analysis report. Subjective quantitative data may also be collected for validation, such as through administering a self-report survey like the National Aeronautics and Space Administration Task Load Index, which captures self-reported perceived workload. Such measures may be used as diagnostic criteria in validation. Finally, it is worth noting that quantitative measures may also be applied to design tests to help establish reasonable confidence that the design can enable its intended users to perform their tasks.

Design testing was demonstrated by LWRS Program researchers with a utility collaborator in the support of their safety-related digital I&C upgrades (Hunton, Kovesdi, and Joe 2023). The project described design testing under the technical activity, *conceptual verification*. Conceptual verification established reasonable confidence that the HSIs being developed for the safety-related and non-safety related platforms could be used to support operator actions associated with the impacted upgrades and that V&V activities could be accomplished successfully without any major deficiencies. Conceptual verification extended the scope of the task analysis (Section 2.2.2.2) to analyze the important human actions in detail using OSA and OSD and to develop criteria for performing the timeline analysis described in NUREG-1852 (2007). The specific results of conceptual verification go beyond the scope of this technical report. However, an important takeaway pertinent to this work is that the use of iterative tests and evaluations was instrumental in establishing reasonable confidence that the design was progressing to an acceptable state that could be submitted for further V&V activities. The results of conceptual verification not only provided early project confidence that the operators could perform the important human actions impacted by the upgrade in the time available but also identified a significant number HSI and procedure items for further enhancement, going into V&V. These items were therefore identified and addressed well before V&V to help establish a safety case for the integrated system design.

The specific results of this work submitted by the utility to the NRC can be found in INL/RPT-23-71063 (Hunton, Kovesdi, and Joe 2023).

- https://www.nrc.gov/docs/ML2309/ML23095A223.pdf

2.2.4 Phase 4: Evaluate Using Verification and Validation

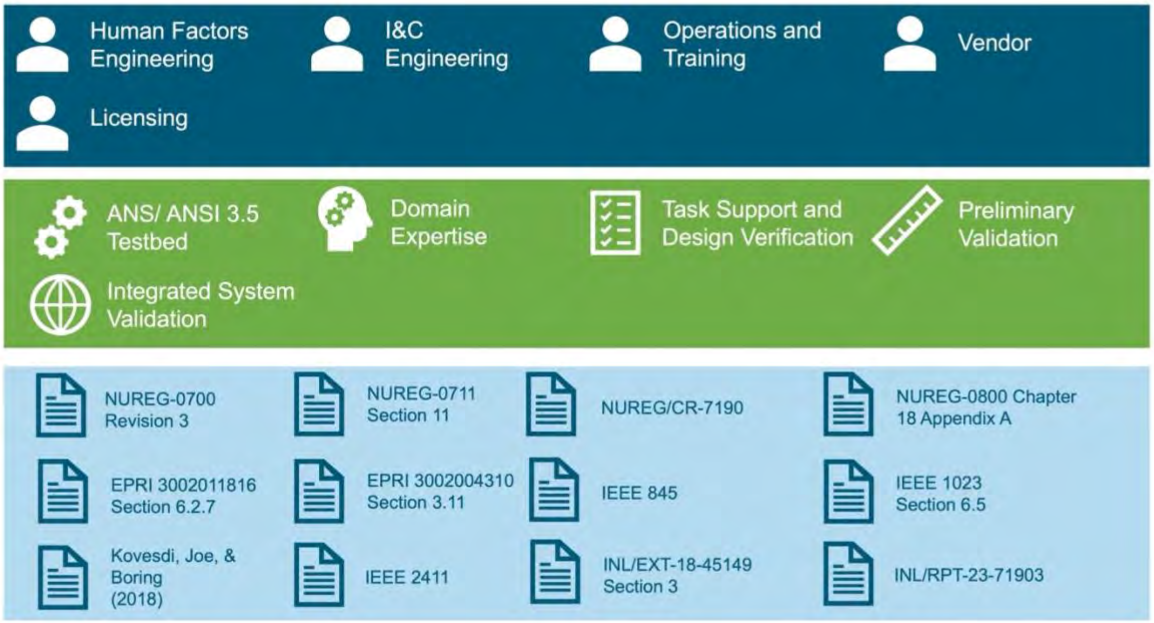


Figure 25. Summary of Phase 4 of the HTI methodology.

The activities under V&V are used to comprehensively determine that the design conforms to HFE design principles and enables users to successfully perform their tasks to ensure plant safety and meet operational goals (NUREG-0711, 2012). Following the NUREG-0711 framework, V&V contains three primary technical activities: task support verification, HFE design verification, and integrated system validation (ISV).

Preparation for these activities includes following a scenario-based approach, such as through sampling operational conditions. The sampling of operational conditions represents conditions that encompass the range of events that could be encountered during the nuclear power plant's operation, reflect the characteristics that impact system(s) performance, and consider the use of any safety-significant HSIs. The operational conditions therefore drive the scope of task support verification and ISV by determining the extent of V&V coverage across key use cases.

An output of the three V&V technical activities includes the identification and disposition of human engineering discrepancies (HEDs). HEDs are a result of any items found during task support verification or HFE design verification in which the HSIs are inconsistent with specific guidelines used. For ISV, HEDs are a result of any unmet performance criteria. All HEDs should be dispositioned, and some may require correction, if they have direct safety consequences (i.e., could adversely impact task performance, which negatively affects plant safety margin).

A significant challenge arises with the traditional application of HFE V&V, as described in NUREG-0711, when following the Alternative Review Process in the recently revised *Digital Instrumentation and Control Interim Staff Guidance* (DI&C-ISG-06) *Licensing Process*, Revision 2, (2018). The Alternative Review Process, applicable for those safety platforms with a generic safety evaluation report, omits an entire review phase when compared to the Standard Review Process, which significantly enhances project efficiency and schedule risk. Following this new process, a safety determination can be made prior to factory acceptance testing. While this process seems significantly beneficial from an I&C project perspective, a key challenge was that the existing HFE guidance, following NUREG-0711, entails gaining safety determination through the ISV results, which is performed after factory acceptance testing.

The issue that the regulator and applicant must deal with is managing expectations in the licensing amendment process when following the Alternative Review Process when ISV results are absent. As a result, the regulator, as well as other bodies of standards and guidelines, have started identifying alternative yet complementary approaches to NUREG-0711 to support V&V. Namely, IEEE 2411 provides guidance in following a multistaged validation approach. The multistaged validation approach is predicated on the notion that early testing and confirmation reduces risk and increases confidence in the system (i.e., such as in determining its safety). Multistaged validation is conducted as a set of discrete validation stages with their own objectives, methods, and results. At each stage, information is generated from the results to form a determination that the system can accomplish its intended use, goals, and objectives in its environment. The stages should incrementally build on the previous results to support final validation conclusions.

In this context, ISV is therefore not omitted but rather is part of a more comprehensive and systematic validation strategy that is embodied in the project lifecycle. In a recent publication by the regulator, the use of a multistaged validation approach was acknowledged as an acceptable path for addressing the challenges posed by the Alternative Review Process (Vazquez, Green, and Desaulniers, 2022). The authors' position is that a safety determination may be made prior to the availability of ISV results based on the applicant's robustness of their overall HFE process along with insights gained from early staged validation results within a robust multistaged validation program. Put simply, the results from early stage validation that provide reasonable confidence that the proposed design maintains plant safety in combination with having a robust validation program in place may be used to issue a safety determination prior to ISV and therefore support the Alternative Review Process for safety-related equipment with a generic safety evaluation report.

In line with this proposed path, LWRS Program researchers have demonstrated a multistaged approach to support a utility collaborator's safety-related digital I&C upgrades. This effort dovetailed the results from conceptual verification (Section 2.2.3.2) into an early validation activity denoted as *preliminary validation* (Hunton, Kovesdi, Joe, and Mohon 2023). Preliminary validation provides high confidence that the time required to perform the impacted important human actions (modeled using OSAs and OSDs in Section 2.2.3.2) could be performed in the time available and determined acceptance criteria for ISV. A secondary goal of preliminary validation was to evaluate the broader set of impacted tasks within key scenarios, presenting a range of plant casualties, that required the crew to use the impacted HSIs and procedures to detect, diagnose, and perform actions for mitigation to ensure plant safety. Preliminary validation was a performance-based evaluation with clearly defined dispositive acceptance criteria and diagnostic criteria. Preliminary validation was intended to be part of a broad HFE validation strategy to support establishing reasonable confidence that the new HSIs could be used effectively by the intended users in the expected use environment, as part of reaching a safety determination by the regulator. In the broader validation strategy, a detailed V&V as described in NUREG-0711 was part of this HFE Program.

The specific result of preliminary validation is documented in INL/RPT-23-71903 (Hunton, Kovesdi, Joe, and Mohon 2023).

- https://www.nrc.gov/docs/ML2317/ML23177A224.pdf

2.2.5 Phase 5: Human Factors Monitoring

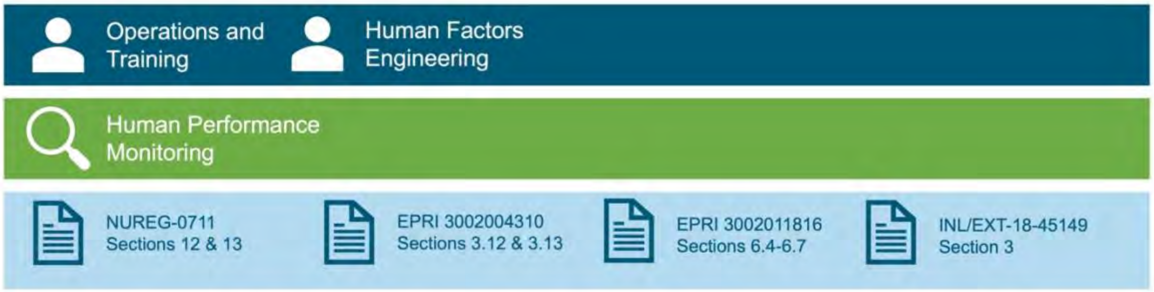


Figure 26. Summary of Phase 5 of the HTI methodology.

The final phase concerns applying HTI after installing and commissioning the new system. There are three primary goals at this phase in the project lifecycle:

- To ensure all HEDs that require correction are resolved and that the modifications are appropriately addressed to the HSIs, procedures, and training program
- To address HFE considerations that could not be directly evaluated previously for reasons such as limitations of the testing environment (i.e., HFE considerations associated with temperature, humidity, or other environmental factors)
- To continuously monitor the newly integrated system, enabling OE to be collected for future modifications.

Following the HTI guidance from Phases 1 through 4, the extent of design issues and HEDs that come out of Phase 5 should be notably fewer and less significant, ultimately reducing total project cost and risk.

2.3 Lessons Learned Through Industry Demonstrations

The following section describes the lessons learned in applying HTI guidance previous covered in Section 2.2 through industry demonstrations. The lessons learned have been derived from the demonstrations documented in INL/EXT-21-64320 (2021), INL/RPT-22-68472 (2022), and INL/RPT-22-70528 (2022). These lessons learned are applied to each of the HTI phases that have been demonstrated in past projects, including the development of a vision and concept of operations, development of HTI requirements, and design synthesis. The following lessons learned are intended to provide a cohesive set of recommendations that can be applied to future modernization efforts.

2.3.1 General Lessons Learned

2.3.1.1 Lesson 1: An integrated team is critical throughout the HTI Process

It is critical to establish an integrated team early to be used throughout the project lifecycle. Key personnel that should be included in the integrated team are key stakeholders from operations, licensing, maintenance, engineering, vendors, and HFE. The team should be utilized throughout each of the HTI phases to align on the project needs and requirements throughout the project lifecycle.

An example of when to use an integrated team is when developing the vision and concept of operations for a project. The integrated team can effectively be utilized throughout all of the planned activities to help develop an endpoint vision, as well as when evaluating the proposed designs with key project stakeholders. The integrated team can also be used to develop HTI integration requirements and help to synthesize the requirements into the design. The integrated team will benefit the project by enabling the effective identification of scenarios, designing early concepts, identifying key considerations to address, and integrating prototype HSIs into the simulator.

2.3.1.2 Lesson 2: A risk-based approach is critical for guiding and prioritizing subsequent HTI activities.

The grading and tailoring of HTI activities should follow a risk-based approach to benefit the execution of the primary HFE activities linked in NUREG-0711 (2012). The development of a new vision and concept of operations can benefit from finding the level of risk proposed by the upgrades when informing a migration strategy. A risk-based approach can be applied when the migration strategy is stepwise in nature by applying the approach to the grade and level of the HFE effort across different phases. Higher risk phases require a higher level of HFE rigor to mitigate risk. A graded approach can determine the highest level of HFE rigor needed when evaluating phases and tasks. Other factors that should be considered include:

- The total extent of modernization, including the tasks impacted, new equipment, and system being impacted
- The degree of change to the concept of operations, including the way users will interact with the new system changes and modifications, the level of automation, and the team coordination changes.

Each migration phase in the project can be graded, but specific tasks can be graded higher depending on the task and its level of risk. This will help direct HTI activities towards the most critical areas of impact.

2.3.1.3 Lesson 3: A clear division of responsibility between parties is pertinent for effective collaboration and minimizing bias.

A clear division of responsibility is needed for two primary reasons. The first is having clearly delineated roles for key stakeholders provides good support management by minimizing ambiguity between task assignments and allows for effective communication between team members by delineating clear responsibilities (INL/RPT-22-68472, 2022). A second benefit that is less explicit is that having clear roles and responsibilities can enable the development of independent teams across the project. The independent teams can be used to help minimize bias when evaluating different HFE activities in the program plan.

2.3.1.4 Lesson 4. Having access to a digital glasstop simulator is instrumental in collecting early feedback from stakeholders.

Glasstop simulators provide a significant value in prototyping and presenting proposed concepts early in the design process. Collaborations in the HSSL have been leveraged to collect stakeholder feedback on early project designs (e.g., Figure 12). The level of prototype fidelity may be different depending on the maturity of the project goals. However, the glasstop simulator designs are iterative and can be modified throughout the project's lifecycle. Early iterations in the vision and concept of operations may still be developed; however, feedback can be collected early from stakeholders to better define the new vision and concept of operations. As the modernization effort matures, additional workshops can be scheduled and supporting HFE activities, such as task analysis and other methodologies, can be performed to incorporate HFE needs and requirements into the design. Additionally, workshops aid in traceability throughout the project to document the new vision and concept of operations throughout the project lifecycle.

2.3.1.5 Lesson 5. Advanced HFE frameworks can complement HTI activities.

The cognitive work analysis is a complementary HFE method that can be useful in evaluating the cognitive and decision processes of users performing tasks with the work system. A cognitive work analysis offers several methods to evaluate system characteristics, such as work domain analysis (WDA), control task analysis (ConTA), strategies analysis (StrA), social organization and cooperation analysis (SOCA), and worker competencies analysis (WCA; Stanton et al., 2017). Each of the methods can be used to evaluate areas where evaluations would help inform the HTI activities depending on the project needs.

2.3.1.6 Lesson 6. *Real-time 3D and digital human modeling can significantly improve design team decision-making.*

3D modeling tools are complimentary tools that can evaluate the ergonomic and anthropometric design considerations related to the new HTI designs. 3D models can be used to address design tradeoffs, such as the placement of new equipment to support user needs. Digital human models can be used with 3D models of the control room to evaluate NUREG-0700 guidance for functional reach, visibility, and line of sight requirements with new HTI designs configurations. 3D models can be modified and iterated to provide early and new state visualizations of the changes throughout the HTI activities for the project to share with stakeholders.

2.3.1.7 Lesson 7. *Using demonstrations, prototypes, and workshops enable effective feedback from stakeholders that drive technology acceptance.*

Having key stakeholder buy-in is important for defining the vision and new concept of operations. Presenting early technology demonstrations and stakeholder inclusion throughout the lifecycle of a project is useful to help achieve early stakeholder buy-in with new technologies by providing familiarity with the new technology, including offering hands-on experiences. The usefulness of the new technologies can be evaluated by stakeholders, which allows them to become familiar with the new technologies and their capabilities that will improve their task needs and requirements.

2.3.1.8 Lesson 8. *The new vision and concept of operations should drive the planning and execution of subsequent HTI activities.*

The development of a new vision and concept of operations should be used to develop the planning and execution of HTI activities throughout the design process. The development of an HFE Program Plan can identify the differences in how a system is currently operated, maintained, and supported and should be used to grade the HFE of current activities and compare them to the new vision and concept of operations. The HFE Program Plan can then be used to identify what specific systems would be impacted by the HTI activities in each phase.

2.3.1.9 Lesson 9. *The vision and concept of operations should be a living document.*

Vision and concept of operations documentation provides a targeted direction to support strategizing the migration of existing controls to the new future system controls. The vision and concept of operations documentation should be realistic; however, updates may be required for reasons such as lessons learned from prior events, advances in technology, or changes to the project scope and budget. It is important to plan feedback loops from previous HTI activities to inform the vision and concept of operations plans to enable the completion of HFE activities.

2.3.1.10 Lesson 10. *Applying a "baseline" evaluation of the existing state offers value in comparing human-system performance to the new state.*

A baseline is an evaluation of system performance at a given point in time to perform human-in-the-loop tests with the existing system configuration. Baseline measures are used to measure human-system performance, workload, situational awareness, and usability to learn how new designs can be used to improve performance and reduce costs. Feedback from system users can be used to help determine what specific tasks need improvements on the existing system configuration. Results from the baseline evaluation are then used to determine how new systems being proposed could help improve performance.

2.3.1.11 Lesson 11. *Focus on knowledge elicitation via qualitative measures is pertinent to the success of addressing HTI requirements.*

The purpose of developing HTI requirements is to translate functions, information, and task requirements into the technical bases of the design and V&V (Kovesdi et al., 2021). The use of qualitative methods and measures is one of the best ways for eliciting knowledge from SME's qualitative methods may include gathering information from observations and interviews with them. Good HFE practices include gathering information from a diverse set of measures, such as talk-throughs and walkthroughs, to observe and capture verbal feedback from SME's during task performance. Walkthroughs include a think aloud protocol to provide insights on workload considerations, such as how the work is performed currently.

2.3.1.12 Lesson 12. *Developing acceptance criteria that demonstrate the safe and effective use of the new HSIs early in the design enables high confidence that the performance criteria will be met in ISV.*

The goal of design tests and evaluations are to support design decisions. The tests may utilize a combination of qualitative methods and measures to identify potential design issues and collect insights on the design. Validation tests are another method used to assess whether the design or its integration meets its intended purpose by using predefined criteria to determine whether the objective is met. Developing acceptance criteria during the late stages of a design process can provide early assurance that the design will be usable when going into the V&V process. Criteria that may be used, based on NUREG-0711 guidance on developing acceptable criteria, are requirements, benchmarks, norms, and expert judgment. Criteria can be dispositive or diagnostic and can be determined based on the project requirements.

2.3.1.13 Lesson 13. *Vendor involvement is critical to ensure the proposed HSI solutions are reasonably achievable.*

Vendor participation was critical to have during the conceptual verification workshop to help determine if proposed solutions with new HSI designs could be reasonably achievable using their software platforms. Vendors were able to address potential limitations and discuss alternative solutions with the integrated team to address operator needs and HFE guidance. Having the vendors available with the integrated team during the workshop provided a valuable advantage by saving time and resources to address potential challenges and scheduling constraints for the project.

2.3.1.14 Lesson 14. *Design input should be prioritized to support timely implementation and preparation for V&V activities.*

A conceptual verification workshop was used to generate design comments to help ensure that the comments would be addressed in new designs and HSI displays in preparation for a preliminary validation workshop. Comments were prioritized to help focus on the most critical comment areas to support operator performance in the preliminary validation workshop.

2.3.2 Applying Lessons Learned to Plant Modernization Activities

The lessons learned described in Section 2.3.1 provide a set of guiding principles to consider when applying HTI to any major plant modification. As such, Table 4 synthesizes these lessons learned and outlines criteria that informed the development of the expanded HTI methodology described in Section 3 and Section 4.

Table 4. HTI guiding principles.

Important Characteristics of Applying HTI at Scale
1. Establish a multidisciplinary team early and iteratively throughout the project lifecycle.
2. Apply a risk-informed approach to prioritize HTI activities to the most risk-significant functions and tasks.
3. Establish a clear division of responsibility across the multidisciplinary team.
4. Leverage simulation tools and iterative tests and evaluations throughout the project lifecycle.
5. Leverage advanced HFE frameworks throughout the project lifecycle.
6. Develop a new state vision to drive modernization efforts and consider the vision a living document.
7. Evaluate proposed modifications in comparison to existing performance.
8. Apply knowledge elicitation methods to drive HTI requirements.
9. Develop acceptance criteria for early tests and evaluations to enable high confidence that the system can be used by the intended personnel.
10. Ensure that any selected vendor is involved in HTI activities.

3. DEVELOPMENT OF HUMAN-TECHNOLOGY INTEGRATION GUIDANCE FOR WORK OPTIMIZATION

Figure 27 is used to discuss the expansion of HTI beyond main control room modernization to other WROs that are characterized across the areas in purple.

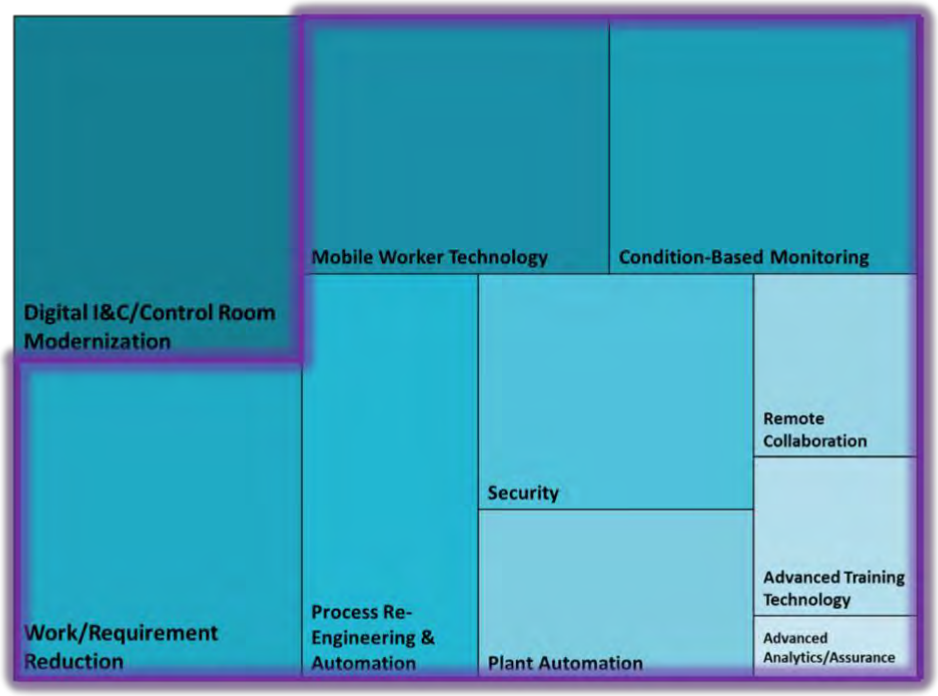


Figure 27. Extending HTI beyond digital I&C and control room modernization (adapted and enhanced from INL/RPT-22-70538).

While the fundamental goals of HTI are primarily around ensuring safety and reliability (Section 2.1.1) and addressing hybrid issues and considerations (Section 2.1.2), the additional WROs comprising the critical work domains shown in Figure 27 place added emphasis on *joint optimization* (Section 2.1.3) and expand the scope of *human readiness* (Section 2.1.4) to other potential technologies that support these WROs such as AI/ML or drones. This shift in scope, coupled with differences in use environment, regulatory policies, and organizational culture, requires a shift of focus for HTI. For instance, while safety is still a fundamental goal and OE can be identified around safety, insights into work system design concerning work process inefficiencies are not explicitly documented through OE. Further, insights gained from events in key problem reporting databases, like the International Research Integration System or the plant's Correct Action Program, may be limited to what was reported and omit important details of the work performed. Likewise, the use environments across these WROs beyond the main control room are diverse, so the application of a simulator test bed may be limited in its usefulness. Finally, the risk analysis prioritization that is foundational for driving the HFE Program for control room modernization is not as formalized in plant functions that are not directly tied to the safe operation of the plant. It goes without saying that WROs beyond the main control room can contain "important tasks" that have significant impacts to the economics of the plant.

To elaborate, the fundamental approach to HTI described in Section 2.2 is relevant to expanding to WROs beyond the main control room. Notable guiding principles and criteria of HTI therefore include (as referred to in Table 4):

- To move towards a “new state vision” of the domain that is business informed and informed through subsequent HTI activities
- To apply a multidisciplinary approach, leveraging subject matter expertise and collecting inputs from a wide range of stakeholders
- To execute HTI strategically (i.e., grading the effort), early, and iteratively throughout the lifecycle of the modernization project
- To leverage advanced HFE tools, methods, and frameworks that are geared at identifying the cognitive requirements of the work domain
- To design innovative solutions that can enable iterative feedback from key stakeholders for refinement and joint optimization and evaluate these concepts based on established acceptance criteria using performance-based approaches.

The proposed approach described in this technical report indeed considers these tenets, while innovating on the HTI methodology to meet the new challenges of WROs. The expanded guidance leverages existing HFE methods and tools while also introducing emerging ones that have been developed in response to the growing demand of applying HTI and HFE to complex sociotechnical systems. The following subsections delve into these emerging methods, discussing the use of recently developed TERA framework, as well as emerging methods to analyze complex sociotechnical systems:

- Section 3.1 discusses the integration of HTI into the TERA framework developed by the LWRS Program, describes TERA, and provides clarity into the basis for embedding HTI within it.
- Section 3.2 introduces the concept of *systems thinking* and describes emerging HTI methods within this umbrella that lend themselves to addressing joint optimization considerations for complex sociotechnical systems and transitions into Section 4, which presents the expanded HTI methodological approach for work optimization that complements TERA and is based on a systems thinking framework.

The scope of these subsections are to provide an overview of these recent approaches as they form the toolset for the extended HTI methodology described in Section 4.

3.1 Embedding Human-Technology Integration into the Technology, Economic, and Risk Assessment Framework

The TERA framework was recently developed by Spangler and colleagues (2023). The TERA framework is a process for evaluating WROs to identify areas of greatest potential and lowest risk. While the key facets of technology, economics, and risk are evident, it is essential to recognize that at the core of these elements are the individuals utilizing the technology to execute their duties. Therefore, evaluating any technology intended for human use necessitates a human-centric approach, anchored in HFE principles. In this section, we will build upon the previous work on the development of the TERA framework by Spangler and colleagues (2023) by integrating HFE and HTI methodologies. Therefore, this section provides the following background to TERA:

- Section 3.1.1 describes the motivations for developing TERA
- Section 3.1.2 presents the primary elements of TERA
- Section 3.1.3 describes the extensions of TERA to include elements of human reliability analysis (HRA).

3.1.1 Evaluating Technological Innovation Projects in the Nuclear Industry

While most WROs carry the potential to reduce operational costs, several factors may produce discrepancies between the projected and actual savings. For example, implementation costs, performance expectations, and risks associated with WROs can be miscalculated, leading to disappointing returns on investment (ROIs). Such challenges can stem from the use of inaccurate or incomplete data, immature technology, uncertainties surrounding achievable cost reductions, organizational inability to effectively communicate modernization benefits to users, lack of human readiness to adopt the technologies, or difficulties in integrating new processes into existing workflows. Such uncertainties can manifest in various ways, potentially rendering a WRO ineffective or even producing a loss on investment.

The intricate, interconnected nature of nuclear power plant processes makes it difficult to accurately predict cost savings and comprehensively screen WROs. The many challenges inherent in nuclear power plants (e.g., conflicting schedules, regulatory compliance issues, and safety concerns) further complicate the screening process. Furthermore, objectively screening WROs becomes increasingly difficult when reporting systems are biased towards reporting regulatory compliance issues vs. economic impact and processes involve multiple plant personnel groups, introducing subjective perspectives, varying priorities, and potential resistance to change.

A systematic and objective approach is crucial for evaluating WROs in consideration of the risks, investment costs, and potential mitigation strategies involved. Using advancements in operations and technological innovation projects, the recent research aimed to bridge the current modernization gap by developing a decision-supporting framework for identifying, evaluating, and selecting modernization strategies that maximize economic benefits and minimize associated risks and uncertainties. The TERA framework was developed to address these concerns and reduce the financial risk associated with WROs. The TERA framework enables stakeholders to integrate technical, economic, and risk perspectives into a comprehensive evaluation of potential WROs. This holistic approach identifies high-priority opportunities that can yield significant benefits for nuclear power plants and also minimize potential risks.

3.1.2 Technical, Economic, and Risk Assessment

When evaluating WROs, the TERA framework serves a twofold purpose: to assess and inform. First, it is used to screen and assess different WROs via a technical, economic, and risk perspective. Although it is easier to analyze WROs from a qualitative perspective, the TERA framework is able to combine qualitative screening with quantitative models by performing the assessment through a systematic screening and model development process. Doing so enables the objective screening of various WROs, with utilities assessing the various options and determining which path is most cost effective and carries the least amount of risk.

Second, the TERA framework’s output can inform the development and implementation of usable technologies to achieve WROs. This is accomplished by performing modeling and simulation to provide clarity on the relationship between performance parameters and the resulting business impacts. During model development and assessment, utilities can set process performance expectations and define key performance indicators (KPIs) for quantifying cost savings and risk mitigation throughout the WRO development.

Although each process evaluated under TERA may vary significantly, the created framework was developed with flexibility in mind. The TERA process consists of three main components: developing a process map of the WRO being investigated, developing models, and using the models to assess the potential cost savings and risk reduction.

The TERA process enables the following:

- *Objective Screening.* The TERA framework uses standardized methodologies and metrics to enable an objective procedure for WRO screening. This approach mitigates subjective biases, ensuring a consistent and unbiased evaluation. Per the standardized methodologies, existing processes are broken down into individual tasks and their attributes, with inefficiencies being identified and then compared based on quantitative metrics.

- *Cost Reductions.* The TERA framework is intended to improve efficiencies and achieve cost reductions across different WROs. Identified WROs are prioritized based on the potential cost savings and risk reduction they convey. Seemingly different WROs can be evaluated based on a standardized cost reducing KPIs, such as net present value (NPV) and total cost of ownership.
- *Risk Assessment.* The TERA framework utilizes risk assessments for evaluating the potential uncertainties associated with integrating new technologies during WRO implementation. These assessments are aimed at identifying and mitigating risks related to regulatory compliance, operational disruptions, technology coexistence, and organizational adoption and ensure that the proposed changes do not compromise overall nuclear power plant performance, reliability, or safety.

3.1.2.1 Technical Assessment

The purpose of the technical assessment is to evaluate the technical aspects of WROs and understand how new technologies and processes can be implemented within the nuclear industry. This assessment involves careful consideration of the current process, how it works, and the causes of any inefficiencies within it. Once the current process is understood, the feasibility, effectiveness, and benefits of the proposed solutions will be evaluated. The output of the technical assessment is a comprehensive analysis of the current process and the technical implications of each proposed solution. The technical assessment involves considering the following facets when analyzing a process and solution:

- *Technical requirements.* Effective problem-solving within the technical domain relies heavily on well-defined requirements, technical knowledge of the process being evaluated, and a thorough understanding of existing challenges. In this context, technical requirements are pivotal for shaping the proposed solution and identifying technologies that align seamlessly with the specified criteria. The technical requirements can be categorized as functional requirements, technological solutions, and objectives alignment. A robust technical assessment encompasses a multifaceted approach that integrates these three categories with the objectives of the utilities. The resulting comprehensive evaluation not only ensures the viability of the proposed solutions but also their potential to drive nuclear industry efficiency, safety, and performance.
- *Technical risk.* Part of the technical evaluation is to assess the technological risk entailed by implementing a new process or altering an existing one with respect to organizational objectives. The key technical risk areas to consider include but are not limited to technology readiness, feasibility, performance, maintenance, scalability, and cybersecurity. During the technology implementation, uncertainties can arise in many areas and should be accounted for to the full extent possible. A comprehensive technical assessment with uncertainty identification can help utilities mitigate risks so as to ensure the successful implementation of the technology.

3.1.2.2 Economic Assessment

The economic assessment evaluates the financial viability of identified WROs via a cost-benefit analysis of the proposed solutions. The goal is to assess the potential ROI and quantify the economic impact of the proposed solutions. This method involves an economic analysis of the current process in terms of labor, materials, and capital expenses. Furthermore, the economic assessment evaluates the proposed solutions in order to quantify any and all economic benefits to the process, including cost savings and NPV estimates.

- *Cost-benefit estimation.* To assess the economic impact of the proposed solution, various economic measures for evaluating cost are used: current process costs, marginal analysis, technology investment cost, regulatory costs, and cost reductions and returns. The cost-benefit calculation is essential for evaluating WROs, and a thorough analysis is key. There may be additional costs not detailed in this list. The point is to perform a comprehensive review of investment costs and cost reductions.

- *Economic risk.* To ensure a successful investment, the economic risk evaluation identifies economic uncertainties and potential risks associated with the estimated costs and returns. Evaluating economic risk should address cost uncertainty, performance uncertainty, and economic model uncertainty. The economic assessment is the key facet in creating a model that maps the functional and performance requirements to the business aspect. By constructing these economic models and incorporating the underlying uncertainty, not only is it possible to assess the business case but also use the models to inform project development. The models can also be utilized during technology development to track performance and ensure economic returns will be achieved.

3.1.2.3 Risk Assessment

The risk assessment is designed to identify and evaluate any potential consequences associated with WRO implementation. Furthermore, WROs will also be evaluated in terms of their impact to the plant's risk and safety profile. For example, if a proposed solution impacts component reliability, the impact to safety will be evaluated in terms of whether it leads to an increase or decrease in related risk. The purpose of the risk assessment is to evaluate proposed solutions and develop risk mitigation and contingency plans to address potential challenges. This evaluation is accomplished through risk identification, risk analysis, and risk mitigation planning. When implementing a new process, the output of the risk assessment will be an analysis of any uncertainties generated by the technical, economic, or safety risks.

- *Personnel and system consequences.* New technology may interact with existing systems and influence nuclear power plant reliability and safety. Furthermore, when an implementation of new technology alters an existing process, the frequency of consequential events may change. Areas of consequence to consider include personnel safety risk; challenges involving systems, structures, and components; plant safety; and failure mode analysis. Assessing the personnel and system consequences that arise from integrating new technology in nuclear power plants is imperative not only to ensure enhanced functionality but also to maintain and improve overall safety and reliability. Thorough evaluations of personnel safety risks; challenges related to systems, structures, and components; plant safety parameters; and failure modes contribute to well-informed decision-making within the dynamic landscape of technological advancements at nuclear facilities.

- *Implementation risk.* The risks of implementing a new technology into an existing business framework can be divided into two broader categories: human readiness and organizational readiness. Understanding HRL and organizational readiness level (ORL), along with preemptively addressing the potential inefficiencies inherent in new solutions, is critical for mitigating the risks associated with implementing novel new technologies into existing business frameworks. These assessments will help inform decision-making and successful technology integration.

3.1.2.4 The TERA Process

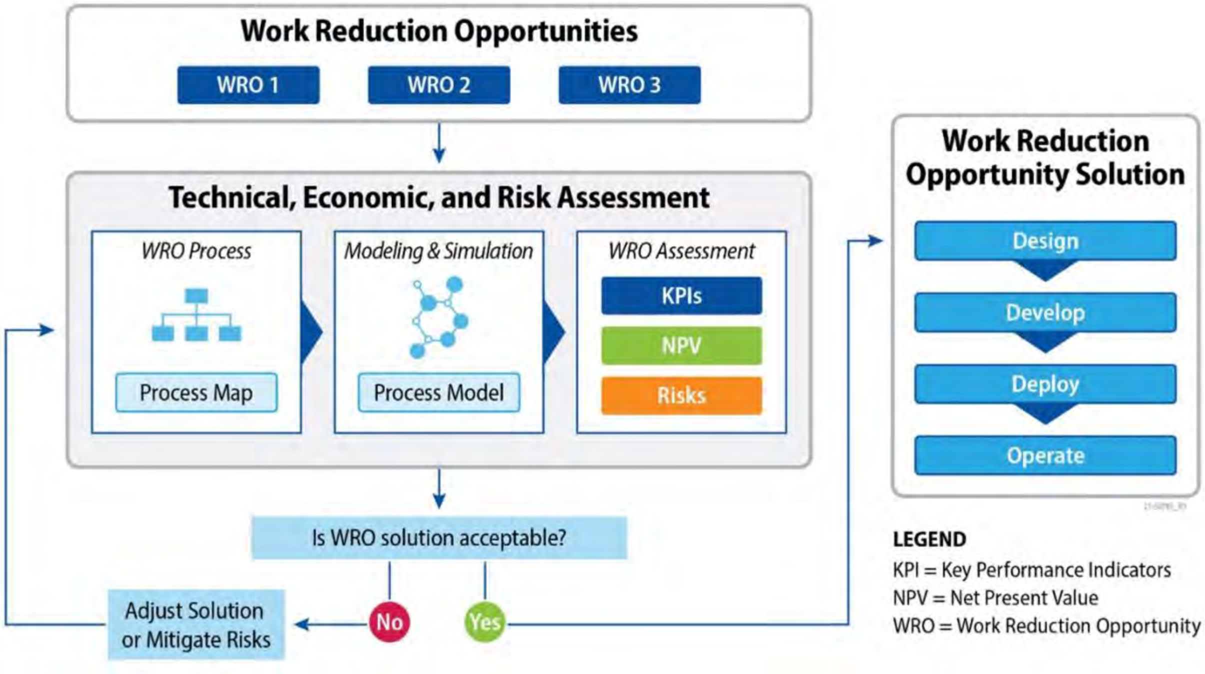


Figure 28. TERA framework (adapted from INL/RPT-23-74724).

WRO screening is an iterative process used to perform cost-benefit analyses and evaluate KPIs for each WRO, thereby enabling risk-informed investments for plant modernization. This screening process employs a combination of process reengineering, Lean Six Sigma, and nuclear power plant modernization guiding principles developed by the ION projects (Remer 2022; Remer et al., 2023; Hunton and England, 2021; Thomas et al., 2020). Integrating these process improvement practices led to the development of an exhaustive WRO screening methodology and potential modernization strategies. Figure 28 gives a flowchart describing how the TERA framework can be used to screen WROs. The steps involved in the TERA process are:

1. *Initial Screen.* WROs are introduced to an impartial screener via interviews with process users, the essence of these discussions being to tap into experiences regarding a given process, discern any challenges, and sketch a preliminary map of the existing process.
2. *Process Mapping.* This phase focuses on further conversations with individuals, diving deeper into the process, the specific tasks within that process, and any bottlenecks encountered. This approach aligns with suppliers, inputs, process, outputs, and consumers (SIPOC) principles but also integrates PTPG so as to afford an ION perspective. With the collected interview data, the screener can craft a process map that captures the relevant vital data, inputs, participants, technology, constraints, governance, and outputs involved in the process.
3. *KPI Identification.* The screener then identifies the KPIs that will define the process performance. These serve to provide the baseline performance threshold for ensuring the final solution enhances the process. The aim is to sidestep investments that yield only negligible performance improvements.

4. *Quantitative Analysis*. Once mapped, the process undergoes a cost estimation, resulting in a preliminary benchmark against which future comparisons can be made. Through this model, each process step is evaluated from a technical, economic, and risk perspective and by attaching costs to each model step.
5. *What-if Analysis*. Utilizing the process model and deduced risk, potential cost reductions or increments are explored by considering various technologies and what-if scenarios. These evaluations involve tweaking the process map in light of the proposed solution, modifying the process model temporal parameters, or adjusting the costs per phase.
6. *Final Evaluation*. The WRO assessment culminates in a decisive cost-benefit analysis. This phase encompasses project costs to gauge the ROI. This final review generates an exhaustive technical, economic, and risk appraisal for each WRO, facilitating risk-informed, performance-based decision-making.

Process Mapping

The process mapping phase consists of reviewing process documents and interviewing numerous people involved in the current process. It incorporates various elements of Lean Six Sigma and ION principles. A summary of process charting techniques is outlined later in this report in Section 3.2.2.3. Combining these well-defined processes and principles has led to the development of a specialized nuclear-specific process mapping framework and methodology. This framework will be employed to assess pain points, the value of information, and the risks associated with new technology.

Process Mapping Methods and Principles

In assessing the process from a technical, economic, and risk perspective, multiple established process evaluation techniques were combined. This includes guiding principles developed in Lean Six Sigma's SIPOC and ION's PTPG (i.e., see Section 3.2.2.3). By understanding the methods in each of these evaluation techniques, the current process and risks associated with implementing a new process can be comprehensively evaluated and well-understood. The result is a process map containing the individual tasks, decisions, data and information flow, and cost information.

The Lean Six Sigma SIPOC method is a proven framework for analyzing processes (Brown, 2018). It breaks processes down into five main categories: SIPOC. Via this method, processes become easy to disassemble so as to identify the pain points or inefficiencies. *Suppliers* are people or organizations who contribute to or are involved in the given process. *Inputs* are the necessary tools, data, or information contributed by the suppliers. *Process* is the steps for transforming inputs into outputs. *Outputs* result from the process or are created during the process. *Consumers* are the receivers of the process outputs or represent the ultimate destination of the outputs.

After applying the SIPOC approach to break down the process, evaluating the process components requires identifying the relationship between each category. This proves beneficial for understanding how alterations in input affect the process, output, and consumer. For instance, a decline in the quality of input to a process would likely alter the process or impact the final product. Utilizing SIPOC, these relationships can be assessed, aiding in the evaluation of how technological or procedural changes will impact overall process performance. For more information on using SIPOC for process analysis (see Brown, 2018; Scholtes, Joiner, and Streibel, 2003).

Part of the ION philosophy is to view the process or capability through various categorical lenses. The ION philosophy categorizes capabilities as being comprised of four interdependent resources: people, technology, process, and governance. Each of these resources determines *how* and *why* the process functions. Breaking down a process into each of these four categories makes it easy to see how the process operates and to determine WROs. The ION philosophy and its integration with PTPG is discussed by Remer et al. (2021).

The process mapping phase includes both data mapping and decision mapping. These are conducted to understand the flow of data and how the data is used to support effective decision-making. Data mapping entails visually charting where the data originates, where they are stored, and how they are used. This helps ensure consistent data quality and data security, while also aiding in process streamlining. Data mapping is especially important for digital modernization and transformations, due to the increasing use of data to support analysis and decision-making activities. Steps typically include identifying data sources, defining data destinations, mapping data fields, and determining data conversion rules. Creating a data map and integrating it with the process map generates a comprehensive picture of where the data are stored, how they are accessed, and how they are used to support process functions. For more information on data mapping, see the works by Sergio et al. (2004) and Shahbaz (2015).

Decision mapping focuses on identifying decision points within a process and understanding the information and actions leading to those decisions. This aids in evaluating critical decision-making points, potential bottlenecks, and areas of risk. The steps involved are chart decision points, detail decision criteria, and analyze dependencies. Decision maps can be helpful when integrating decisions and processes together into a single cohesive process. They are also helpful when creating and understanding process flows, input and output relationships, and the functional requirements for a given process. Decision maps can be combined with process maps, with the output of a decision leading to a process that will in turn lead to another decision—continuing until the process is finally complete.

Performance Metric Identification

Before process performance can be quantified, an attempt must be made to determine which KPIs will be used to define the success criteria. The one requirement for the defined success criteria is that they be measurable, meaning that the intended improvement or change in a process must be well-defined. This step requires an understanding of the business case and how it is affected by the given process. The following three key areas should be considered when defining success criteria:

- *Technical.* Defining technical KPIs is important for measuring process improvements from a technical performance perspective. This encompasses metrics such as efficiency, accuracy, time, and labor reductions.
- *Economic.* Financial metrics help define business success and ensure investment returns. Financial metrics, such as yearly cost savings, breakeven point, NPV, ROI, and internal rate of return, are commonly employed when comparing investment opportunities, as they provide insight into the monetary viability and gains of the process.
- *Risk.* Metrics in this area, which pertains to the gauging of risk mitigation, could involve assessing reductions in operational, financial, regulatory, safety, or strategic risks. Each of these can be quantified based on changes in frequency, severity, or other relevant measures.

By defining measurable criteria, KPIs can be used to evaluate the performance of the implemented process throughout its entirety.

Process Modeling

The quantitative analysis phase marks a pivotal stage in which the high-level process map is transformed into a process model. This transition enables a quantitative analysis of the process in terms of process dynamics, allowing for a deeper dive into the process technical, economic, and risk quantifications.

Process Cost Estimation

The process cost estimation phase entails a comprehensive approach to quantify the financial aspects of the modeled process and any proposed changes to that process. This is where potential process changes and technologies can be evaluated in terms of their ability to reduce overall costs. This phase serves as a critical foundation for evaluating the economic feasibility and potential ROIs of the proposed process enhancements.

First, the current process cost must be calculated. This entails identifying and analyzing cost factors associated with the various components outlined in the process map. These factors include cost elements, such as labor, technology, and governance, all of which are assessed in terms of their impact on the overall process cost. Next is to identify the level of performance reasonably achievable thanks to the process changes or technology integrations. By altering the process map and model by updating them with potential solutions, the change can be quantified and will serve as the baseline cost reduction using the new technology. Note that it is important to include new technology process costs (e.g., additional labor, technology maintenance, or governance) that may not have been included in the previous process model.

Sensitivity Analysis

Sensitivity analysis is a technique for quantifying the impact of changes in individual parameters on the output variable, thus facilitating a determination of their relative importance. Moreover, it enables an assessment of how uncertainties in parameters contribute to the overall output variability. This process helps identify the expected outcomes for a range of parameter values. Additionally, the impact of changing parameters can be quantified and used for risk mitigation or resource allocation. Values with large uncertainties or large impacts are flagged for further investigation. This will allow utilities to focus squarely on those model parameters that have the greatest impact on cost.

A sensitivity analysis has several main advantages in the context of the TERA approach, such as providing risk assessments, helping determine resource allocation, validating model parameters, and quantifying uncertainty. Sensitivity analyses empower decision makers to evaluate the intricate interplay between model and process parameters and their business impact. It provides a quantitative framework for prioritizing resource allocation by identifying influential parameters, optimizing efforts and resources, and focusing on aspects of the model that exert the most significant impact on costs.

Cost-Benefit Evaluation

The cost-benefit evaluation delves into crucial financial metrics employed in assessing the feasibility and success of WRO implementation. An NPV provides an economic perspective that incorporates the time value of money, which is used to evaluate the performance of an investment at a given discount rate. In other words, the NPV evaluates whether the project represents a good investment. The NPV evaluates whether the project will exceed the returns generated by using that same investment to accrue interest. The formula for calculating the NPV is:

$$NPV(T) = \sum_{t=0}^{T} \frac{C}{(1+r)^t} - C_0 \tag{1}$$

where C_0 is the initial investment cost, C is the net yearly cash flow (or cost savings), r is the discount rate at which the value of future cash flows is discounted back to present value, and T is the total number of time periods covered in the NPV calculation. The initial investment cost includes all upfront costs related to the WRO, such as screening, development, and deployment. The discount rate—usually expressed as a percentage—is used to evaluate the ROI and accounts for the time value of money, inflation, and investment risk. The net yearly cash flow (or cost savings) is the net annual financial benefit realized by implementing the WRO solution, and should consider existing process costs, new process costs, operational expenditures pertaining to the new process (new ongoing costs), and expected usage rate. The usage rate serves to incorporate the risks associated with a failed implementation or a low adoption rate by the relevant organizations.

3.1.3 Human Reliability Integration into TERA

To integrate human reliability into a stochastic process model, we have created an additional state and process flow that models the error and consequence. To do this, we have added an additional state called error. In this model, the error state will determine whether or not an error occurred and will endure a cost (consequence). A representation of the modified process model can be seen in Figure 29.

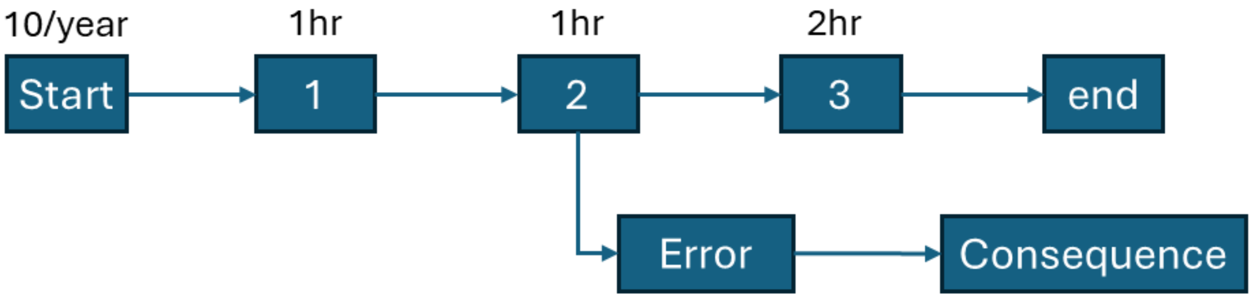


Figure 29. Process model integrated with human reliability and error modes.

In the process model, there are distinct states for each step in the process. The duration of each step is determined by data (expert opinion in the absence of data) and then modeled using transition rates. The transition rates are used to model the time spent in that specific state. By using transition rates, the process model can be considered a Markov model, which enables the possibility of advanced analysis techniques where we can interrogate the model, such as using sensitivity analysis, value-of-information analysis, and what-if scenario analysis through parameter adjustment.

To provide a mathematical framework for integrating the model into one value for analysis, we have can defined the process cost as:

$$\text{Process Cost} = \text{Frequency} \times (\text{OPEX} + \text{CAPEX} + \text{Risk}) \tag{3}$$

where:

- *Frequency* is the number of times the process happens per unit of time
- *OPEX* is the operational expenditures per process
- *CAPEX* is the capital expenditures per process
- *Risk* is the probability and consequence of the error mode for a particular step.

We can break down each of these further into the following definitions. If we define C as the process cost, f as the frequency, t as process step duration, l as labor cost, a as capital costs, γ as error rate, and k as consequence cost, the equation for the process cost then becomes:

$$C = f(tl + a + \gamma k) \tag{4}$$

The process steps will usually have more than one error mode that can occur during any particular step; therefore, we must sum the potential risk modes together into one singular model and governing equation. A model depicting multiple error modes can be seen in Figure 30. Summing across several error modes and their consequences, the process cost equation then becomes:

$$C = f\left(tl + a + \sum_{n}^{N} \gamma_n k_n\right) \tag{2}$$

where n is the error mode identifier and N is the total number of error modes.

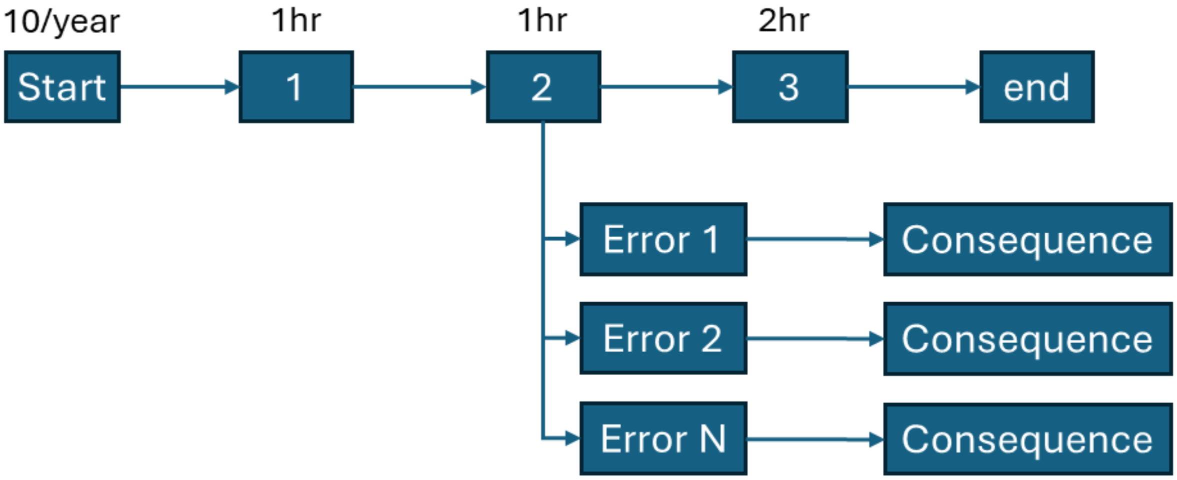


Figure 30. Process model with multiple human reliability error modes.

3.1.3.1 Identification of Consequences Causes (Errors)

Identifying the causes of errors is crucial for understanding potential consequences and mitigating risks associated with WRO implementation. This involves analyzing the current process and identifying areas where errors or failures are most likely to occur. Factors such as human error, equipment malfunction, or process inefficiencies should be considered.

3.1.3.2 Quantification of Causal Rates

Quantifying the causal rates of errors helps in assessing the likelihood of different failure modes occurring. This involves assigning probabilities to each identified failure mode based on historical data, expert judgment, or simulations. The goal is to estimate the likelihood of each failure mode and prioritize them based on their potential impact and likelihood of occurrence.

3.1.3.3 Identification of Consequences

Identifying the consequences of errors is essential for understanding the potential impact of failures on nuclear power plant operations. This includes assessing the impact on plant safety, reliability, and cost-effectiveness. Consequences can range from minor disruptions to major safety hazards, depending on the nature of the error and its context within the overall process.

3.1.3.4 Quantification of Consequences

Quantifying the consequences of errors involves estimating the potential impact of failures in terms of safety, reliability, and cost. This can be done through simulations, case studies, or expert judgment. The goal is to assess the potential consequences of each failure mode and prioritize them based on their severity and likelihood of occurrence.

3.2 The Need for Systems Thinking in Plant Modernization

The operation, maintenance, and support of a nuclear power plant involves the purposeful coordination of organizations, individuals, equipment, and tools. This coordination is accomplished at least in part through policies, procedures, training, and other administrative controls. Moreover, the manner in which work is planned and executed is shaped by different environmental and situational factors. Collectively, these considerations necessitate a need to analyze, design, and evaluate such work systems within nuclear power plants beyond the focus of the plant's associated plant systems and equipment and within the lens of interactions between the people and organizations for joint optimization.

The characteristics of a nuclear power plant lead it to be denoted a complex sociotechnical system, which further lends the use of *systems thinking* as a philosophy for analyzing, designing, and evaluating new innovations that significantly improve work processes. The systems thinking philosophy focuses on the interaction and interrelationships of agents (i.e., organizations, people, equipment, or tools) when initiating goal-directed behavior (i.e., to perform some function). Systems thinking therefore operates under the notion that complex systems are open systems (i.e., interacts with other systems through its inputs and outputs) and the interaction of parts (i.e., the cumulative whole) is oftentimes nonlinear and difficult to predict (Dekker, 2016; Leveson and Thomas, 2018). Consequently, traditional decompositional methods are less effective at identifying and designing for risks and enabling joint optimization.

Such concerns have been stated in the human factors community. For instance, Hamer and colleagues (2021) performed a literature review to:

> critically reflect on the past HFE research for nuclear safety as applied to the industry and provides insights into how HFE approaches can better address current challenges for nuclear safety and future changes. (page 2)

The authors' literature review examined trends in HFE across the nuclear industry from 1970 through 2021. Through a rigorous identification, screening, and inclusion process, the authors critically reviewed 334 peer reviewed journal articles across six major journal databases. One of their key findings was that, through the past six decades, the types of approaches used in the nuclear industry have largely remained the same. That is, they found that many of the HFE approaches followed in the nuclear industry have mostly favored methods that focus only on how actions fail but not while also focusing on the variability in everyday performance from comparing work as imagined (WAI) to work as done (WAD). The latter can be broadly characterized by Hollnagel's *Safety II* approach (2017). Rather than only managing safety by what went wrong (i.e., Safety I), a Safety II perspective also focuses on the everyday work processes to effectively learn as an organization and operate effectively and safely. This work views Safety II as complementary to Safety I, and part of systems thinking.

To further illustrate the importance of systems thinking, a salient example that emphasizes this point is the Boeing 737 MAX accidents (Skraaning and Jamieson, 2023). As highlighted in Skraaning and Jamieson (2023), these accidents were attributed to a sensor malfunction, which led to incorrect information of the aircraft's climb angle being sent to the Maneuvering Characteristics Augmentation System (MCAS). This signal falsely invoked the aircraft's automation to push the aircraft's nose down towards the ground. The pilot was at the sharp end to intervene, but aircraft provided the pilot no explicit indication that the MCAS would be activated. Furthermore, there was no training on the new MCAS, which was installed in older Boeing 737 MAX models. A traditional decomposition approach like failure, modes, and effects analysis would have examined each system failure independently. However, this very interaction of system actors (i.e., including the sensors, MCAS, propulsion system, pilot, procedure, and training) that explains these accidents is in essence the use case of following a systems thinking philosophy.

Like an aircraft, the operation, maintenance, and support of a nuclear power plant or fleet of nuclear power plants requires considering the interaction of respective agents (i.e., both people and equipment at a micro- and macrolevel) for safe, reliable, and economical operation. Therefore, leveraging recent work from Salmon and colleagues (2023) on sharing a host of systems thinking approaches and expanding upon it, the following subsections describe a number of systems thinking approaches that are characterized around four primary approach types (i.e., as characterized by Salmon and colleagues 2023):

- *Retrospective Analysis Approaches.* These approaches focus on an in-depth analysis of previous accidents and incidents after they have occurred (Section 3.2.1).
- *System Characterization Approaches.* These approaches characterize the system attributes, including the goals and missions, functions and tasks performed, system architecture, and even the training and competencies needed to perform work (Section 3.2.2).

- *Proactive Analysis Approaches.* These approaches focus on an in-depth analysis of potential risk modes or leverage points within the system proactively (Section 3.2.3).
- *Modeling Approaches.* These approaches simulate system behavior (Section 3.2.4).

Like Salmon and colleagues' (2023) emphasis in combining approaches from each type, this work also advocates for the value in applying a multimodel systems thinking approach to the extent practical. As such, Section 3.2.5 provides a basis for doing so and is a central tenet for the specific HTI methodological extension presented in Section 4.

3.2.1 Retrospective Analysis Approaches

The first key type of approaches encompassed by systems thinking pertains to retrospective analysis approaches. The methods described here are rooted in accident and incident investigation and have consequently been applied when performing such analyses on existing events. Within a systems thinking framework, the application of these retrospective analysis approaches is to support learning from past events to better inform system design (Salmon et al., 2023). Three key methods encompassed under retrospective analysis include:

- Casual Analysis based on Systems Theory (CAST)—Section 3.2.1.1
- Accident Network Method (AcciNet)—Section 3.2.1.2
- Root Cause Analysis—Section 3.2.1.3.

3.2.1.1 Casual Analysis based on Systems Theory: CAST

CAST is a retrospective accident analysis approach based on the System-Theoretic Accident Model and Processes (STAMP; Leveson and Thomas, 2018). STAMP is an accident causality model based on systems theory (e.g., see Section 3.2). A distinct feature of STAMP is that safety is treated as a *dynamic control problem* instead of a failure prevention problem. As such, there is emphasis made on enforcing constraints on system behavior rather than preventing failures.

CAST is the retrospective methodology whereas STPA (see Section 3.2.3.1) is the proactive methodology built upon the STAMP model. CAST and STPA identify risks within the system through analyzing the controls and feedback mechanisms across the entire system, including organizations, people, systems, and processes. This is accomplished by characterizing the system as a *control structure* (Figure 31). The control structure encompasses all agents of the system of interest (SOI), including organizations and people. CAST therefore focuses on the interaction between these agents using the control and feedback mechanisms depicted by the downward and upward arrows, respectively. Performing CAST can be accomplished in six primary steps, described next. The application of each step may be iterative depending on the availability of resources in completing any one given step.

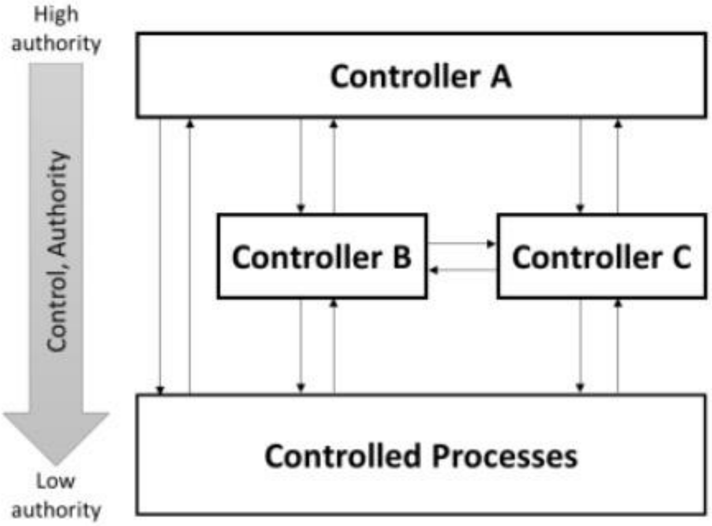


Figure 31. Generic control structure (adapted from Leveson and Thomas, 2018).

Prerequisites for CAST

One the potential limitations of STAMP-based methods, like CAST or STPA, is that the analyst(s) must have a familiarity (at least) or expertise in the approach to be effective in its use (e.g., Dallat et al., 2018; Hunton et al., 2023). Additionally, subject matter experts (SMEs), particularly those with direct experience with the accident or incident, within the specific work domain are needed to accurately perform CAST. Therefore, its use should be determined based on whether there is expertise available in STAMP, as well as in the work domain of interest. In circumstances where expertise is available, CAST offers a comprehensive approach to an accident and incident analysis and is complementary to the STPA described in Section 3.2.3.1, providing a clear understanding of weaknesses in the controls structures across organizational factors, personnel factors, equipment factors, or process factors.

Step 1. Determine the purpose and scope of using CAST

The first step involves determining the purpose and scope of CAST. For nuclear power plant modernization, this step entails:

- Defining the SOI and its system boundaries
- Identifying potential WROs through initial ION-based analyses and time scales to perform a CAST data search (e.g., to determine how far back in time to begin performing accident and incident data collection)
- Determining project resources available (i.e., determining available SMEs, available databases, documents, etc.) and constraints (i.e., schedule and budget).

The scope of CAST in terms of WRO may go beyond emphases on safety to examining the SOI for opportunities to reduce cost through innovations defined by ION. In many cases, the scope may include WROs that have a positive influence on both safety and economy.

Step 2. Collect accident and incident data

Step 2 entails collecting accident and incident data of the SOI and associated WROs. Salmon and colleagues (2023) characterize four main types of data:

- Data of the SOI itself, including the identification of different staff roles and responsibilities
- Data that describes the control and feedback mechanisms used within the SOI

- Data that describes the work processes, activities, and tasks within the SOI
- Data on the accident(s), incident(s), and associated contributors that influenced their occurrence.

The specific sources of data across these data types range from databases like the International Research Integration System and Correct Action Program to procedures and related site documentation to interviews with SMEs. Using a combination of these sources is often needed to the extent practical.

Step 3. Develop the control structure

Step 3 entails developing a control structure (e.g., Figure 31) that captures the SOI, including all agents, such as organizations, personnel, equipment, and processes. Leveson and Thomas (2018) provide guidance in developing a control structure within its use in STPA. Developing the control structure for the SOI can begin at a more abstract level and iteratively become more detailed depending on the scope and aims of the analysis defined in Step 1. Leveson and Thomas suggest that one way to begin developing the control structure is to first identify the basic subsystems needed to constrain and prevent the hazard(s) contributing to the accident(s) and incident(s). It is important to note that the control structure depicts the hierarchy of control where agents of highest authority are located at the top of the control structure and moving downward to the bottommost processes that are controlled. Additional guidance in developing the control structure is described by Leveson and Thomas (2018), Salmon and colleagues (2023), France (2017), and Joe and colleagues (2023). For example, Joe and colleagues (2023) share recent advancements to the CAST control structure, such as the consideration of coordination between agents (i.e., additional to control actions). Also, France's (2017) expanded control structure model added clarity into developing the "human controller" by accounting for the perceptual, cognitive, and motor processes, see Figure 32.

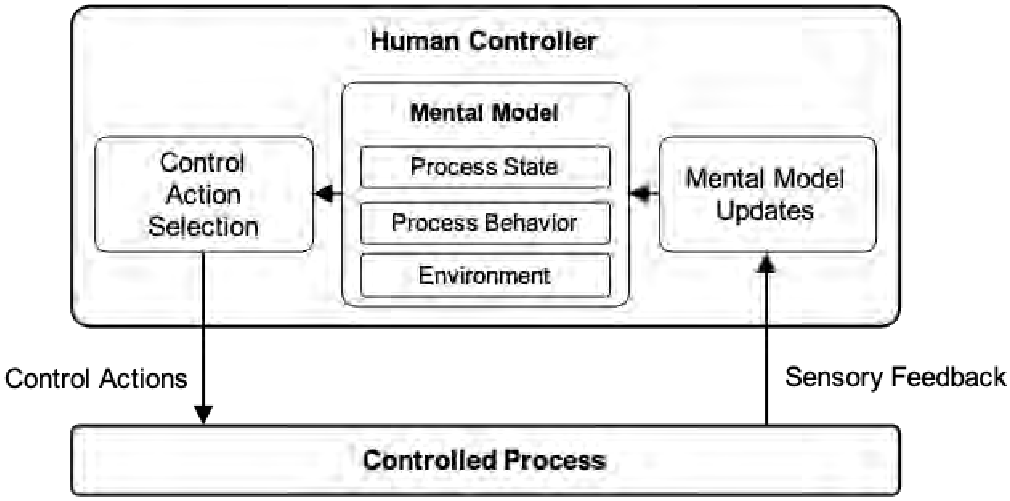


Figure 32. Extended human controller model for the STAMP control structure (adapted from France 2017).

Step 4. Determine the course of events

In Step 4, a map or timeline (e.g., see Section 3.2.2.4) can be developed to determine the likely course of events that took place leading up to the incident or accident (Salmon et al., 2023). The development of a timeline that presents the course of events was an approach added to CAST in response to better support an analysis with the control structure (Düzgün and Leveson, 2018). For instance, Underwood and colleagues (2016) performed a small-scale field investigation to evaluate the effectiveness of STAMP-based methods, such as CAST. The authors used a simulated accident focused on a railway-based accident scenario involving a train colliding with two track maintenance engineers. The participants were asked to use CAST to investigate the simulated accident and then provide feedback on their experience applying this method.

A salient finding from this work was that the inclusion of a timeline would serve as an important addition to performing an accident investigation with CAST.

Step 5. Identify contributors to the accident or incident.

Step 5 entails identifying contributors to the accident or incident, using the data sources from Step 2 (Salmon et al., 2023). This step also entails using the control structure developed in Step 3 and the timeline in Step 4 in identifying contributors. By doing so, the CAST analysis can provide a comprehensive analysis across all levels of the control structure, including organizational factors, personnel factors, equipment factors, or process factors.

Step 6. Classify contributors using the STAMP-CAST taxonomy

Step 6 pertains to classifying the contributors identified from Step 5 into the STAMP-CAST taxonomy (Table 5). The purpose of this step is to provide a consistent way of classifying contributors identified within the CAST analysis. As such, human factors design principles can be readily applied to support the WRO(s).

Table 5. STAMP-CAST taxonomy (adapted from Salmon et al., 2023).

STAMP-CAST Category	STAMP-CAST Taxonomy
Inadequate enforcement of constraints	Unidentified hazards
	Inappropriate, ineffective, or missing control actions for identified hazards – Flaws in creation process – Process changes without an appropriate change in control process – Incorrect modification or adaptation
	Inconsistent, incomplete, or incorrect process models – Flaws in creation process – Flaws in updating process – Time lags and measurement inaccuracies not accounted for
	Inadequate coordination among controllers and decision makers
Inadequate execution of control actions	Communication flaw
	Inadequate actuator operation
	Time lag
Inadequate or missing feedback	Not provided in system design
	Communication flaw
	Time lag
	Inadequate sensor operation (incorrect or no information provided)

3.2.1.2 The Accident Network Method: AcciNet

AcciNet is a method developed in response to addressing emergent human factors issues associated with increased levels of automation, AI, big data, and robotics (Salmon et al., 2020). AcciNet was developed based on three tenets of accident and incident causation:

- That all accidents are created by an interacting network of behaviors from different agents (i.e., including people and automation) within the SOI
- That the interacting network of causal behaviors involved in accidents and incidents, including *work as imagined* (i.e., as indicated in procedures), *work as done* (i.e., “normal performance”), and decisions and actions governing performance, are characterized as being suboptimal

- That *emergent risks* play a key role in accident and incident causation, occurring when multiple behaviors interact and create an unexpected and difficult to foresee consequence.

It is worth noting that AcciNet is complementary to the proactive Networked Hazard Analysis and Risk Management System (Net-HARMS) analysis method described in Section 3.2.3.2 (Dallat, Salmon, and Goode, 2018; Salmon et al., 2023). The primary product of AcciNet includes the development of a task network; a secondary product produced through AcciNet entails developing an actor[5] network. Both of these products that come out of AcciNet can be reused in Net-HARMS for a proactive analysis (Salmon et al., 2020). The application of each step may be iterative depending on the availability of resources in completing any one given step. The steps involved in performing AcciNet are described next.

Prerequisites for AcciNet

AcciNet is a task-centric retrospective analysis, unlike STAMP-CAST, which is based on developing a control structure of the system. As such, the availability of a task analysis output or process map would be readily usable for AcciNet without further transformation. Therefore, it is reasoned that expertise in the area of general HFE and of the work domain of interest is needed, but specialty expertise in a specific sociotechnical theory (e.g., STAMP) is not.

That said, the development of the graph and use of a social network analysis (i.e., an optional component to AcciNet) can be used with AcciNet, which does require some level of understanding of the theory and tools for developing the graph. For instance, the tools used in the examples below were developed using the *R* programming environment and specifically the *igraph* library (Csardi and Nepusz, 2006), which is developed to support graph theory. Having some level of proficiency in such tools may significantly enhance the efficiency and effectiveness of AcciNet.

Step 1. Determine the purpose and scope of using AcciNet

The first step involves determining the purpose and scope of AcciNet and is analogous to Step 1 in CAST.

Step 2. Perform task analysis on the work domain in question

The next step entails describing the task performed in terms of what high-level goals and subgoals can be achieved. This is accomplished through task analysis. The suggested task analysis approach given by Salmon and colleagues (2023) is to use HTA (Section 3.2.2.2). However, we believe that other potential methods should be considered, such as a process chart (Section 3.2.2.3). The primary goal of Step 2 is essentially to identify the tasks performed across the work domain and SOI. An example of a process chart output is shown in Figure 33 while an example of an HTA output is shown in Table 6. It is worth noting that the process map developed through TERA (Section 3.1.2.4) can be directly used in this step.

The development of a task analysis, regardless of the specific method used, requires collecting task data from various sources, including procedures and related site documentation (e.g., training materials), as well as performing interviews with SMEs as needed.

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[5] The term *actor* is synonymous with the term *agent* used in this technical report.

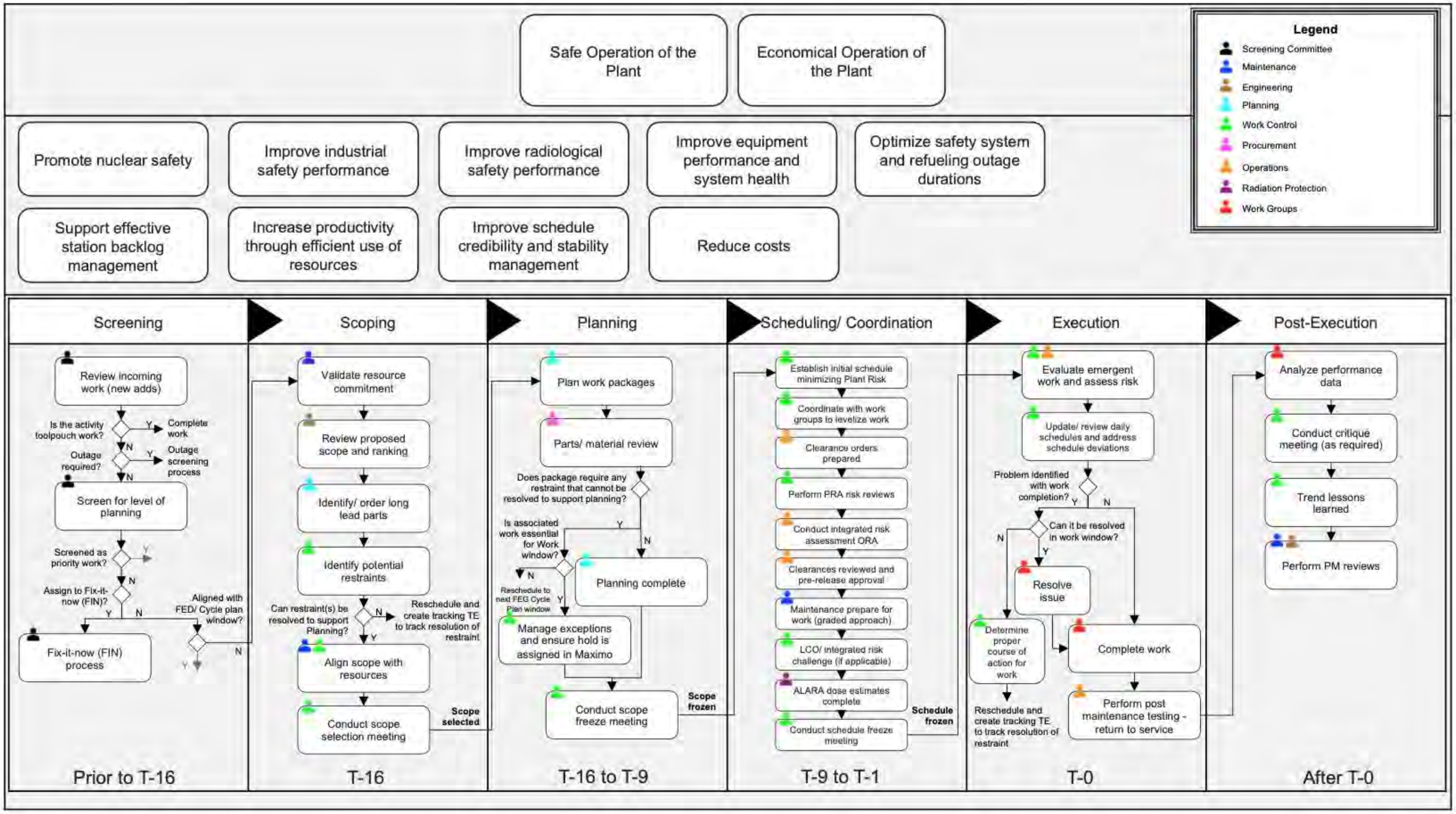


Figure 33. Process chart example of a nuclear power plant work management process.

Note: The process chart provided in Figure 33 is intended for illustrative purposes only to demonstrate AcciNet output.

Table 6. Tabular HTA example of a nuclear power plant work management process.

Goal	Subgoal	
1) Screening *(Prior to T-16)*	1.1.	Review incoming work (new adds)
	1.2.	Screen for level of planning
	1.3.	Fix-it-now process
2) Scoping *(T-16)*	2.1	Validate resource commitment
	2.2	Review proposed scope and ranking
	2.3	Identify and order long-lead parts
	2.4	Identify potential restraints
	2.5	Align scope with resources
	2.6	Conduct scope selection meeting
3) Planning *(T-16 to T-9)*	3.1	Plan work packages
	3.2	Parts and material review
	3.3	Planning complete
	3.4	Manage exceptions and ensure hold is assigned in Maximo
	3.5	Conduct scope freeze meeting
4) Scheduling and Coordination *(T-9 to T-1)*	4.1	Establish initial schedule minimizing plant risk
	4.2	Coordinate with work groups to level work
	4.3	Clearance orders prepared
	4.4	Perform performing probabilistic assessment risk reviews
	4.5	Conduct integrated risk assessment ORA
	4.6	Clearances reviewed and prerelease approval
	4.7	Maintenance prepares for work (graded approach)
	4.8	Limiting conditions for operation and integrated risk challenge (if applicable)
	4.9	ALARA dose estimates complete
	4.10	Conduct schedule freeze meeting
5) Execution *(T-0)*	5.1	Evaluate emergent work and assess risk
	5.2	Update and review daily schedules and address schedule deviations
	5.3	Resolve issue
	5.4	Determine proper course of action for work
	5.5	Complete work
	5.6	Perform post-maintenance testing—return to service
6) Post-Execution *(After T-0)*	6.1	Analyze performance data
	6.2	Conduct critique meeting (as required)
	6.3	Trend lessons learned
	6.4	Perform project management reviews

Note: Table 6 is intended for illustrative purposes only to demonstrate AcciNet output.

Step 3. Develop an initial task network graph

Step 3 entails developing an initial *task network graph*. The task network graph is used as the primary tool to identify task risks and emergent risks. The task network graph represents the tasks identified in the Step 2 output and then extends this output by representing the relationships between tasks (Salmon et al., 2023). The relationships between tasks can be established from any of the four conditions:

- Tasks that are linked sequentially

- Tasks that are performed concurrently
- The interlinking of tasks by one's outcome influencing another
- Contingencies in the completion of a task prior to executing a given task.

The task data used in Step 2 can also be used to develop the initial task network graph. For example, the output of a process chart (Figure 33) already indicated tasks that are sequentially linked and potentially tasks performed concurrently (i.e., Conditions #1 and #2). To identify task relationships under Conditions #3 and #4, it may be useful to have access to a SME within the given work domain. Potential questions to ask may include some variant of the following:

- If [Task A] is not successfully performed, what other tasks are impacted?
- What tasks are dependent upon the completion of [Task A]?

While the original approach to developing the task network graph by Salmon and colleagues (2020) does not explicitly provide recommended tools to create the task network, one approach that can be used is to adopt the graph theory and social network analysis (e.g., Kovesdi and Le Blanc, 2021). Using graph theory, the nodes represent tasks and the relationship based on the four conditions represents links (i.e., connections between nodes). An example of a task network graph is shown in Figure 34 and is developed based on the results of a corresponding *transition matrix* shown in Figure 35.

Figure 34. Example task network graph of a work management process.

Note: The task network graph provided in Figure 34 is intended for illustrative purposes only to demonstrate AcciNet output.

	(Screening) Review incoming work (new adds)	(Screening) Screen for level of planning	(Planning) Plan work packages	(Screening) Fix-it-now (FIN) process	(Scheduling and Coordination) Establish initial schedule minimizing Plant F	(Scheduling and Coordination) Coordinate with work groups to levelize wor	(Scheduling and Coordination) Clearance orders prepared	(Scheduling and Coordination) Perform PRA risk reviews	(Scheduling and Coordination) Conduct integrated risk assessment ORA	(Scheduling and Coordination) Clearances reviewed and pre-release appro	(Scheduling and Coordination) Maintenance prepare for work (graded appr	(Scheduling and Coordination) LCO/ integrated risk challenge (if applicable	(Scheduling and Coordination) ALARA dose estimates complete	(Scheduling and Coordination) Conduct schedule freeze meeting	(Execution) Evaluate emergent work and assess risk	(Execution) Complete work	(Planning) Parts/ material review
(Screening) Review incoming work (new adds)	0	■	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Screening) Screen for level of planning	0	0	■	■	■	■	■	■	■	■	■	■	■	■	■	■	0
(Planning) Plan work packages	0	0	0	0	■	■	■	■	■	■	■	■	■	■	■	■	■
(Screening) Fix-it-now (FIN) process	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Scheduling and Coordination) Establish initial schedule minimizing Plant Risk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Scheduling and Coordination) Coordinate with work groups to levelize work	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Scheduling and Coordination) Clearance orders prepared	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Scheduling and Coordination) Perform PRA risk reviews	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Scheduling and Coordination) Conduct integrated risk assessment ORA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Scheduling and Coordination) Clearances reviewed and pre-release approval	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Scheduling and Coordination) Maintenance prepare for work (graded approach)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Scheduling and Coordination) LCO/ integrated risk challenge (if applicable)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Scheduling and Coordination) ALARA dose estimates complete	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Scheduling and Coordination) Conduct schedule freeze meeting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Execution) Evaluate emergent work and assess risk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Execution) Complete work	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(Planning) Parts/ material review	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 35. Example task network transition matrix of a work management process.

Note: The task network transition matrix provided in Figure 35 is intended for illustrative purposes only to demonstrate AcciNet output.

The task network graph and complementary task network transition matrix provide a mapping of relations between tasks. In the transition matrix, the tasks presented by row indicate a relationship, based on one of the four conditions, where the corresponding tasks are represented by the columns colored in black. A “0” represents no relationship between tasks. This same information is graphically visualized in the task network graph in Figure 34 with task nodes being interrelated as indicated by the edges (i.e., lines).

The basis for developing the task network graph is to provide mapping of immediate and emergent risks when performing the accident and incident investigation in the subsequent steps. With this, it provides a foundation to expand AcciNet, a retrospective analysis method, to Net-HARMS, a proactive analysis method. In the generic example given, the task for screening for the level of planning and planning work packages have downstream consequences on the remaining tasks, which is indicated through the task network graph. This information can then be used to support fostering an understanding of accident and incident causation for the subsequent investigation steps. Likewise, it is possible that these subsequent steps may inform the task network graph, and so iterations can be made to it. This crosscheck is done in Step 5.

Step 4. Collect accident and incident data

Step 4 entails collecting detailed and accurate data of the accident or incident in question. The nature of identified data should include event report data, as well as descriptive information for the SOI. Salmon and colleagues (2023) characterize three primary forms of data that should be captured:

- Data on the work activities, tasks, and process itself
- Data on the incident or accident itself
- Data on the SOI in terms of the roles and responsibilities, coordination between staff and automation, key decisions made, and technologies used.

The sources of data range from the outputs of the task analysis and task network graph outputs to additional reviews of procedures and related site documentation (e.g., training materials) to interviews with SMEs.

Step 5. Review and refine the task network graph

Step 5 entails reviewing the initial task network graph outputs in Step 3 against the detailed data collected and analyzed in Step 4 (Salmon et al., 2023). The scope of this review should entail verifying that the task relationships originally mapped are accurate, as well as identifying any new task relationships.

Step 6. Develop the actor network graph (optional)

In complex systems, it is likely that there are different roles and uses of automation assigned to work functions under the SOI. The actor network graph uses the data from the task relationships but indicates *who* (i.e., whether personnel or automation) is responsible for the given task. The specific agents within the SOI can be mapped directly to the task network graph (e.g., by labeling each node or presenting an icon such as seen in Figure 33).

Alternatively, an *actor graph* can be created by reviewing the interactions between roles in performing their tasks. In the generic work management process shown in Figure 33, the actor graph is developed by recording when a given task is completed by a specific role and *who* is the recipient of that given task result. Referring to the process map in Figure 33, Table 7 presents a *transition matrix* of exchanges between different roles across the entire work management process.

Table 7. Actor graph transition matrix for a generic plant work management process.

	Screening Committee	Maintenance	Engineering	Planning	Work Control	Procurement	Operations	Radiation Protection	Work Group
Screening Committee	3	1	—	—	—	—	—	—	—
Maintenance	—	—	1	—	1	—	—	—	—
Engineering	—	—	—	1	—	—	—	—	—
Planning	—	—	—	—	1	1	—	—	—
Work Control	—	2	1	1	9	—	3	1	2
Procurement	—	—	—	1	1	—	—	—	—
Operations	—	1	—	—	2	—	1	—	1
Radiation Protection	—	—	—	—	1	—	—	—	—
Work Group	—	—	—	—	1	—	1	—	1

Note: Table 7 is intended for illustrative purposes only to demonstrate AcciNet output.

The actor graph transition matrix shows that work control has the most interactions across different roles. For example, there are three interactions between work control and operations. This is specific to performing probabilistic assessment reviews during scheduling and coordination, updating and reviewing daily schedules and address schedule deviations during execution, and analyzing performance data during post-execution. The graphical equivalence to the transition matrix is presented in Figure 36.

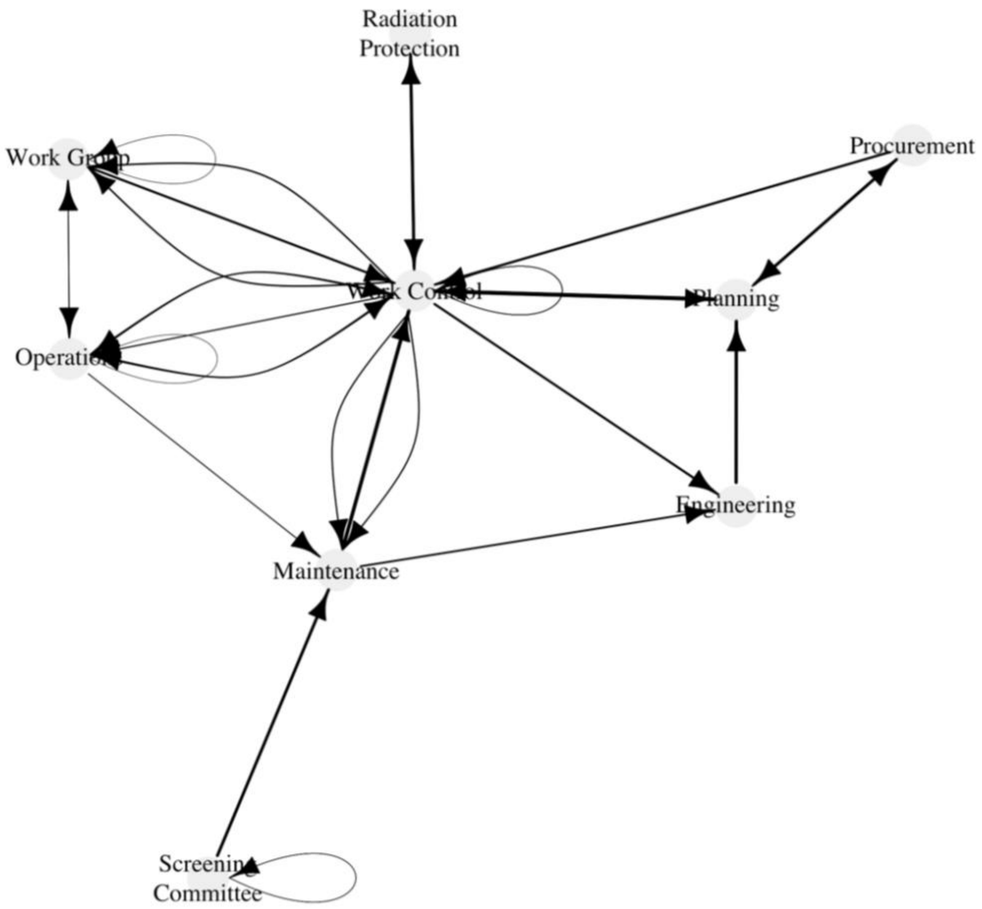
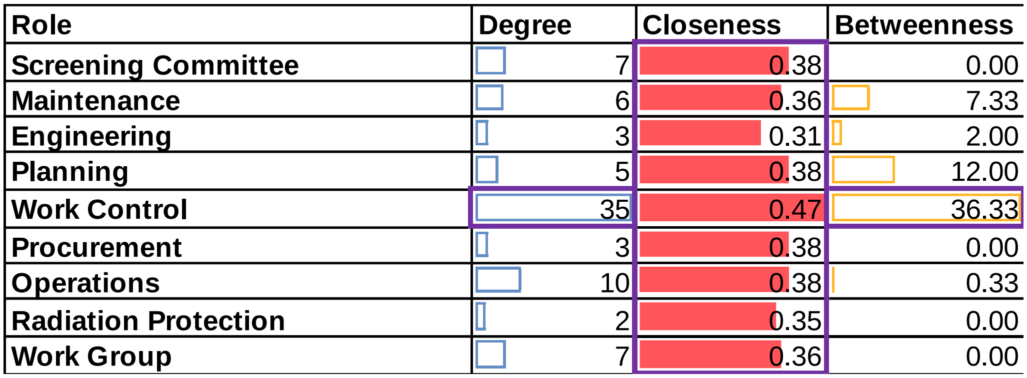


Figure 36. Example actor graph of a work management process.

Note: The actor graph provided in Figure 36 is intended for illustrative purposes only to demonstrate AcciNet output.

The actor graph outputs can be analyzed even further using *social network analysis* measures. In fact, this approach has been used to support function allocation considerations for complex sociotechnical systems (Schmid, Korn, and Stanton, 2020). Notable social network analysis measures include degree centrality, closeness, and betweenness (Guastello, 2015; Kovesdi and Le Blanc, 2019; Schmid, Korn, and Stanton, 2020).

Degree centrality is the proportion of the number of nodes (i.e., agents) a given node (i.e., agent) is connected to. In the case of the actor graph, degree centrality can be used to evaluate the degree to which a given agent (e.g., work control) interacts with others; a higher number indicates greater interaction. *Closeness* is the extent to which a given node (i.e., agent) uses the minimum number of nodes (i.e., agents) between itself and each other agent. Closeness can measure how quickly, or directly, a given agent (e.g., work control) interacts with other agents (e.g., operations, maintenance, engineering). Finally, *betweenness* is the degree to which a node (i.e., agent) acts as a mediator to other nodes (i.e., agents); it measures how often a node (i.e., agent) is between two other nodes (i.e., agents). Betweenness may indicate potential control or authority. Figure 37 presents the results of a social network analysis using the actor graph from the generic work management example.



Role	Degree	Closeness	Betweenness
Screening Committee	7	0.38	0.00
Maintenance	6	0.36	7.33
Engineering	3	0.31	2.00
Planning	5	0.38	12.00
Work Control	35	0.47	36.33
Procurement	3	0.38	0.00
Operations	10	0.38	0.33
Radiation Protection	2	0.35	0.00
Work Group	7	0.36	0.00

Figure 37. Example social network analysis from the actor graph of a work management process.

Note: Figure 37 is intended for illustrative purposes only to demonstrate AcciNet output.

The results in this example indicate work control having notably higher degrees of centrality, closeness, and betweenness. Such findings could therefore indicate work control as a central role in the work management process, requiring a very high degree of coordination between other roles and acting as a key “touch point” in coordinating tasks. The results of the social network analysis may indicate particular attention is needed to ensure that work control has proper information of the entire work management process to effectively perform their tasks and coordinate between other roles. This information could therefore be used to support the accident and incident investigation, as well as with identify contributors in Step 7.

Step 7. Identify contributors to the accident and incident

Step 7 entails identifying contributors to the accident or incident in question (Salmon et al., 2023). This step entails using the data from Step 4 in combination with the task network graph to identify and map contributors to the incident or accident. A recommended approach is to perform a systematic review of each task within the task network graph and evaluate whether the conduct of the given task or outcomes were responsible, at least in part, for the accident or incident. If an HTA was performed (e.g., see Table 6), contributors can be described within the context of the corresponding task in the task analysis table. When performing Step 7, it is particularly important to have the right level of expertise participating. This includes having an SME from the work domain at hand, as well as someone who is versed in HFE or root cause investigation. Having concurrence on the plausible contributors using a multidisciplinary team will strengthen the validity of this step.

Step 8. Classify contributors using a preferred taxonomy

Once plausible contributors have been identified and concurrence between the team established, these contributors are then classified using a preferred taxonomy. There are several different taxonomies that are available, such as taxonomies from STAMP (e.g., see CAST taxonomy in Table 5), Net-HARMS (Table 8), or Systematic Human Error Reduction and Prediction Approach (SHERPA; Boring, 2014). The purpose of this step is to provide a consistent way of classifying contributors identified within the AcciNet analysis so that human factors design principles can be readily applied to support the WRO(s). The results of the contributor classification can be documented in the task analysis table along with the results in Step 7.

Step 9. Map the contributors to the task network graph and document contributors into a summary table

Step 9 entails taking the results from Steps 7 and 8 and mapping these classified contributors to the task network graph. In doing so, a final verification of the results can be made by examining whether there were plausible downstream contributors associated with a given contributor identified within a particular task; this is accomplished by referencing the task relationships indicated from the task network graph. Finally, if the classified contributors were not already documented in a summary table in Steps 7 and 8, creating a summary table should be done at this step, as it is used to then identify innovations to address the contributors in Step 10.

Step 10. Identify risk controls that address the contributors.

The final step is to identify risk controls (i.e., innovations) that will address the identified contributors. In this last step, having a multidisciplinary team is critical, including SMEs in the work domain, HFE or root cause investigation, as well as key stakeholders responsible for purchasing or configuring such remedies. The results should further be informed through a business case (i.e., ION).

3.2.1.3 Root Cause Analysis

Root cause analysis (RCA) is a retroactive analysis approach that has been adopted by all U.S. and international nuclear power plants. IAEA safety standards (2007) and guidelines, as well as NRC regulations 10 CFR Part 50, Appendix B, Criterion 16 (2021), require the identification of the fundamental cause of the significant adverse condition so that corrective actions can be taken to “preclude repetition” of future similar events. As a result of these regulations, each nuclear power plant has a trained group of individuals that perform root cause investigations when events occur. Root cause trained managers review the completed investigations and certify the conclusions. In the case of events in which there is a potential impact on nuclear safety, the investigations are forwarded to the regulator for review and acceptance as well.

Although RCA has been in use by many industries since before the construction of the first commercial nuclear power plants, it has continuously been refined and adapted by the nuclear industry, and with each new evolution, the accuracy of the process has improved, transforming this process more from an art to a science. Even in its current evolved state, there are still many factors that can affect the accurate outcome of the event. If the root cause(s) are not properly identified and corrected, only symptoms that result from the actual root cause are corrected, but future similar events are not prevented.

To date, there are dozens of RCA methods and techniques in use by nuclear power plants worldwide. Regardless of the root cause analysis methodology used, the RCA process relies on the occurrence of events (retroactive analysis) to identify the underlying root cause of an issue or event. However, getting to the true root cause is also heavily dependent on many elements, including:

- The identification of the correct scope or depth of the investigation at the beginning of the investigation
- The completeness and accuracy of the information that was gathered and analyzed
- The proficiency and experience of the root cause investigator that is leading the investigation
- The objectivity of the RCA team and its management review team to be able identify the true cause of the event, while ignoring the potential repercussions of their conclusion
- Senior leadership’s understanding that the root causes are based on weaknesses in organizational or programmatic design that, when challenged, allow events to occur.

Each of these factors helps the RCA team to correctly identify the underlying root causes. However, the accurate identification of root causes is only the first step in preventing a recurrence of similar issues. There are other factors besides the identification of the correct root causes that can still impact the successful outcome of the investigation. Throughout the evolution of the “nuclearized” RCA process, various techniques have been added to the basic process to ensure that the breadth and depth of the investigation is adequate. An accurate performance of these additional techniques and tools has further improved the performance of most nuclear power plants internationally and are included in most utilities' training manuals.

Although most utilities have seen significant improvements in plant performance throughout the evolution of the RCA process, nuclear utilities identified that performing a full root cause investigation for every event deemed potentially significant was costly, time consuming, and labor intensive, with the performance of the investigation and management review costing $50,000 or more for each investigation. An independent analysis of completed investigations revealed that there was a good business case to identify and strengthen the first identified failed barrier, because a high percentage of the time, even though this was not the root cause of the issue, correction at this point would mitigate the recurrence of the issue to a more tolerable amount. Although from a regulatory perspective, root cause investigations still need to be performed for nuclear-safety-related significant events, a lesser investigation from a risk and cost management viewpoint would be adequate. Therefore, nuclear power plants began performing apparent cause evaluations in lieu of full RCAs. With the advent of the "Nuclear Promise," U.S. nuclear power plants even further reduced the frequency at which they performed full RCAs, and they migrated towards performing many more apparent cause evaluations instead. Currently in the United States, there is approximately a 25:1 ratio of apparent cause evaluations performed for every root cause investigation. Most nuclear power plants perform less than 10 full RCAs per year.

3.2.2 System Characterization Approaches

The second type of approaches, *system characterization*, refer to a broad set of methods used to describe the characteristics of the SOI. The nature of information collected from these methods broadly include identifying the goals and functions of SOI and work domain, understanding how work is done, identifying the cognitive requirements of performing tasks within the SOI, and understanding the communication and coordination requirements for performing tasks with multiple agents (i.e., whether person or automation). There are five candidate methods described here:

- Defining excellence—Section 3.2.2.1
- HTA—Section 3.2.2.2
- Process charting—Section 3.2.2.3
- Cognitive task analysis—Section 3.2.2.4
- Cognitive work analysis—Section 3.2.2.5

3.2.2.1 Defining Excellence

Defining *excellence* is important because it defines an objective to be achieved that is more favorable than the current state of operations. However, it can be difficult to define because it is relative to each plant and utility. Factors that impact the ability to identify excellence may include plant design, fleet size, budget, culture, available resources, and the organizations readiness to adapt to new technologies or process improvements.

For example, the Enterprise Asset Management (EAM) system in use to manage a nuclear power plant's work may have limitations and require work arounds to be able to navigate and produce accurate KPIs, yet it is too expensive to upgrade the EAM program to a better system. A knowledge elicitation process described in Section 4, the "DERIVE" process, helps to identify a nuclear power plant's current state of performance when the evaluation is performed by SMEs in the process being evaluated. Only by knowing where an organization is currently performing with respect to their peers, and normalizing the variations between those plants, can an organization define what they consider *excellence*. If they have the paradigm that they are currently performing excellently compared to other similar plants, their solution readiness may be minimized because there is no motivation to improve.

3.2.2.2 Hierarchical Task Analysis

The HTA is one of the most widely used techniques and typically serves as input for other HFE methods. An HTA describes the SOI and its behavior in terms of its goals, subgoals, operations, and plans (Stanton et al., 2013; Stuster, 2019). An important characteristic of HTA is that these characteristics of the SOI can refer to both personnel and automation.

Prerequisites for HTA

HTA is one of the most common HFE methods (Stanton et al., 2013). That said, Salmon and colleagues (2023) highlight that, in order to perform HTA with sufficient accuracy and completeness, expertise is needed. Given that HTA is a staple method for human factors practitioners, a reasonable suggestion is to ensure that HTA is performed with a multidisciplinary team where a human factors engineer leads the development of the HTA.

Step 1. Define the scope of performing an HTA

The first step for conducting an HTA is to clearly define its purpose and to delineate the SOI in question from any external factors that may influence the SOI (Salmon et al., 2023). The identification of specific WROs would serve as primary input in this step.

Step 2. Collect data

Data about the task is then collected to inform the analysis. The information necessary to conduct an HTA are the steps involved in the task, technology used, interaction between people and technology, decision-making components, and task constraints. The sources of data used can be diverse, including procedures, related site documentation (e.g., training materials), and interviews with SMEs. Further, reuse of a previously developed HTA may be applicable.

Step 3. Determine the primary goal of the task

The main goal of the task should be the overall reason for conducting it and should be broad and brief. Figure 38 below at the top node (i.e., Track Stay Time) provides an example of a goal.

Step 4. Determine the subgoals

Next, the subgoals of the task need to be determined. Typically, there are four or five subgoals, but that is in no way the requirement. The subgoals should be meaningful and contribute to achieving the main goal when combined. Using Figure 38, an example of a subgoal would be monitoring work stay times.

Step 5. Decompose the subgoals

The subgoals are then broken down into other subgoals and operations. This process continues until the appropriate operation for the task is identified. The lowest level of the HTA should always be an operation. Operations are the actions needed to complete the subgoals and main goal and are completed by the agent within the system. Figure 38 illustrates a typical HTA output, illustrating the hierarchical branching of goals, subgoals, and operations.

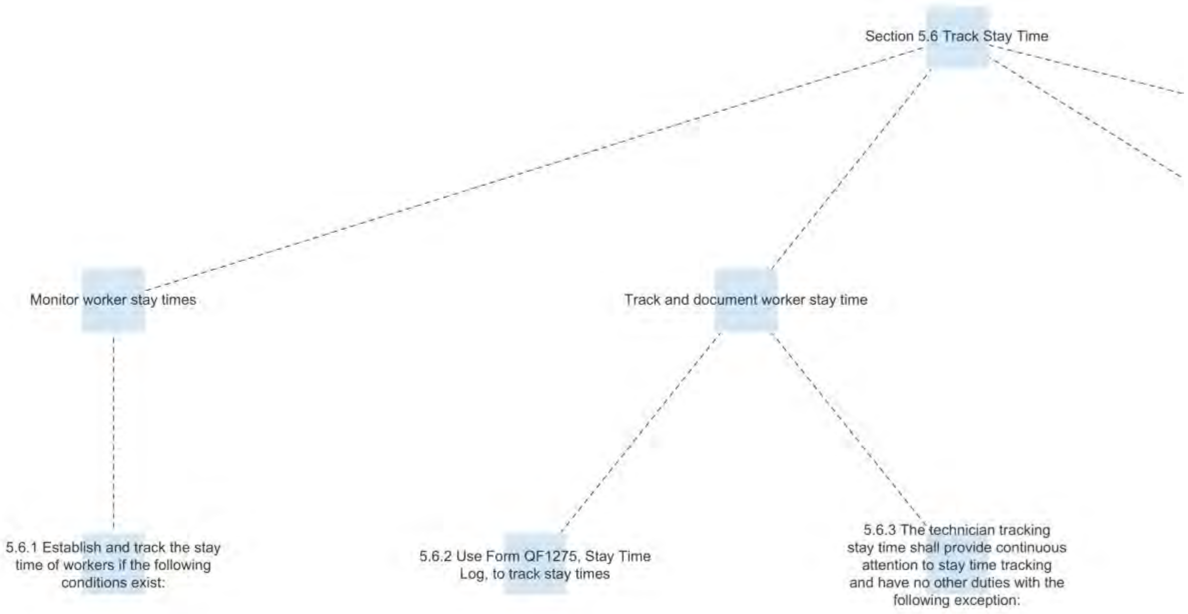


Figure 38. Example hierarchy developed from task analysis.

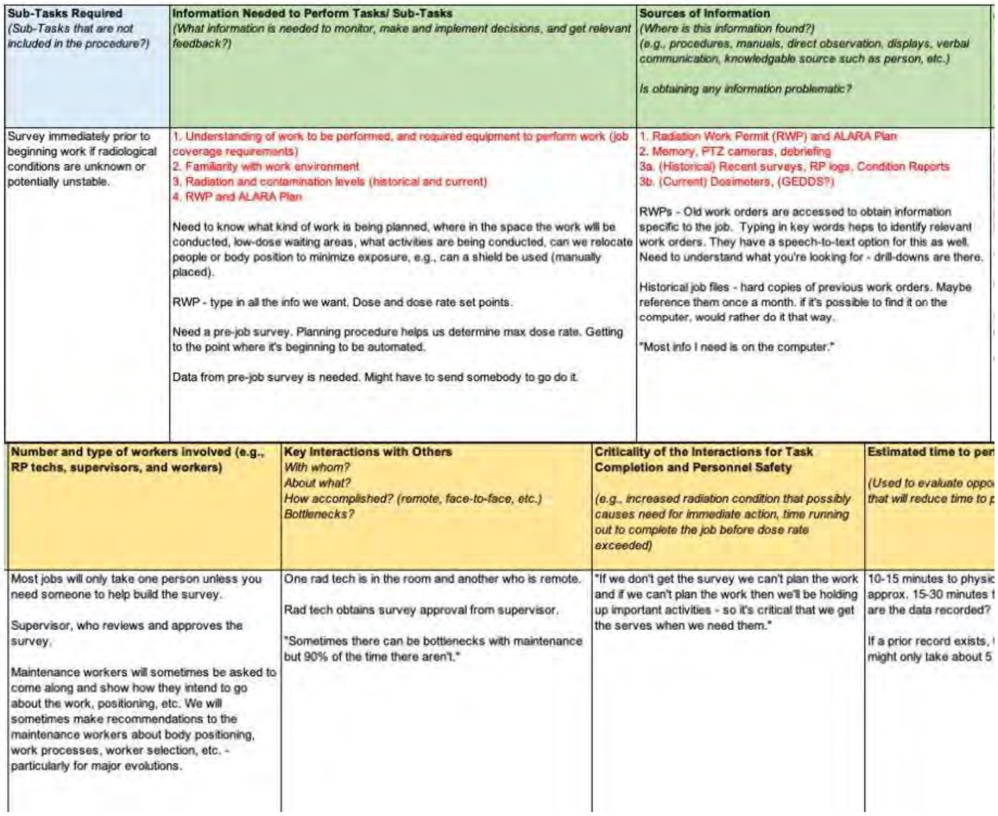
Step 6. Plan analysis (optional)

After decomposing the subgoals and getting to operations within the task, the analyst can then add the plan to the HTA. Plans show how the goals are achieved with each step. Below is a list of the types of plans that can be used in an HTA:

- Linear—Do 1, then 2, then 3
- Nonlinear—Do 1, 2, and 3 in any order
- Simultaneous—Do 1, then 2 and 3 at the same time
- Branching—Do 1 if X is present. Then do 2 and then 3, but if X is not present then exit
- Cyclical—Do 1, then 2, then 3 and repeat Y times
- Selection—Do 1, then 2 or 3.

Step 7. Convert the HTA into a tabular format (optional)

The HTA created in the previous step can then be converted to a tabular format (i.e., TTA) by placing the bottom-level operations from the HTA into columns (Stanton et al., 2013). Figure 39 provides an example of TTA previously used by Kovesdi et al. (2021; see INL/EXT-21-64428). Also, refer to Table 6 as an example of a TTA developed for work management. It is worth noting that Figure 39 illustrates how task data can be extended for TTA by collecting specific task information related to information needs, worker competencies, communication and coordination, and estimated completion time to name a few.



Sub-Tasks Required *(Sub-Tasks that are not included in the procedure?)*	**Information Needed to Perform Tasks/ Sub-Tasks** *(What information is needed to monitor, make and implement decisions, and get relevant feedback?)*	**Sources of Information** *(Where is this information found?)* *(e.g., procedures, manuals, direct observation, displays, verbal communication, knowledgable source such as person, etc.)* *Is obtaining any information problematic?*
Survey immediately prior to beginning work if radiological conditions are unknown or potentially unstable.	1. Understanding of work to be performed, and required equipment to perform work (job coverage requirements) 2. Familiarity with work environment 3. Radiation and contamination levels (historical and current) 4. RWP and ALARA Plan Need to know what kind of work is being planned, where in the space the work will be conducted, low-dose waiting areas, what activities are being conducted, can we relocate people or body position to minimize exposure, e.g., can a shield be used (manually placed). RWP - type in all the info we want. Dose and dose rate set points. Need a pre-job survey. Planning procedure helps us determine max dose rate. Getting to the point where it's beginning to be automated. Data from pre-job survey is needed. Might have to send somebody to go do it.	1. Radiation Work Permit (RWP) and ALARA Plan 2. Memory, PTZ cameras, debriefing 3a. (Historical) Recent surveys, RP logs, Condition Reports 3b. (Current) Dosimeters, (GEDDS?) RWPs - Old work orders are accessed to obtain information specific to the job. Typing in key words heps to identify relevant work orders. They have a speech-to-text option for this as well. Need to understand what you're looking for - drill-downs are there. Historical job files - hard copies of previous work orders. Maybe reference them once a month. if it's possible to find it on the computer, would rather do it that way. "Most info I need is on the computer."

Number and type of workers involved (e.g., RP techs, supervisors, and workers)	**Key Interactions with Others** *With whom?* *About what?* *How accomplished? (remote, face-to-face, etc.)* *Bottlenecks?*	**Criticality of the Interactions for Task Completion and Personnel Safety** *(e.g., increased radiation condition that possibly causes need for immediate action, time running out to complete the job before dose rate exceeded)*	**Estimated time to per** *(Used to evaluate oppo* *that will reduce time to p*
Most jobs will only take one person unless you need someone to help build the survey. Supervisor, who reviews and approves the survey. Maintenance workers will sometimes be asked to come along and show how they intend to go about the work, positioning, etc. We will sometimes make recommendations to the maintenance workers about body positioning, work processes, worker selection, etc. - particularly for major evolutions.	One rad tech is in the room and another who is remote. Rad tech obtains survey approval from supervisor. "Sometimes there can be bottlenecks with maintenance but 90% of the time there aren't."	"If we don't get the survey we can't plan the work and if we can't plan the work then we'll be holding up important activities - so it's critical that we get the serves when we need them."	10-15 minutes to physic approx. 15-30 minutes t are the data recorded? If a prior record exists, might only take about 5

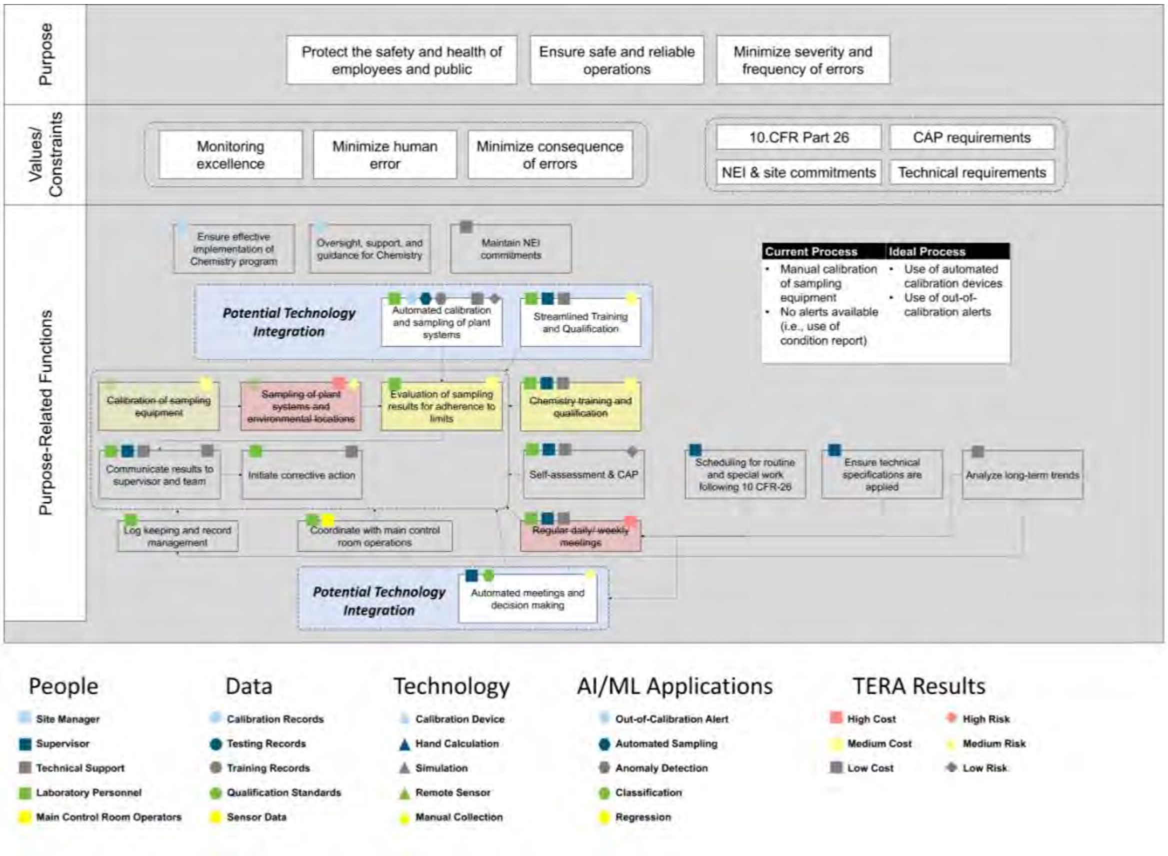
Figure 39. Portion of TTA used in previous LWRS Program sociotechnical R&D (adapted from INL/EXT-21-64428).

3.2.2.3 Process Charting

Process mapping consists of reviewing process documents and interviewing numerous people involved in the current process. The process mapping phase consists of elements of Lean Six Sigma, ION principles, and Lean Startup Methods. Through the combination of these well-defined processes and principles, the process map can be used to evaluate pain points, the value of information, and new technology risks. The following in this section highlights different types of process charting techniques used for TERA (Section 3.1).

Process Mapping

When evaluating the process from a technical, economic, and risk perspective, we have combined several well-known process evaluation techniques. This includes guiding principles developed in Lean Six Sigma's SIPOC, ION's PTPG, HRL, and ORL. By understanding the methods in each of these evaluation techniques, the current process and risks associated with implementing a new process can be comprehensively evaluated and well-understood. The result is a process map that contains the individual tasks, decisions, data and information flow, and cost information. An example of a high-level process map can be seen in Figure 40.



Current Process	Ideal Process
• Manual calibration of sampling equipment • No alerts available (i.e., use of condition report)	• Use of automated calibration devices • Use of out-of-calibration alerts

Figure **40**. Example of a process map for a chemical safety process.

This process map shows an example of how indicators can be used to highlight important features of the process. Included features of this process indicate the people, data, technology, and results of the TERA.

Lean Six Sigma—SIPOC

Another method for analyzing processes is through the Lean Six Sigma method known as SIPOC. This method breaks a process down into five main categories:

- *Suppliers*—people or organizations that contribute to or are involved in a process
- *Inputs*—necessary tools, data, or information contributed by suppliers
- *Process*—steps that transform inputs into outputs
- *Outputs*—result of the process or an item created in the process
- *Consumers*—receiver of the output from the process or where the output goes.

Using the SIPOC approach to break it down, we can evaluate the process by identifying the relationship between each of the categories. For example, as the input to the system changes, we can analyze the effect this has on the process, output, and consumer. If the input to a process decreases in quality, we can evaluate how that will affect the output and how the quality of the output affects the quality of the final product received by the consumer. An example of a SIPOC diagram can be seen in Figure 40. For more information on using SIPOC for process analysis, see Brown (2018) and Scholtes and colleagues (2003).

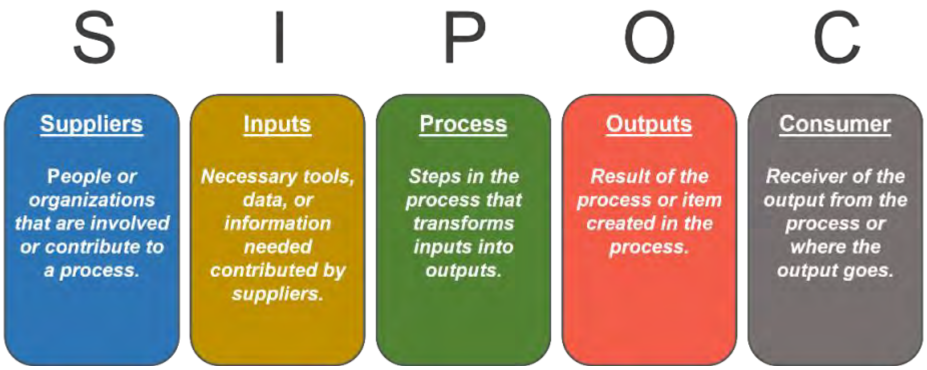


Figure **41**. An example of a SIPOC diagram used to analyze a process.

PTPG—People, Technology, Process, and Governance

Part of the philosophy for ION is viewing the process or capability through the lens of various categories. The ION philosophy categorizes capabilities as being comprised of four interdependent resources: people, technology, process, and governance. Each of these resources determines how and why the process functions. By breaking down a process into each of these four categories, it becomes easy to see how the process operates and to determine WROs. The ION philosophy and integration of PTPG can be seen in Figure 41.

Figure **42**. The relationship between ION's focus of people, technology, process, and governance.

Data Mapping

Data mapping involves visually charting where data originates, where they are stored, and how they are used. This aids in ensuring consistent data quality and data security, while also aiding in process streamlining. This is especially important for digital modernization and transformations due to the increasing use of data to support analysis and decision-making. The steps typically include:

1. *Identifying Data Sources.* Pinpoint where your data are coming from, whether it is databases, files, or even manual inputs
2. *Defining Data Destinations.* Determine where these data need to end up, which could be in any system used within the organization
3. *Mapping Fields.* Connect source data fields to their destination counterparts

4. *Conversion Rules.* If needed, set rules for data transformations
5. *Implement and Test.* Apply the mapping and test it rigorously to ensure there is no data loss or discrepancies.

Creating a data map and integrating it with the process map creates a comprehensive picture of where data is stored, how it is accessed, and how it is used to support process functions. For a more information about data mapping, see Sergio and colleagues (2004) and Shahbaz (2015).

Decision Mapping

Decision mapping focuses on identifying decision points within a process and understanding the information and actions leading to those decisions. This helps in evaluating critical decision-making points, potential bottlenecks, and areas of risk. The steps involve:

1. *Chart Decision Points.* Identify all decision junctions within the process
2. *Detail Decision Criteria.* What information is needed to make each decision
3. *Visualize Outcomes.* For each decision point, map out potential outcomes
4. *Analyze Dependencies.* Determine if certain decisions rely on previous ones or on specific data points.

Decision trees can be helpful when integrating decisions and processes together into one cohesive process. These are also helpful when creating and understanding process flow, input-output relationships, and functional requirements for a given process decision. An example of a decision tree can be seen in Figure 43.

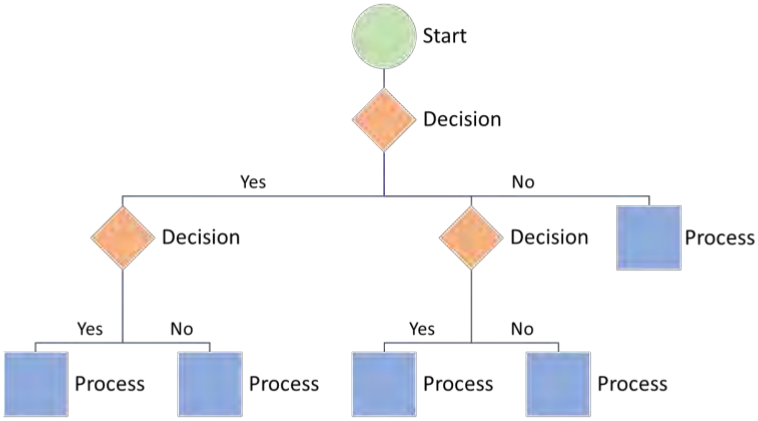


Figure **43**. Example decision tree.

Eliciting Information to Develop Process Maps

Eliciting information involves gathering detailed, accurate, and relevant information from various sources to gain a comprehensive understanding of the process. This could be done through observations, interviews, questionnaires, or analyzing existing documentation. There are several methods used when employing information elicitation, but the most effective will be a combination of:

- *Observations.* This is a direct method to observe the process in real-time. This method provides first-hand experience of this process.
- *Interviews.* Conducting one-on-one or group discussions with stakeholders, experts, or participants. This method allows for deep diving into topics, pain points, and enables quick clarification.

- *Questionnaires.* Use of written sets of questions that can be distributed to a large audience. This method helps gather information from a large group, can help ensure anonymity, and minimize potential bias.
- *Document Analysis.* Reviewing existing documentation, records, or reports relevant to the process. This method can help provide historical context and help quickly understand the standard documented process.

Although this is not an exhaustive list, it is important to consider the type of process, the KPIs used, the people involved, and the information needed. A comprehensive method for gathering information is imperative to correctly identifying the costs and potential benefits for any WRO.

3.2.2.4 Cognitive Task Analysis

Cognitive task analysis is a broad class of knowledge elicitation, data analysis, and knowledge representation methods that enable understanding the cognitive processes used by people and technology within the SOI (Stanton et al., 2013; Kovesdi et al., 2021). Crandall, Klein, and Hoffman (2006) provide detailed guidance in performing cognitive task analysis for which they provide an overarching approach in executing cognitive task analysis, regardless of the variants of its specific methods. Their work characterizes performing cognitive task analysis in terms of three aspects critical to the success of performing cognitive task analysis. These aspects are summarized next. The reader should refer to Crandall, Klein, and Hoffman (2006) for detailed guidance across these aspects, as well as detailed cognitive task analysis methods.

Prerequisites for cognitive task analysis

There are several specific methods that fall under the cognitive task analysis umbrella (e.g., Stanton et al., 2013). While each method contains differences in their execution, they all converge in the sense that they seek to understand the cognitive processes required to perform work (Crandall, Klein, and Hoffman, 2006). In order to collect valid and reliable data of the cognitive processes of work, deep familiarity in cognitive science can significantly support the generation of such results. Furthermore, it is equally important to have someone who is versed in the intricacies of the work being performed, and hence the availability of work domain SMEs is needed.

Aspect 1. Knowledge elicitation

Knowledge elicitation is characterized as a set of methods that can be used by the human factors engineer to collect information about what people know (i.e., in relation to the work they perform) and how they know this information (Crandall, Klein, and Hoffman, 2006). There are different ways in which such data can be collected, including interviews, self-report surveys, observation, or automated capture. Each approach has specific advantages and disadvantages and therefore must be selected based on the specific circumstances of the project, such as the knowledge elicitation objectives, the schedule, and the availability of SMEs. Typically, a combination of data collection methods can be done to leverage the benefits of each to further enrich knowledge elicitation.

Aspect 2. Data analysis

The synthesis of data collected is another important aspect of cognitive task analysis (Crandall, Klein, and Hoffman, 2006). Key activities for this aspect include structuring the data, identifying key findings, and assigning meaning to these findings based on the objectives of the analysis. A particular challenge in data analysis for cognitive task analysis concerns dealing with large amounts of semistructured or unstructured data types, such as qualitative text, photographs, or videos. INL/EXT-20-58538 (2020) describes a systematic approach to support the analysis of such data types. A thematic analysis is a systematic process of translating qualitative data into codes, then into themes, and finally into insights that can be used to represent knowledge in a cognitive task analysis (Figure 44). The process is illustrated in

Figure 44 and can be performed by one or more analysts, with the latter enabling greater validity. This process is described further in INL/EXT-20-58538.

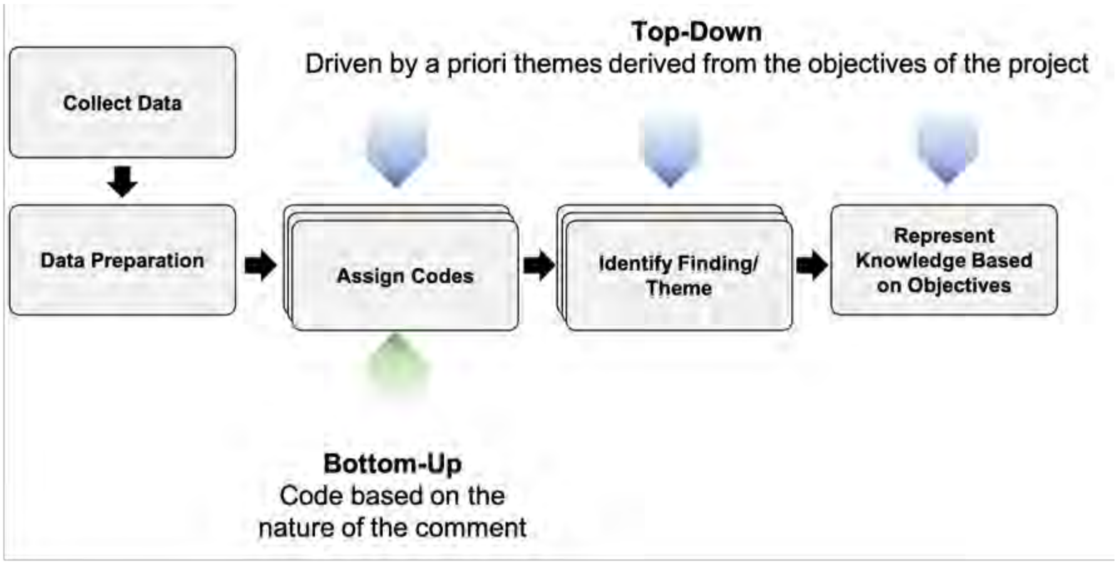


Figure 44. Thematic data analysis for qualitative data (adapted from INL/EXT-20-58538, 2020).

Aspect 3. Knowledge representation

Knowledge representation refers to the presentation and communication of insights gained from knowledge elicitation and sufficiently analyzed (Crandall, Klein, and Hoffman, 2006). There are several ways in which cognitive task analysis results can be represented, many of which include:

- *Narratives.* Used to describe specific incidents
- *Timelines.* Used to represent chronological events
- *Tables or Charts.* Used to compare different cognitive aspects of work across multiple categories
- *Process Charts.* Used to describe a work process (Section 3.2.2.3)
- *Concept Maps.* Graphical representation of knowledge structure (e.g., mental model)
- *Cognitive Models.* Used to represent dynamic nature of cognition in work (Section 3.2.4.3).

3.2.2.5 Cognitive Work Analysis

A cognitive work analysis is an integrated set of analytical tools that can be applied to represent different constraints imposed on the SOI (Salmon et al., 2023; Roth et al., 2019). This analysis type is goal-focused and describes the SOI in terms of the governing constraints across the work domain. Unlike task analysis approaches that begin with focusing on the personnel's task demands, cognitive work analysis begins by examining the SOI, starting at its environment and its overall purpose (Burns and Hajdukiewicz, 2017). As a result, a cognitive work analysis tends to provide rich information into first-of-a-kind systems or modifications to an existing system that is substantial or "disruptive."

A cognitive work analysis includes five primary phases, including WDA, ConTA, StrA, SOCA, and WCA. Each phase provides additional insights into the work domain, but a cognitive work analysis does not prescribe any specific phase or series of phases to be undergone. Rather, the analyst may choose which of the five phases are applicable. Nevertheless, WDA tends to be most used, and it is generally the first phase to begin a cognitive work analysis. Moreover, the typical sequences in which a cognitive work analysis is completed can be summarized in Figure 45.

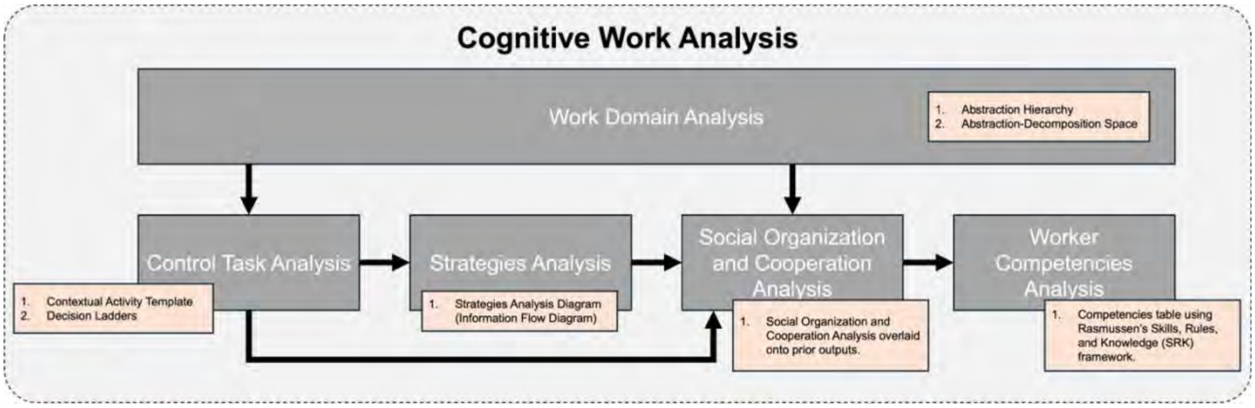


Figure 45. Cognitive work analysis primary phases and sequences of completion.

Figure 45 illustrates that the typical starting point for a cognitive work analysis begins with WDA (i.e., the orange boxes summarize the key outputs of each phase). If the analyst determines additional phases are needed from WDA, the analyst may proceed to ConTA or SOCA. From ConTA, the analyst may perform StrA or SOCA, as indicated by the arrows. The remaining sequences show the progression from WDA, ConTA, StrA, SOCA, and to WCA. A description of each phase regarding their purpose is provided next.

Prerequisites for cognitive work analysis

The full application of cognitive work analysis can require significant resources, time, and expertise (Salmon et al., 2023). For valid and reliable results, a multidisciplinary team is needed, which should include someone with experience in performing cognitive work analyses and access to SMEs of the work domain. It should be reemphasized that cognitive work analysis does not require all phases to be completed in its entirety, which can streamline its use. The most common way of applying a cognitive work analysis is by performing only the WDA phase. This phase can be completed relatively quickly and in conjunction with other system analysis techniques like HTA, process charting, and cognitive task analysis. In fact, Figure 33 illustrates the combination of WDA performed with the process chart of work management. Read and colleagues (2016) offer prompting questions that can be used to generate a cognitive work analysis output.

Phase 1. WDA

WDA defines the goals and constraints (i.e., functional structure) of the SOI's work domain (Hugo, 2015; Stanton et al., 2017). These constraints may either be manmade (i.e., whether physical or policy) or natural phenomena. WDA decomposes the work domain into different levels of abstraction, beginning with the fundamental purpose of the SOI. Each additional level of abstraction flows into more detailed attributes, including the values and constraints of the SOI, to abstract and system-level functions, until the physical objects are defined. Each level of abstraction is interlinked through a means-end relationship. The means-end relations form the basis for understanding *what* constraints govern the domain, *why* they exist, and *how* they are currently or could be achieved (Hugo, 2015). The graphical depiction of the means-end relations is formed in an abstraction hierarchy (AH). Examples of an AH are in Figure 7, as well as in Figure 33 (i.e., referencing the three layers of abstraction—goals, values and constraints, and processes). Additionally, a recent work performed by Joe and colleagues (2023) presents an AH of a preventative maintenance system (i.e., Figure 20 in INL/RPT-23-74217).

Phase 2. ConTA (Optional)

ConTA identifies specific situations where the functions identified in WDA exist (Stanton et al., 2017). There are two primary products developed at this phase: the contextual activity template (CAT) and decision ladder. The CAT indicates the relationship of each function identified from WDA to specific situations that invoke these functions. Decision ladders are used to describe the data processing and cognitive activities undergone by the SOI. Both products can be particularly useful in examining the effects of function allocation on work distribution, such as with the reassignment of functions to automated agents (Roth et al. 2019); this is accomplished by performing ConTA in combination with SOCA.

For example, Schmid, Korn, and Stanton (2020) applied a cognitive work analysis and social network analysis to evaluate a reduced flight deck crew concept. The ConTA CAT was used in combination with SOCA to examine the impacts of a reduced crew concept of operations across different flight situations, such as departing, cruising, and approaching landing. The authors compared the number of functions assigned to each flight deck crew role across the three flight situations and compared the reduced operation concept to existing flight operations. CAT-SOCA was then extended to quantify the functional loading on staff across flight situations to compare the reduced operation concept to existing operations. The authors were able to utilize CAT-SOCA to therefore identify salient situations in which functional loadings for the pilot were significantly impacted.

Decision ladders can be used to analyze the interactions of new technologies with people in terms of how each agent supports work in terms of decision-making processes. An example decision ladder in Figure 46 illustrates the analysis of decision interactions with the use of an adaptive cruise control (ACC). The decision ladder combines SOCA with the decision ladder where key questions are listed at each decision-making process of the decision ladder, using color to show if such decision is performed by the driver, the ACC system, or both. In this example, the questions posed at each process in the decision ladder can help the designer focus on what sort of information would be needed to support a cohesive interaction between the driver and ACC system. It should be noted that both CAT and decision ladders can be applied. For example, during specific situations identified by the CAT, decision ladders can be developed to aid in understanding key decisions that help generate information requirements that support human-automation coagency (e.g., Naiker, Brady, Glenn Moy, and Kwok, 2023).

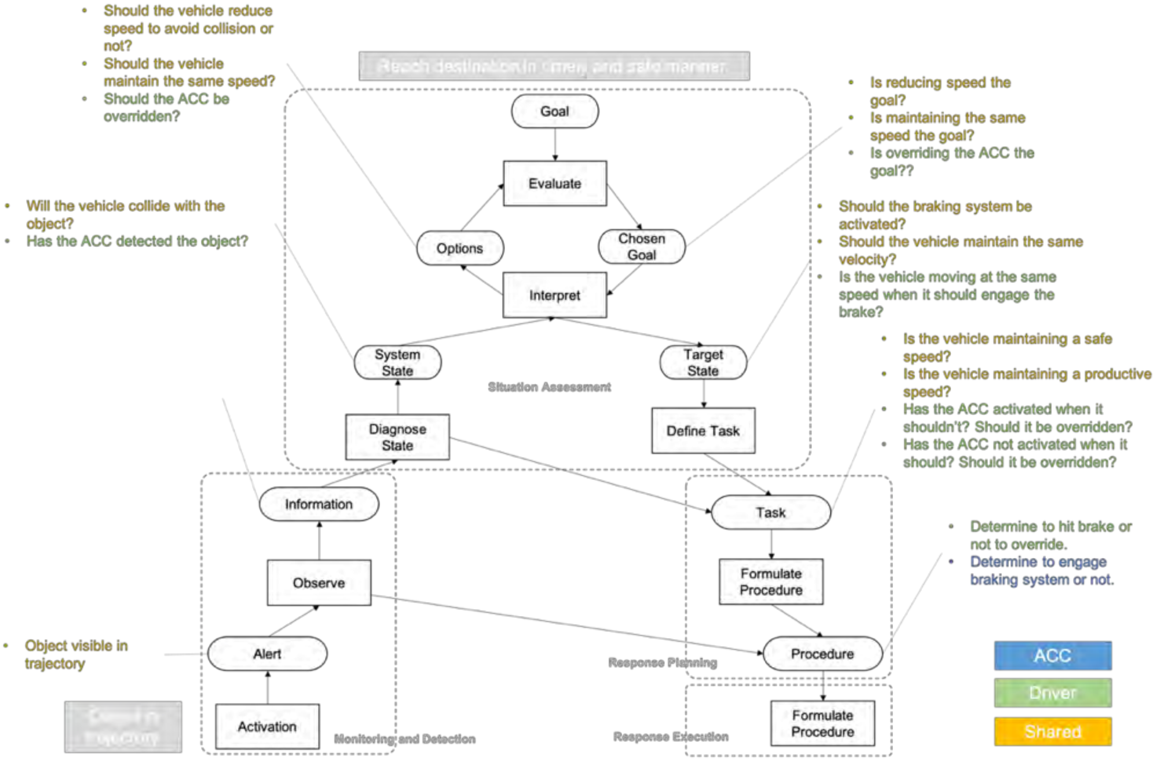


Figure 46. Example decision ladder to illustrate function allocation for an ACC system (adapted from INL/EXT-21-64320).

Phase 3. StrA (Optional)

StrA focuses specifically on how work can be accomplished, regardless of agent (Naiker, Brady, Glenn Moy, and Kwok, 2023). It uses the information flow map as a product to analyze the different strategies that can be used to accomplish work (Stanton et al., 2017). The information flow map can be represented as a process chart representing the different processes that can achieve the same function. SOCA can be applied to the information flow map to further show the role of specific agents at each primary activity.

Phase 4. SOCA (Optional)

SOCA focuses on the specific roles and responsibilities of each agent (Stanton et al., 2017). The functional assignment of key elements to each agent in SOCA is typically represented through color shading over the other cognitive work analysis products (e.g., the AH in WDA or the CAT in StrA). The decision ladder in Figure 46 presents the SOCA layer, illustrated as shaded coloring across key questions that each agent must fundamentally address at each element of the decision ladder.

Phase 5. WCA (Optional)

WCA is the final phase of cognitive work analysis; this phase analyzes the behavior required by personnel in the SOI within the scope of their role and responsibilities. A common approach to WCA is to use Rasmussen's skills, rules, and knowledge (SRK) taxonomy, see Figure 47.

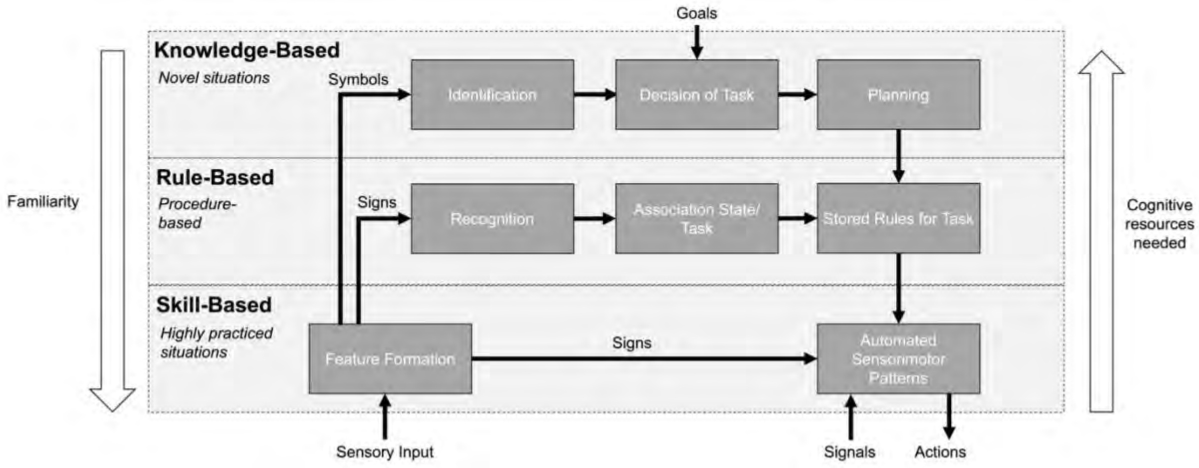


Figure 47. Rasmussen's SRK framework (adapted from Lee et al., 2017).

The figure illustrates different levels of information processing at each SRK level. Starting at the bottom is *skill-based behavior*. Here, the initial processing of sensory input (e.g., an alarm) may necessitate a direct means to pattern identification and response. An example of this may be during a specific plant event, as the operator can immediately discern a pattern from the alarms or environment and perform an action (e.g., trip the reactor) directly from this signal.

Next, *rule-based behavior* takes place. Rule-based behavior is driven by recognizing similar instances based on sensory input processing. An example of rule-based behavior would be identifying a particular procedure upon perceiving the alarm. Here, the operator recognizes that the particular alarm is associated with a certain kind of condition, but the specific course of action is not immediately clear.

Finally, *knowledge-based* behavior is invoked when there is a novel situation in which the operator must perform under their own analytical processing of the situation. An example of knowledge-based behavior may be observed when there is a leak in the plant with an unknown location and size. In this circumstance, there is a high degree of ambiguity. The degree of cognitive resources needed to operate with knowledge-based behavior is greatest. The SRK taxonomy can be used to analyze the different competency requirements across each of these levels when performing specific tasks assigned to personnel.

3.2.3 Proactive Analysis Approaches

The third type of approaches refer to a set of methods used to “forecast” potential risks with an existing system, as well as the proposed redesign. Characterized as being systems thinking approaches, these methods focus not only on the failure modes of specific components but also on the interactions among components at the personnel, technological (i.e., automation), and organizational levels. Two notable proactive analysis approaches are:

- STPA—Section 3.2.3.1
- Net-HARMS—Section 3.2.3.2

3.2.3.1 Systems Theoretic Process Analysis: STPA

STPA is a proactive analysis based on STAMP (Leveson and Thomas, 2018). Like CAST, STPA identifies risks within the system through analyzing the controls and feedback mechanisms across the entire system. And with leveraging the STAMP framework, the primary means for analysis is through developing an SOI control structure (i.e., see Figure 31). STPA provides a means to proactively analyze the interaction between agents within the SOI using the control and feedback mechanisms depicted in the control structure. It is worth noting that STPA is currently being applied within the LWRS Program to proactively analyze ineffective control actions (ICAs) within an information automation ecosystem (e.g., Joe, Hettinger, Yamani, Murray, and Dainoff, 2023). In this work, STPA is being explored as a method that can identify vulnerable parts of the information automation ecosystem control structure. Leveson and Thomas (2018) provide detailed guidance in applying STPA across a range of domains in their *STPA Handbook*. The resource is open source, and a link can be found below:

- https://psas.scripts.mit.edu/home/get_file.php?name=STPA_handbook.pdf

STPA can be essentially completed in five[6] primary steps. While the reader should refer to Leveson and Thomas (2018) for detailed guidance, a summary of these five steps is provided below.

Prerequisites for STPA

One the potential limitations of STAMP-based methods, like CAST or STPA, has been that the analyst(s) must have a familiarity (at least) or expertise in the approach to be effective in their use (e.g., Dallat et al., 2018; Hunton et al., 2023). For example, Hunton and colleagues (2023) applied STPA in conjunction with a risk assessment method developed by EPRI (Report 3002016698, 2021) to support the major safety-related digital I&C upgrade. In this effort, the authors concluded that having a dedicated team who establish and maintain proficiency in this approach would be beneficial.

Additionally, SMEs within the specific work domain are needed to accurately perform STPA. Therefore, its use should be determined based on whether there is expertise available in STAMP, as well as in the work domain of interest. In circumstances where expertise is available, STPA offers a comprehensive proactive analysis approach and is complementary to CAST, as described in Section 3.2.1.1.

Step 1. Identify the purpose and scope of STPA—Page 15 of Leveson and Thomas (2018)

The first step is to identify the purpose for applying STPA to the SOI. The essence of STPA is to identify key losses for the SOI and associated hazards that can lead to a loss. It is therefore important to consider the SOI boundaries and to identify any important external factors. Losses are the consequences that are to be avoided and can be broad, pertaining to safety, economic, or even organizational reputation. Losses are caused by hazards when certain conditions are met. Hazards are interrelated to losses and can

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[6] Leveson and Thomas (2018) describe STPA in terms of four steps. However, as a proactive systems thinking approach, a fifth step is added to identify risk controls that can remedy the ICAs identified in the analysis.

form a one-to-many relationship. Leveson and Thomas (2018) provide a structured approach to documented and tracing losses to hazards (i.e., page 18).

Step 2. Develop the control structure—Page 22 of Leveson and Thomas (2018)

Next, an SOI control structure is then developed (e.g., Figure 31). If CAST had been performed, the control structure from it can be leveraged. In any case, the control structure typical is first developed at a higher level where greater detail is added throughout the course of the project (e.g., Leveson and Thomas, 2018; Salmon et al., 2023). The primary components of the control structure include models of a control loop, which include the controller, the controlled process, the control algorithm of the controller, and process model of the controller. The controller provides control of the controlled process through control actions set out by the control algorithm. The controller is informed by feedback coming from the controlled process using the controller's process model. A control structure can include many control loops in which controllers of higher authority are positioned towards the top of the control structure.

Step 3. Identify ICAs—Page 35 of Leveson and Thomas (2018)

The next step is to identify ICAs while using the control structure. ICAs are control actions that *could* lead to a hazard, consequently causing one or more losses. It is worth noting that the traditional term used is *unsafe control actions*. The term ICA is used here as it infers a broader interpretation of control actions that may be more rooted in economical or a loss in reputation, instead of only safety. This term was developed by Joe and colleagues to expand the use of STPA to ineffectiveness in communication and potential confusion in the information ecosystem (Joe et al., 2023). Leveson and Thomas describe four ways in which control actions can be ineffective (i.e., ICA *type*):

- Failing to provide a control action (omission)
- Providing a control action that leads to a hazard, an inherently unsafe action (commission)
- Providing a safe control action but done so sequentially incorrect either too early, too late, or in the wrong order (commission)
- Providing a safe control action but done so that it is temporally incorrect, being either too long or stopping too soon (commission).

ICAs can occur from the system, person, or organizational level and are analyzed further through loss scenarios in Step 4. In Step 3, ICAs are listed within the context of the four possibilities for each control action, mapping to the hazard(s) associated with it. A structured way in which ICAs are documented is provided below (i.e., an example from INL/RPT-23-74217):

- *<Controller> <ICA Type> <Control Action> <Context> [<Link to Hazard(s)>]*

- *ICA-1: Supervisor does not authorize work when preventive maintenance of equipment is required [H-3, H-4, H-5]* (adapted from Joe et al., 2023, Table 5)

Step 4. Identify loss scenarios—Page 42 of Leveson and Thomas (2018)

In Step 4, causal factors that lead to ICAs and their corresponding hazards and losses are described (i.e., referred to as *loss scenarios*). Important considerations that should be addressed in developing loss scenarios include:

- Why would ICAs occur (i.e., what characteristics about the interaction between sensors, feedback, process model and beliefs, and control algorithm may create the ICA)?
- Why would the control action be improperly executed or not executed?

An ICA may occur due to one of four reasons: failure in the controller, inadequate control algorithm, ineffective control input from another controller, or inadequate process model. For each ICA, loss scenarios can be developed by examining each controller and identifying plausible ineffective behavior through one of these four risk modes. Next, plausible causal factors that can lead to the identified risk modes are identified and documented. Scenarios that include the influencing factors and causes are detailed.

Step 5. Identify risk controls to remedy ICAs

A final step entails identifying specific risk controls, or WROs, to remedy the ICAs analyzed through the loss scenarios. This step should include members of the multidisciplinary team, including STPA analysts, work domain SMEs, and stakeholders responsible for either purchasing or configuring such remedies. The results should further be informed through a business case (i.e., ION).

3.2.3.2 The Networked Hazard Analysis and Risk Management System: Net-HARMS

Net-HARMS is a proactive analysis developed in response to a need of having a more contemporary risk assessment method that applies systems thinking principles in dealing with increasingly complex systems that demand going beyond traditional “linear thinking” for accident causation (Dallat, Salmon, and Good, 2018). The authors developed Net-HARMS as a potential alternative proactive analysis approach to other systems thinking methods, such as STAMP-STPA or the functional resonance analysis method (Hollnagel, 2004). They assert that Net-HARMS has three fundamental advantages to other systems thinking methods:

- Net-HARMS provides a simplistic approach that is usable by practitioners
- The method offers a broader and more usable taxonomy than STPA[7]
- It permits the concept of emergence to be described and predicted.

Net-HARMS was developed based on considering several HFE methods commonly used, including HTA, SHERPA, and HRA. These methods were expanded in Net-HARMS by refocusing HTA to account for system-level goals (i.e., rather than just operator actions), and the SHERPA element was modified considerably, including changes to the risk mode taxonomy and inclusion of identification of *emergent* risks.

Prerequisites for Net-HARMS.

Net-HARMS is a task-centric proactive analysis, unlike STAMP-STPA, which is based on developing a control structure of the system. For Net-HARMS, the availability of a task analysis output or process map would be readily usable without further transformation. Therefore, it is reasoned that expertise in the area of general HFE and of the work domain of interest is needed, but specialty expertise in a specific sociotechnical theory (e.g., STAMP) is not. It should be noted, however, in recent research examining the validity and reliability of common systems thinking methods, Net-HARMS required the most time to complete when compared to other systems thinking methods like STPA or the functional resonance analysis method, which was attributed to the fact that Net-HARMS includes an additional emergent risk assessment step (McCormack et al., 2023).

Step 1. Determine the purpose and scope of using Net-HARMS

The first step involves determining the purpose and scope of Net-HARMS.

Step 2. Perform task analysis on the work domain in question

Similar to AcciNet (Section 3.2.1.2), Step 2 entails describing the task performed in terms of what high-level goals and subgoals of the SOI are to be achieved. This is accomplished through task analysis, such as using HTA (Section 3.2.2.2) or a process chart (Section 3.2.2.3). Data sources that can be used to support

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[7] Claimed by the authors.

Step 2 include a documentation review of procedures and related site documentation (e.g., training materials), as well as performing interviews with SMEs.

Step 3. Develop a task network graph

Step 3 entails developing a task network graph. The task network graph is used as the primary tool to identify task risks and emergent risks for Net-HARMS. The development of the task network graph for Net-HARMS is analogous to that of AcciNet (Section 3.2.1.2); in fact, the same task network graph developed with AcciNet can be reused for proactive analysis purposes via Net-HARMS. The reader can refer to Step 3 in Section 3.2.1.2 for details in developing a task network graph.

Step 4. Identify task risks

In Step 4, plausible task risks are identified for each task within the task network graph. To do so, the analyst uses the Net-HARMS risk mode taxonomy (Dallat, Salmon, and Goode, 2018; Table 8) or a similar taxonomy.

Table 8. Net-HARMS risk mode taxonomy.

Behavior	Risk Mode
Task	T1—Task mistimed
	T2—Task omitted
	T3—Task completed inadequately
	T4—Inappropriate task performed
Communication	C1—Information not communicated
	C2—Wrong information communicated
	C3—Inadequate information communicated
	C4—Communication mistimed
Environment	E1—Adverse environmental conditions

The identification of risk modes is completed in collaboration with a work domain SME. It is worth noting that the data collected from AcciNet can be used to inform risk modes in Net-HARMS. A description of the specific characteristics of the risk mode identified should also be given to provide risk clarity and to better support identifying risk controls performed in Step 6. Also, the likelihood and severity of each risk can be assigned, even using an ordinal scale (i.e., low, medium, high; Dallat, Salmon, and Good, 2018). This task data can be documented in tabular format like in TTA (e.g., Figure 39).

Step 5. Identify emergent risks

Net-HARMS is an extension of the well-known SHERPA method (Dallat et al., 2018). What makes Net-HARMS unique to SHERPA is the added component of identifying plausible *emergent risks* by using the task network graph. The question at this step is, "what is the impact of risk X happening at task Y on the related task Z?" The basis for Step 5 is that additional risks may be realized due to the interaction of risks between interrelated tasks. For example, using the generic work management system presented in Figure 33 and example task network graph in Figure 34 and Figure 35, the task *plan work packages* is interrelated to several downstream tasks. A risk mode that occurs as planning work packages (e.g., T3—task completed inadequately) may create an emergent risk mode on a downstream task such as maintenance preparing for work (e.g., E1—adverse environment conditions). Step 5 provides a formal approach to systematically reviewing each task relationship from the task network graph and identify plausible emergent risks based on these task relationships.

Step 6. Identify risk controls to remedy task risks and emergent risks

The final step is to identify risk controls (i.e., innovations) that will address the task risks and emergent risks identified. Like in AcciNet (Section 3.2.1.2), having a multidisciplinary team is critical, including SMEs in the work domain, HFE and root cause investigation, and key stakeholders responsible for purchasing or configuring such remedies.

3.2.4 Modeling Approaches

The final type of approaches entails a range of methods used to simulate dynamic system behavior, herein referred to as *modeling approaches*. Modeling approaches are used to analyze the behavior and dynamics of complex systems over time (Salmon and Read, 2019). There are a number of modeling methods that fall under this type. The methods determined to be most useful to work process optimization and addressing HTI considerations are:

- Process Modeling—Section 3.2.4.1
- Human-in-the-Loop Simulation—Section 3.2.4.2
- Human Performance Models—Section 3.2.4.3

3.2.4.1 Process Modeling

Process modeling consists of turning a process map into a quantitative model. To do this, several mathematical modeling frameworks can be used to model the target states or variables in a system. In the context of process evaluation, quantitative modeling can be used to interrogate complex and interconnected systems to quantify how system parameters can affect the process outcome. For example, a process may be labor intensive, and errors in the system can cause rework. By creating a quantitative model of this system, the error rates can be perturbed to understand how changes to the process can result in improved performance. Furthermore, systems understanding can be used in a quantitative cost-benefit analysis to map how investments can provide economic returns by reducing error rates, labor, and variability.

To expand on the concept of process modeling, particularly with a focus on stochastic modeling, we can delve into specific approaches like Markov models and influence diagrams. Stochastic modeling is an invaluable tool in process modeling as it accounts for randomness and uncertainty in systems. It uses probability distributions to predict future behavior (which can be based on historical data), allowing for the analysis of various scenarios and their potential outcomes. This approach is particularly useful in processes where outcomes are not deterministic and can vary due to various factors.

One common stochastic modeling approach is the use of Markov models, which are particularly suited for processes where the future state depends only on the current state and not on the sequence of events that preceded it. In Markov models, each state of the system is modeled as a node in a graph, with transitions between states representing the probabilities of moving from one state to another. This allows for the modeling of complex processes in a structured and quantifiable manner, facilitating the analysis of long-term steady-state behavior as well as short-term transitions.

Influence diagrams, on the other hand, offer a graphical and quantitative representation of the relationships and dependencies among different variables in a system. They help in identifying the key factors that influence the process outcome and in understanding how changes to these factors can impact overall system performance. Influence diagrams combine decision nodes, uncertainty nodes, and value nodes to map out the decision-making process, making them a powerful tool for decision analysis and strategic planning.

By integrating these approaches into the process modeling framework, comprehensive models can be created that not only quantify the target states or variables but also incorporate the inherent uncertainties of the system. This enables an improved understanding of the process and aids in developing strategies that are robust against the variability and unpredictability of real-world systems.

Markov Processes

Once the high-level process mapping is completed, the analysis phase can begin by converting the process map into a Markov process. In the context of the TERA evaluation, Markov processes serve as a dynamic framework where the process's progression is characterized by transitioning between different states. Each state represents a distinct stage or condition within the process, and the transitions between states are governed by probabilities. For time-dependent processes, such as a task-centric or labor-intensive process, it is simple to convert the time-dependent process into a probabilistic process. A diagram of an example process is shown in Figure 48.

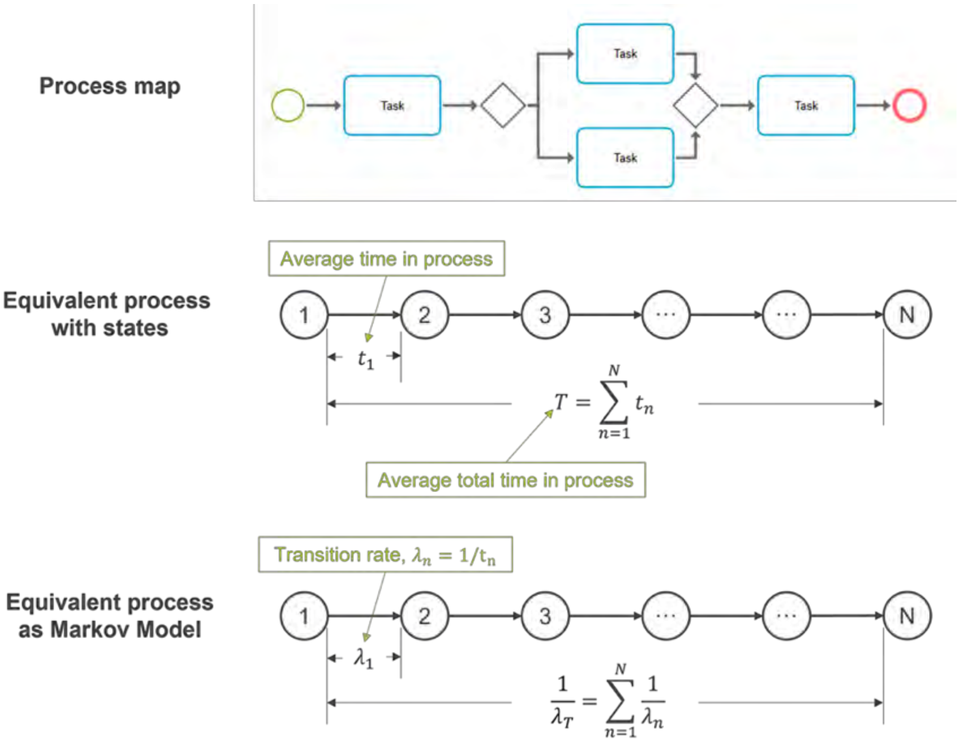

Figure **48**. A process map (top) can be turned into an equivalent stochastic Markov model (bottom).

In this example, the process map contains steps with a defined start and finish. To convert the process into a Markov chain, the steps in the process are turned into states, as shown in the middle of Figure 48. In this intermediate model, the average time spent in each state is defined as t_n, where n denotes the state. The total time spent in that process, T, can be defined as the sum of time for all states in the process, where $n = 1, \dots, N$. Next, the process can be converted to a Markov chain where the time dependencies between each state are transition rates defined as $\lambda_n = 1/t_n$.

By linking several processes together, we can model a complex series of tasks as a probabilistic model, see Figure 49.

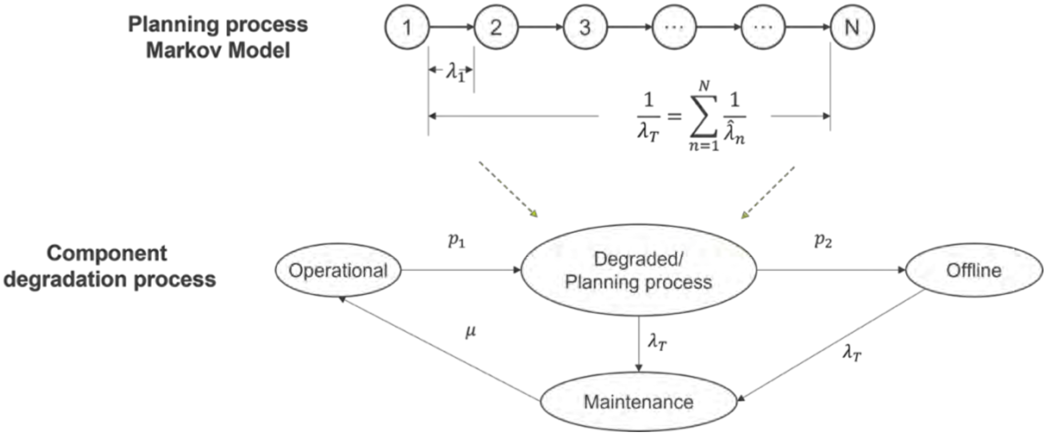

Figure **49**. A Markov model with transition rates (top) and integration of the Markov model to describe component degradation (bottom).

In this example, the step-by-step process is integrated into a larger Markov process that models a component degradation process. In this model, the component may be in one of four states: operational, degraded or planning, offline, and maintenance. In this process, the amount of time the component spends in an operational state depends on the amount of time spent in the other processes. The transition rates that connect each of the states determine that amount of time. These rates are defined at p_1, p_2, μ, and λ_T. Rate p_1 is determined by the reliability of the component and the probability of entering a degraded state from healthy operation. Likewise, the probability of entering an offline state from a degraded state is p_2. The rate λ_T defines the average amount of time it takes to finish going through the planning process and entering a maintenance state. This process can represent the amount of planning required before a maintenance action is chosen and started. The rate μ defines the average time spent in maintenance, returning the component to an operational state.

Steady-State Analysis

At the core of the TERA is the steady-state analysis. This describes the long-term average behavior of the process when it reaches an equilibrium of transitions between different states. This describes the average behavior of the process and can be used for predicting dynamics and process behavior. An example of a steady-state analysis for a system with three states can be seen in Figure 50.

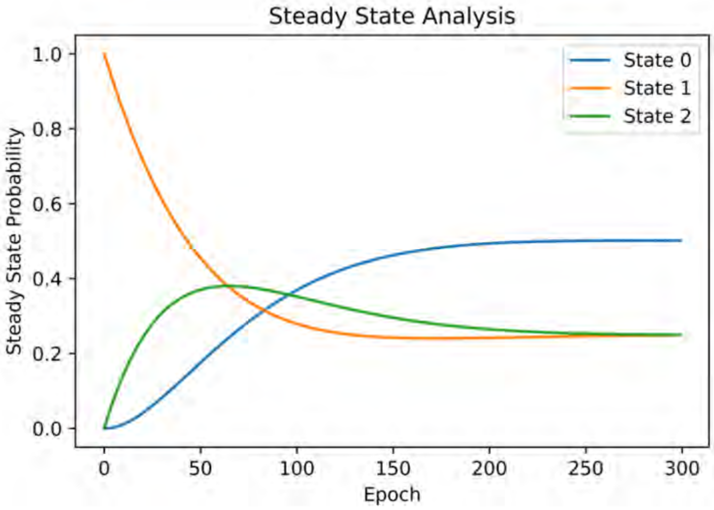

Figure **50**. Steady-state analysis example with three states.

To perform a steady-state analysis, the Markov process is used in mathematical computations that determine the probabilities of the process over an extended period of time. By identifying the equilibrium state of the process and the resulting probabilities of residing in each specific state, we can evaluate the cost of that process by assigning a cost to each state and multiplying those times the probability (or time spent) of being in each state.

There are several computational methods used for performing a steady-state analysis. The three methods we will use for this research are:

- *Direct Solution Methods.* These involve solving linear algebraic equations to derive the steady-state probabilities directly. These are commonly referred to as numerical solution methods (Stewart, 1995).
- *Iterative Methods.* An initial estimate of the probabilities is repeatedly refined to converge to the steady-state solution. For more detailed information on iterative and numerical methods, see the work by Bini and colleagues (2005).
- *Monte Carlo Simulations.* Through repeated random sampling, this method estimates outcomes. It's particularly valuable when the system is complex and deterministic methods are computationally intensive or infeasible. For more information about Markov processes and Monte Carlo simulations, see the work by Bremaud (2001).

Selecting the computational method relies on the characteristics of the specific Markov model. For example, while direct solution methods can be efficient for small systems, iterative methods might be preferred when dealing with larger and more complex systems due to the computation simplicity. On the other hand, Monte Carlo simulations can be best for systems where nondeterministic behaviors or nonlinearities exist, making conventional methods inadequate.

Through a steady-state analysis, we can develop an understanding of the equilibrium states and the respective probabilities of a stochastic process. This can lead to more informed decisions regarding system design, operational strategies, and performance metrics.

Influence Diagrams

In the context of process modeling, influence diagrams aid in capturing and analyzing the decision-making effects and dynamics of a system. Influence diagrams can be considered an extension of Markov models where uncertainty in the system model can be combined with decisions and values to evaluate how uncertainty can impact decision-making. These diagrams provide a graphical representation that illustrates the relationships and dependencies among variables, decisions, and outcomes within a process. By using decision nodes, uncertainty nodes, and value nodes, influence diagrams encapsulate the decision-making framework, allowing for an in-depth analysis of how different factors interact and affect the process outcome.

For example, in a nuclear power plant maintenance scenario, an influence diagram can be used to model the decision-making process for maintenance scheduling. Decision nodes may represent choices like scheduling immediate repairs or delaying maintenance for further assessment. Uncertainty nodes could encompass variables like the probability of equipment failure or the occurrence of unforeseen events affecting the maintenance timeline. Value nodes would then quantify the impact of these decisions and uncertainties, such as costs, downtime, or safety risks. A representative graphic of a similar scenario can be seen in Figure 51.

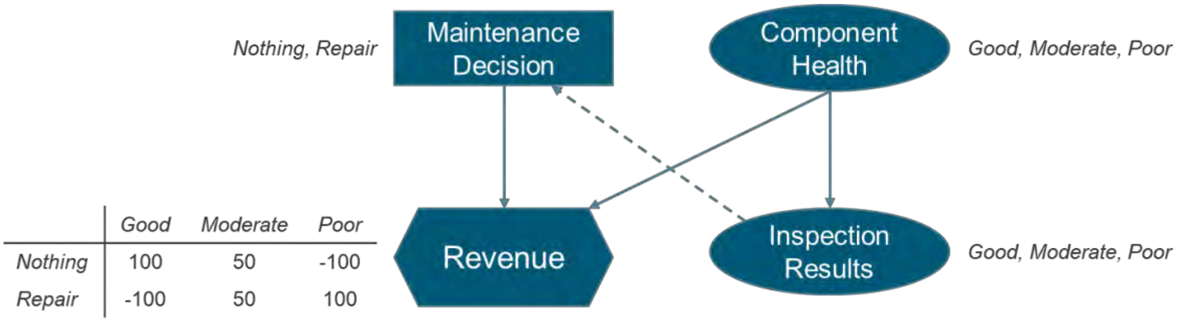

Figure **51**. Example influence diagram illustrating decision, uncertainty, and value nodes centered on a maintenance decision scenario.

Figure 51 depicts the component health states and their probabilistic influence on inspection outcomes. These outcomes subsequently guide the maintenance decisions, ultimately affecting the expected revenue.

By mapping out these elements, an influence diagram aids in visualizing the causal relationships and potential ripple effects throughout the system. This visualization enables stakeholders to identify critical factors that drive process outcomes and to evaluate the implications of various decision paths. The quantitative aspect of influence diagrams, facilitated by assigning probabilities and values to different nodes, supports a rigorous analysis of potential strategies. This analysis helps in determining the most effective approach to minimize risks, optimize performance, and achieve cost-effectiveness in the process.

Process Cost Estimation

Once the steady-state probabilities are identified, costs are assigned to each state to assess the average cost for that process. The steady-state probabilities are assumed to be the average time spent in each state over a long period of time. For example, a process with two states, A and B, may have an interaction where the probability of being in the states at any given time would be 0.25 and 0.75, respectively. For calculating the amount of time in each state, this means that 25% of the year will be spent in State A while 75% of the year will be spent in State B.

To identify the time spent in each state during a given time period, each probability is multiplied by the total time available. Continuing the same example, the time spent in each state over a period of $T = 1{,}000$ hours can be calculated as:

$$T_A = P(A) \times T = 0.25 \times 1{,}000 = 250 \text{ hours}$$

$$T_B = P(B) \times T = 0.75 \times 1{,}000 = 750 \text{ hours}$$

To calculate the cost for this process, hourly costs can be assigned to each state. If the costs for each state are \$10/hour and \$5/hour for States A and B, respectively, the total costs for each state can be calculated:

$$C_{Total} = C_A T_A + C_B T_B$$

$$C_{\text{Total}} = \left(\frac{\$10}{\text{hour}}\right)(250 \text{ hours}) + \left(\frac{\$5}{\text{hour}}\right)(750 \text{ hours})$$

$$C_{\text{Total}} = \$6{,}250$$

Now that the method for estimating the total cost of the process is established, it can be used to calculate the cost of a new process. By altering the Markov model or the parameters according to the WRO solution, the new cost after implementation can be calculated. By comparing the total cost for each process over a given time span, the WROs can be compared for cost savings.

Sensitivity Analysis

A sensitivity analysis is a method for quantifying how changes in one parameter affect the output variable. By doing so, the importance of each parameter can be identified. Additionally, a sensitivity analysis can be used to quantify the effect that parameter uncertainty has on the output. This process helps to identify the expected outcome for a range of parameter values.

Using a sensitivity analysis, the impact of changing parameters can be quantified and used for risk mitigation or resource allocation. The values with large uncertainties or large impact are identified and can be reviewed for further investigation. This will allow utilities to focus on the model parameters that have the greatest impact on cost.

A sensitivity analysis has four main advantages in the context of TERA:

- *Risk Assessment.* By understanding which variables most affect the output, decision makers can understand where the biggest risks lie
- *Resource Allocation.* Knowing which parameters are most influential can help in focusing efforts and resources
- *Model Validation.* If the model shows high sensitivity to parameters believed to be less influential based on empirical data or expert opinion, it may indicate that the model is not accurate or needs refinement
- *Uncertainty Quantification.* In cases where the exact parameter values are unknown, a sensitivity analysis can help to understand how this uncertainty translates to uncertainty in the outcomes.

A sensitivity analysis can help decision makers evaluate the interactions between model and process parameters and their business impact, providing a quantitative prioritization for resource allocation.

3.2.4.2 Human-in-the-Loop Simulation

Simulators can serve as valuable test beds for evaluating or validating aspects of operations that support control room modernization efforts or the validation of new concepts of operations using human-in-the-loop simulations (Section 2.3.1.4; Gideon and Boring, 2023). Human-in-the-loop simulations are used for a range of activities, including to support system tests and evaluations, as well as to explore academic and applied HFE research where control room concepts can be applied and validated.

Many studies completed in the HSSL at Idaho National Laboratory have supported both endeavors. For instance, the HSSL has been used to compare the current and future states of nuclear power plants currently undergoing control room modernization efforts (e.g., Sections 2.2.3.2 and 2.2.4). It has also been used to evaluate impacts to the concept of operations when adding new plant functions and capabilities, such as with an integrated energy system that not only utilizes the energy produced by the nuclear power plant for electricity generation but also for hydrogen production (e.g., Ulrich et al., 2020). The HSSL is fully reconfigurable to represent different nuclear power plant control room concepts and is capable of modeling normal, abnormal, and emergency plant conditions.

Human-in-the-loop simulation provide researchers and industry partners with direct observations of how operators interact with the current and future states of the control room. Early design issues can be discovered early in the project lifecycle to improve insight into arraignment, manufacturing, and operational issues throughout the design process. Additional measures, such as usability, workload, and situation awareness, can be collected during human-in-the-loop simulations to evaluate the current and future states of operations. Scenarios are evaluated during simulator studies to measure whether tasks are able to be completed successfully. Simulations can be modeled to simulate the task flow and procedures, running the task in real or fast time to find if operators encounter issues, errors, or high workload conditions. Test plans are then developed by HFE professionals to set up measures to evaluate how operators interacted with the current and new proposed systems. Collecting operator performance data is essential to understand how operators interact with the current and new proposed systems.

Low- or high-fidelity simulations can be created to test out early design concepts in parallel with design engineering activities. This helps to verify that the task requirements are being met throughout the design. Lower fidelity activities can be used to test out new design concepts, such as testing new HSI displays being developed to identify if any issues are present (e.g., Section 2.2.1.2). Higher fidelity simulations can be used towards the end of the project to further support quantitative validation activities to support preliminary validation and ISV for the proposed new designs (e.g., Section 2.2.4).

3.2.4.3 Human Performance Models

Human performance models are useful tools that can help predict the analysis and modeling of user actions and tasks for current and new planned upgrades in nuclear power plants in the absence of actual users. The objective of the human performance model review is to verify a process is available to ensure that no safety degradation would occur based on the changes being made to the plant (O'Hara, 2009). Many human performance measures can be modeled, such as:

- Response time
- Workload
- Salience or prominence of alarm signals
- Effect of visual, audio, or a combination of signals on situation awareness
- The effect of signal redundancy on response time.

SMEs are an essential source of information in model development by providing information on tasks and procedures in order to develop a methodology to measure human performance during human-in-the-loop simulations. Physical and cognitive models can be developed to measure and validate human performance characteristics early and throughout the design process and are discussed in the following sections.

Physical Models

Physical human performance models focus on human physical characteristics, such as physiological dimensions, capabilities, and limitations, which lead to several areas of study, including anthropometrics, ergonomics, and biomechanics (Urbanic and Bacioiu, 2013). Modeling human performance is essential to understand where limitations may occur in a design, such as an operator not being able to perform critical human actions in the allotted time allowed. By modeling anthropometrics, biomechanics, and ergonomics in a control room simulation, researchers can observe how operators would move and interact with controls in the control room during human-in-the-loop simulations. Human performance data can then be collected from researchers' direct observations or using human monitoring tools (e.g. keyloggers, screen recorders, and other tools).

Cognitive Models

Cognitive models are useful for modeling human performance to understand mechanisms that underlie and model human behavior when performing tasks. There are several cognitive human performance models used to understand visual input, physical output, memory, problem-solving, and decision-making (Urbanic and Bacioiu, 2013). Cognitive human performance models are also useful to evaluate human-computer interactions by breaking down tasks into simplified actions to consider how performance varies from one person to another (Urbanic and Bacioiu, 2013). The following section will discuss several cognitive human performance models and how they are used in nuclear power plant evaluations.

GOMS

The Goals, Operators, Methods, And Selection (GOMS) rules methodology uses a top-down approach for decomposing tasks, starting with the user's goals and breaking them down into subgoals (Kovesdi and Joe, 2019). Goals represent high-level tasks the user seeks to complete, operators are the actions the human can take, methods are the steps or subgoals to the human task for task completion, and selection rules relate to the decisions the human can take (Boring and Rasmussen, 2016). GOMS was originally developed as a task analytic tool for modeling behavioral primitives of HSI users (Boring, Ulrich, and Rasmussen, 2018). GOMS also shares some similarities with task analysis by breaking down human actions into a series of subtasks (Boring and Rasmussen, 2016). This approach has been generalized in many HFE HSI evaluation methods to model proceduralized activities. One limitation of this method is that it is time consuming and labor intensive to model.

HUNTER

Human Unimodel for Nuclear Technology to Enhance Reliability (HUNTER) is a dynamic HRA method. Dynamic HRA operates at the task level rather than the HFE level. HUNTER is being used to quantify human error probabilities using GOMS-HRA (GOMS-Human Reliability Analysis). GOMS has traditionally been used to evaluate HSI applications and is now being adapted to HRA (Boring, Ulrich, and Rasmussen, 2018). The GOMS-HRA method is used to provide a taxonomy of task-level primitives to activities that correspond to human error probabilities and task timing (Boring, Ulrich, and Rasmussen, 2018). In HUNTER, human activities are modeled at the subtask level for activities that do not feature formal written procedures. The HUNTER method is looking at ways to extract task-level errors from procedure steps to modify their influence using performance-influencing factors. HUNTER has not resolved the subtask error issues yet; however, additional research is being conducted to address the issues and create greater consistency using the method.

IDHEAS

The Integrated Decision-tree Human Event Analysis System (IDHEAS) is an HRA method used to reduce variability and improve estimates of human error probabilities (NRC, 2012). IDHEAS is used to address cognitive aspects of human behavior with a qualitative analysis (Liao et al., 2013). A framework of 14 crew failure modes (CFMs) are used in IDHEAS to represent human failures found in nuclear power plants (Liao et al., 2013). Decision trees are then constructed for each CFM to determine probabilities of the CFM occurring within different contexts within the decision tree.

Keystroke-Level Model

Keystroke-level models (KLMs) are used to model a set of primitives to show skilled users interacting with a computer system in an error free manner to understand time needed for keystrokes and mouse clicks (Kovesdi and Joe, 2019). The application of KLMs focuses on execution times of keystrokes and mouse clicks to predict an overall predicted task time. An example of how KLM is used in HSI modeling is observing the time it takes a trained operator to find a control on the HSI display. There are some disadvantages when using the KLM model, such as that KLM assumes primitives are sequential and there is a set order for task completion and some KLM primitives may be too general to capture differences between HSI display concepts.

CogTool

CogTool is a method that uses an open-source program to expand the KLM model approach to make more precise predictions (Kovesdi and Joe, 2019). This method can be used with the HSI modeler to generate storyboards in the HSI of the tasks under evaluation to develop quantitative predictions with imported HSI design requirements into the tool (Kovesdi and Joe, 2019). One advantage of CogTool is that it can build models through point and click storyboards efficiently to allow for rapid HSI prototyping. Another advantage of CogTool is that it has minimal training requirements, which allows for more rapid storyboards to be built efficiently. CogTool uses predicted task times that are within 20% of the observed human performance times to present the range of predicted performance. Some limitations with CogTool are that it may not be as reliable to determine whether a design is faster than another to use, that CogTool applications only apply to computer-based interactions, and that it cannot model interactions with physical controls.

Cogulator

Cogulator is an open-source program that uses GOMS to generate predicted task times (Kovesdi and Joe, 2019). Working memory load and mental workload are also predicted with the tool. Cogulator provides a comprehensive functionality when modeling HSIs for nuclear power plant HSI evaluations. Cogulator contains predefined primitives based on KLM, GOMS, and other frameworks. Models in Cogulator are capable of modeling multitask activities, workload estimates, and interactions with physical controls and provide access when adding additional primitives into the model. One advantage of Cogulator is its flexibility with modeling due to built-in primitives. Cogulator also provides a timeline visualization of primitives used along with a map of working memory impacted during tasks. Some limitations of Cogulator are that it has a harder learning curve when creating models and that model creation can be tedious when having to add information in a syntax-based design.

3.2.5 Combining Approaches: A Multimethod Systems Thinking Approach

A central theme in Section 3.2 and its subsections is that addressing HTI in large-scale modifications of a nuclear power plant requires not only considering the risk potentials of specific components but also their interactions and potential emergent risks that come with these interactions. As such, Section 3.2 presents a set of recently developed systems thinking methods grouped across four types of approaches. Looking at these methods, there are clear differences in their execution and, perhaps more importantly, their theoretical bases and resulting underlying assumptions. For example, STAMP-based methods are largely driven by control theory, whereas AcciNet and Net-HARMS follow a task-centric perspective; a cognitive task analysis focuses on specific cognitive tasks required of agents in the SOI whereas a cognitive work analysis begins at the underlying constraints of the work domain.

In the analysis and design of complex systems, like a nuclear power plant, it is important to note that there are multiple layers of analysis that can be undergone, such as with the equipment and hardware, data and applications, personnel interactions, and even the organization. As such, the systems thinking methods address this scaling challenge by developing SOI models that each have their own unique theoretical perspective (Salmon and Read, 2019). These models can be described as a reduced-order representation of a nuclear power plant that can be applied to systematically identify existing design deficiencies, to understand the work system, or predict or forecast risk modes at each layer, or to simulate the behavior of a process or activity for evaluation purposes.

There are definite advantages and disadvantages to each method presented in this technical report. However, to leverage the advantages of these methods and to reduce the impacts of their limitations, we suggest that the thoughtful combination of multiple methods to analyze, design, and evaluate complex systems like a nuclear power plant should be done to the extent practical. The combination of multiple systems thinking methods is described as a *many model systems approach* (Salmon and Read, 2019). It has the advantage of providing a concurrence of specific insights (i.e., triangulation), while also providing unique details using each different method to provide a deeper understanding of the SOI. So rather than portraying the different systems thinking methods as competing with one another, the many model systems approach views them as complementary. Figure 52 illustrates this viewpoint.

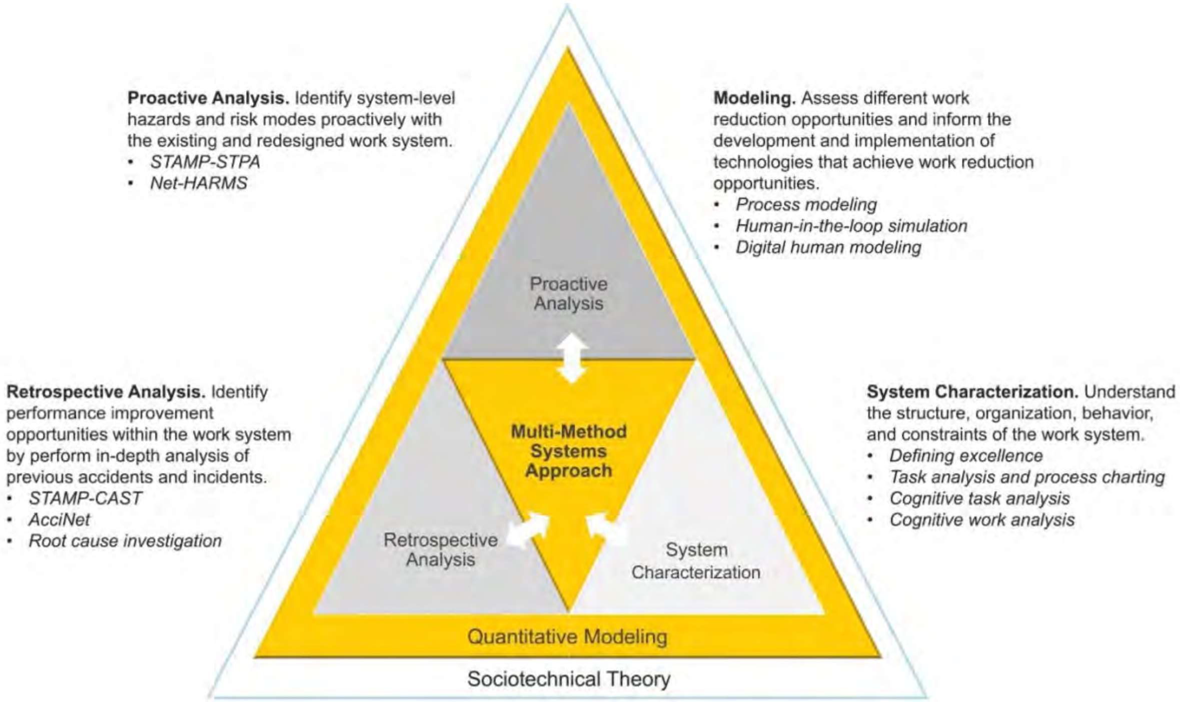

Figure 52. Systems thinking methods toolbox framework following a multimethod approach to enable triangulation.

Figure 52 forms the basis of a systems thinking methods toolbox framework. It communicates that, to obtain a deeper understanding of the work domain in order to make meaningful changes that support joint optimization, the application of multiple systems thinking methods previously described should be considered to the extent practical. The advantage of such an approach allows the WROs to be informed from past events and by anticipating potential risks when integrating the WROs. It also enables the modernization team to have a deep understanding of the work domain requirements, including the goals, functions, success criteria, key decisions, and information needed to perform work. Finally, it allows for a dynamic simulation of system or process behavior to evaluate potential impacts on safety or productivity to enable work optimization. Indeed, the systems thinking methods toolbox is a key element to the extended HTI methodology and is described in Section 4.

4. HUMAN-TECHNOLOGY INTEGRATION TASK FORCE FOR WORK OPTIMIZATION METHOD: HITT

The following section describes the extended HTI methodology to support work optimization, herein referred to as HITT. The following sections are used to describe this extension to the HTI methodology:

- Section 4.1 provides an overview of HITT.
- Section 4.2 presents key features of HITT, illustrating how these features enhance work optimization.
- Finally, Section 4.3 describes HITT in detail.

4.1 Overview of HITT

HITT is an extension from the HTI methodology described in INL/EXT-21-64320 to support work optimization. It follows a systems thinking approach and is meant to be used within a broader systems engineering effort for large-scale digital modifications at a plant or fleet level. With this, HITT is tightly integrated with existing LWRS Program research areas, particularly with TERA. HITT provides a key element within TERA to address macro- and microlevel HTI considerations with modernizing an existing nuclear power plant or fleet of plants. As such, HITT provides a means to evaluate the human readiness (i.e., the extent that a solution can be safely used) and organizational readiness (i.e., the extent that the organization is ready to embrace change) of a potential solution within a broader context of evaluating the total readiness of the solution, which also includes digitalization readiness (i.e., the extent that an organization is prepared to digitalize), technology readiness (i.e., the maturity of the technology), and solution effectiveness (i.e., the extent that the solution effectively reduces costs without unacceptable risks; Figure 53).

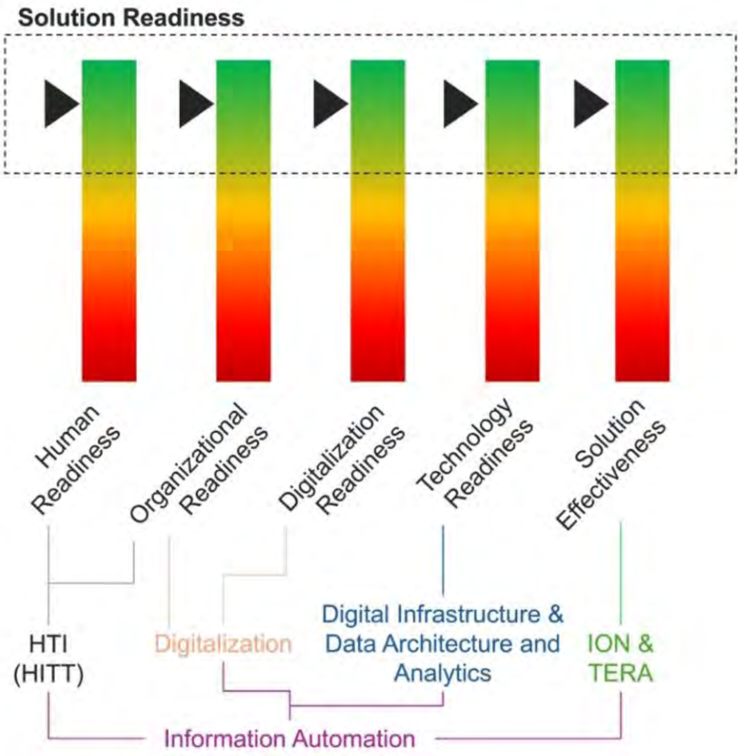

Figure 53. Solution readiness scorecard conceptualization.

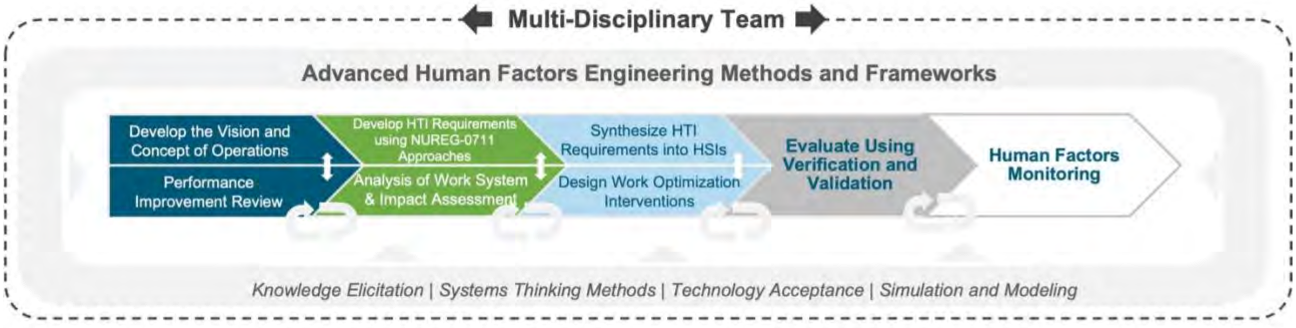

Figure 54. Extended HTI methodology using HITT.

This extension to the HTI methodology is illustrated in Figure 54. Notable updates are seen in the first three phases (i.e., as indicated in teal, green, and light blue of Figure 54). Main control room modernization HTI activities are illustrated in the top portion of these phases; the guidance described in Section 2.2 corresponds to these activities. HITT, which is applied across other WROs beyond main control room modernization, is illustrated in the bottom portion of these phases, including:

- *Performance Improvement Review.* The purpose of this phase is to begin identifying WROs of greatest impact, to assemble a multidisciplinary team, and then to perform a detailed knowledge elicitation analysis of the SOI to identify gaps in current work processes when comparing WAI to WAD.
- *Analysis of Work System and Impact Assessment.* The purpose of this phase is:
    - To characterize the SOI, including identifying key functions, impacted staff, defining roles and responsibilities, and tasks performed
    - To identify and evaluate potential WROs, system risk modes, and "leverage points" for work optimization using qualitative and quantitative methods that compare the existing SOI to the SOI with proposed interventions.
- *Design Work Optimization Interventions.* This phase includes developing interventions to support work optimization and takes a broader approach when compared to design synthesis in main control room modernization, as potential innovations identified may span beyond HSIs, such as the use of drones, AI/ML, or even work process changes. In any case, where HSIs are within scope, the HTI approaches used in main control room modernization can be leveraged if deemed appropriate (e.g., developing an HSI style guide or performing design tests using a glasstop simulator), following a graded approach.

4.2 Key Features of HITT

There are three key features of HITT that enable a rich understanding of the SOI and work domain and identify high-value improvements that will improve safety, reduce cost, and increase worker satisfaction:

- *Knowledge Elicitation.* First, following the lessons learned in Section 2.3, HITT emphasizes knowledge elicitation early in the process to understand how work is intended to be performed (i.e., WAI), how work is actually performed (i.e., WAD), the modernization vision, and potential gaps between WAI and WAD. Knowledge elicitation is achieved by engaging domain experts throughout the "DERIVE" process, which includes the following steps: Define new state vision for work management, evaluate department performance factors, review relevant performance information, interviews of stakeholders, valuate current organization digitalization level, end-state gap analysis (DERIVE). The rich data that comes from the DERIVE process forms the basis of the subsequent HTI and TERA analyses within HITT, minimizing the number of assumptions needed to identify work system risks and WROs and model system behavior.

- *Rich Data Sources.* DERIVE develops a rich understanding of the work domain and opportunity space through the review of multiple data sources, including multiple databases, utility documents, and validated survey instruments and interviews.
- *Systems Thinking Methods Toolbox*. HITT leverages the use of advanced HFE and HTI frameworks to gain a deep understanding of the SOI via triangulation, primarily through the use of the systems thinking methods presented in Section 3.2.

4.2.1 Knowledge Elicitation of the Work Domain Through DERIVE

Nuclear power plants generate many KPIs for accurately measuring overall performance of the nuclear power plant, as well as to measure the performance of a specific work domain. It is the simple truth that there is always a disparity between actual performance and indicated performance of anything that is measured. The smaller the disparity, the harder it is to detect using conventional measurement methods.

In order to accurately measure work domain performance, many dimensions must be evaluated so that, when there is a deviation from expected performance, appropriate actions can be taken to close the identified gap in performance. If the proper parameters are measured, the cause of the deviation is properly identified, and the correct actions are taken, the deviation can usually be corrected relatively quickly. However, there are many factors that can cause a deviation, with some being easier to measure than others.

The design basis of the knowledge elicitation process or DERIVE process is to perform a “deep dive” into the subject work domain using both objective performance data and subjective information to identify as many factors affecting performance as possible. This way, gaps can be identified and improvements can be proposed that will help to achieve excellence in whatever work domain is being evaluated. More details for the methodology employed by the DERIVE process are included later in this section.

4.2.2 Data Sources for DERIVE

To conduct a thorough analysis and quantification of the plant processes, it is imperative to integrate data from diverse sources. Each data source provides unique insights that contribute to a holistic understanding of the plant's operations, efficiencies, and potential areas for improvement. The following data sources can be employed during analysis:

- *Controlled Records and Process Documents.* This includes operational manuals, process flow diagrams, standard operating procedures, safety protocols, and engineering drawings. These documents are crucial for understanding the designed operational framework, technical specifications, and safety standards of the power plant. They facilitate the identification of discrepancies between planned and actual operations, helping to pinpoint process optimization opportunities and enhance safety and efficiency.
- *Expert Opinion.* Consulting with industry experts and experienced personnel within the plant is a cornerstone of a process analysis. Individuals bring a wealth of knowledge and insight into the plant's operations, potential bottlenecks, and areas of risk. Their qualitative assessments will be instrumental in validating data-driven findings and offering context to numerical analyses.
- *Surveys.* Surveys can be conducted among plant employees and stakeholders to gather subjective data on various aspects of plant operations. This may include satisfaction with current processes, identification of perceived inefficiencies, and suggestions for improvement. Surveys uncover leading indicators of future performance and help identify the human factors influencing plant performance, as well as capturing the collective experience of the workforce.
- *Employee Time Tracking.* Data on how employees allocate their time across different tasks and processes will be critical in quantifying labor efficiency and identifying potential areas of process improvement. This information will also assist in understanding workflow patterns, peak operational periods, and resource allocation.

- *Accounting.* Financial records and accounting data will provide insights into the economic aspects of the plant processes. This includes costs associated with operations, maintenance, procurement, and other financial transactions. Analyzing these data will enable a thorough cost-benefit analysis of different processes and provide insights on the importance of those processes to plant leadership, through an analysis of the allocation of funds. This will be fundamental in identifying cost-saving opportunities and the organizational readiness to implement those improvements.
- *Incident Reporting.* Incident and event reports can be analyzed to identify patterns and trends in plant safety and operational risks. This data is crucial for understanding past failures, compliance with safety regulations, and areas requiring preventative measures to mitigate future risks. Analyzing the distribution of the incident reporting also provides insights as to how well the reported data represents the actual performance and health of the organization, especially when compared to the breakthrough events that have occurred.
- *Process Tracking.* Real-time and historical data on process performance will be essential for quantifying the operational efficiency of the plant. This includes data on production rates, equipment performance, maintenance schedules, and process bottlenecks. By tracking and analyzing these data, we can identify trends, forecast future performance, and recommend optimizations for process improvements.
- *Maintenance Records.* Detailed records of maintenance activities, including scheduled and unscheduled maintenance, repair histories, and downtime statistics, are invaluable for analyzing the reliability and performance of plant equipment. This data helps in identifying trends and patterns in equipment failures, maintenance efficiency, and the overall impact on plant operations.
- *Supply Chain and Inventory Data.* Information related to the supply chain and inventory levels is crucial for understanding the logistics and material flow within the plant. This includes data on supplier performance, lead times, inventory turnover, and stockout incidents. Analyzing this data can highlight potential vulnerabilities in the supply chain and opportunities for optimization.
- *Energy Generation Data.* Monitoring and recording energy generation can provide insights into the plant's operating efficiency with respect to plant processes that may lead to generation loss. These data are essential for assessing the impact of the plant operations and for planning initiatives and investments.
- *Regulatory Compliance Data.* Records of compliance with industry standards and regulatory requirements are crucial for understanding the legal and regulatory landscape in which the plant operates. This includes data on inspections, audits, and compliance incidents, which are important for managing legal risks and ensuring operational compliance.

Together, these data sources will provide a comprehensive view of the plant's operations, enabling a robust analysis and quantification of the processes. The integration of qualitative and quantitative data will ensure a well-rounded approach to identifying efficiencies, understanding operational dynamics, and proposing actionable insights for process optimization.

4.2.3 Systems Thinking Methods Toolbox

A third feature of HITT to support work optimization is the *systems thinking methods toolbox*. This toolbox leverages the systems thinking methods described in Section 3.2 following a multimethod approach. *Retrospective analysis* approaches are used to support learning from past events to better inform system design. *System characterization* approaches are used to describe the SOI's goals and functions, understand WAI and WAD, and identify cognitive and communication requirements of the SOI based on a conceptualized assignment of function. *Proactive analysis* approaches are used to "forecast" potential system risks and identify leverage points for work optimization with an existing system, as well as the proposed redesign. Finally, *modeling* approaches are used to analyze the behavior and dynamics of complex systems over time (i.e., including economic performance, time, or cognitive processes). The systems thinking methods toolbox is presented in Figure 55.

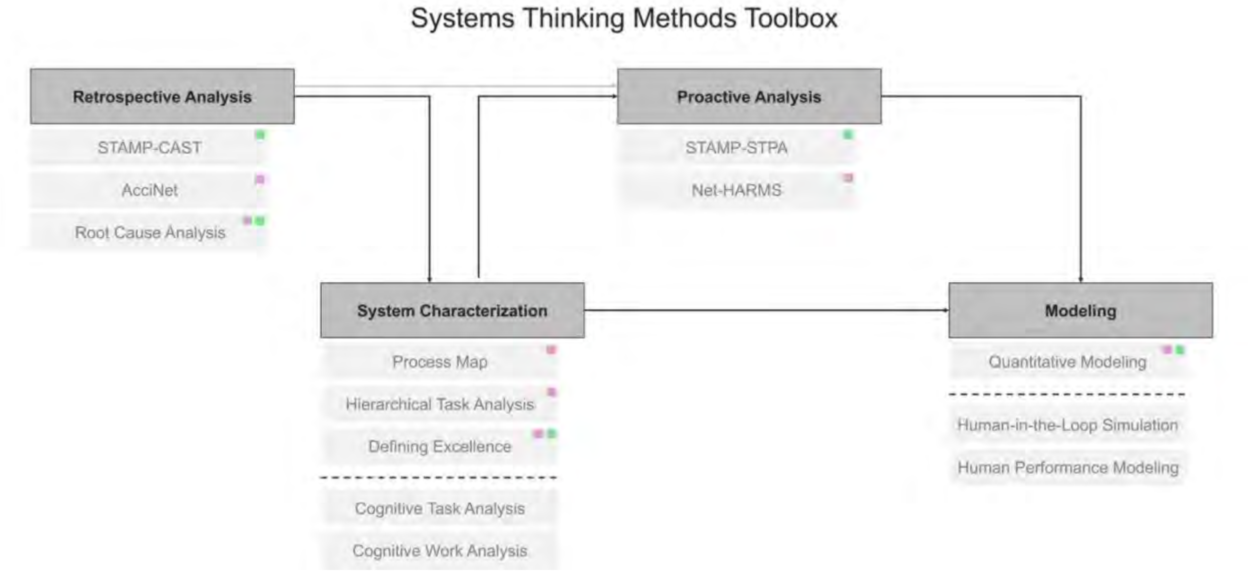

Figure 55. Systems thinking methods toolbox for HITT.

The four types of systems thinking approaches are indicated in dark gray. The use sequence for each method type is indicated by the dark gray arrows, beginning with retrospective analysis. The light gray arrow connecting retrospective analysis with proactive analysis represents a secondary use sequence in which proactive analysis follows retrospective analysis. Specific methods are presented in light gray below each type of systems thinking approach. For each method, "pairing" between potential approaches is mapped using the green and violet tags collocated in each method. Finally, methods underneath the dashed dividers represent systems thinking methods that may be supplementary but not central to HITT. These approaches (e.g., cognitive work analysis) can enrich system characterization but should be considered at the discretion of the project.

With this, there are two potential paths that can be followed using the systems thinking methods toolbox. On one path, STAMP-based methods can be leveraged including CAST and STPA. These methods require an analyst to be versed in STAMP but can be scaled to other uses, such as with information automation (Joe et al., 2023). The second path follows the task-based approaches, including AcciNet and Net-HARMS. These approaches leverage task analysis outputs, such as process charts or HTA. Other methods can be applied in either path (e.g., RCA). A final point worth mentioning is that both paths can be applied if practical. Using both proactive and retrospective methods together helps to build the most complete understanding of the SOI by leveraging the unique qualities of each method.

4.3 Detailed HITT Process

Figure 56 presents the detailed HITT process. There are 10 steps in applying HITT. These steps are presented across four generalized activities, including performance improvement review, analysis of work system, innovation impact assessment, and design interventions.

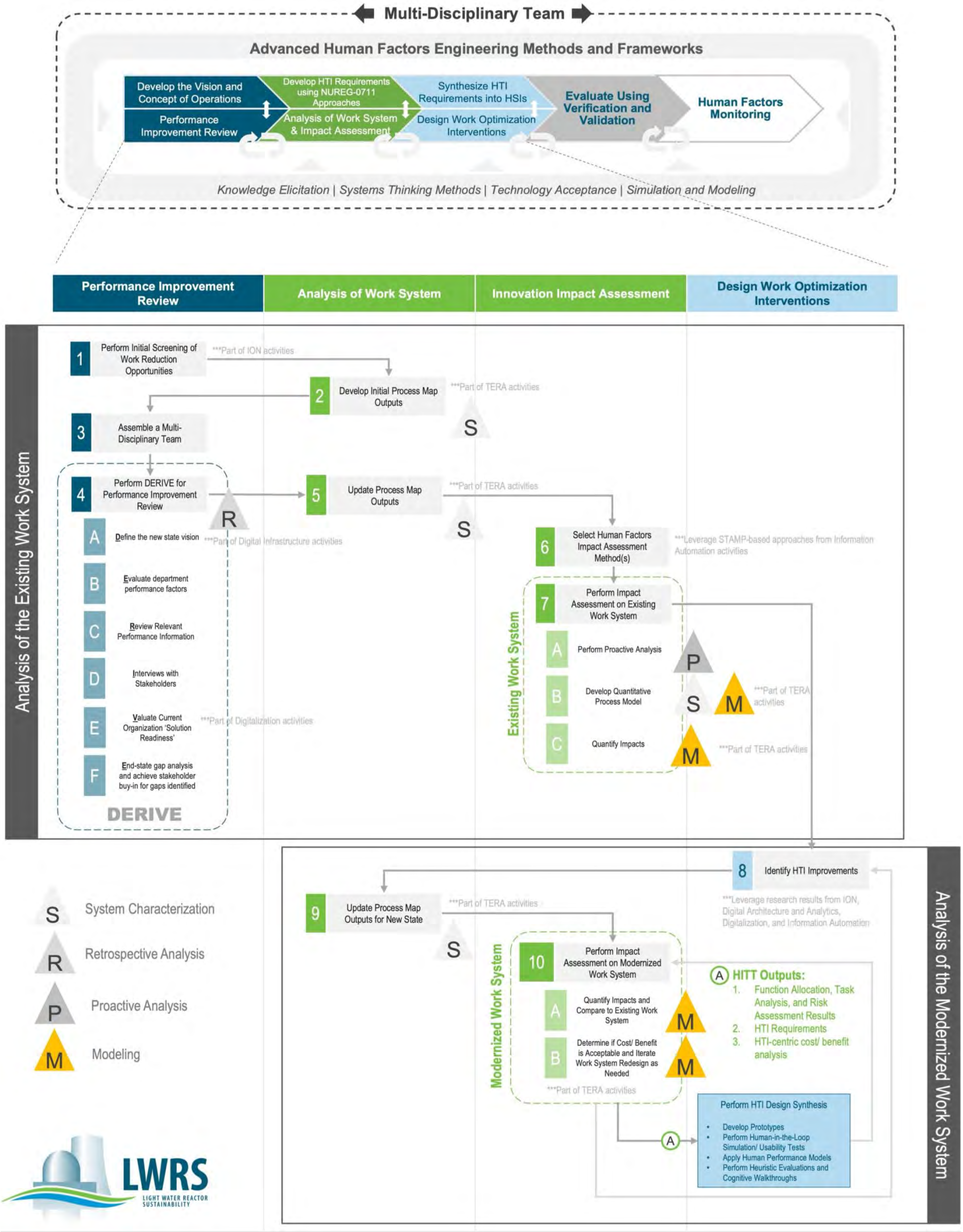

Figure 56. Detailed HITT process overview.

The colors of these activities correspond to the phases of the HTI methodology (Figure 54). Where systems thinking methods can be applied, a symbol (e.g., "R" for retrospective analysis) is indicated by the step or substep. For instance, in the case of applying retrospective analysis, systems thinking methods like STAMP-CAST, AcciNet, or RCA can all be used. Another important element of the HITT process is that some steps also correspond to key activities from other LWRS Program research areas. For example, Step 1 corresponds to an ION activity. As such, HITT assumes a multidisciplinary approach is followed. A final point to mention is that HITT can be best leveraged early in the project lifecycle, specifically when scoping and during conceptual design; this is indicated at the top of Figure 56.

The remaining subsections describe each step in greater detail, providing practical guidance with detailed supplementary information where necessary. Each step contains a graphical summary following the format of Figure 9. These graphical summaries contain navigation to the HITT quick guide location in the Executive Summary of this technical report

4.3.1 Step 1. Perform Initial Screening of Work Reduction Opportunities

Figure 57. Step 1 of the HITT process.

Practical Guidance: In the first step, WROs are presented to an objective screener, typically through structured interviews. The goal for the screener is to assimilate comprehensive insights within a set timeframe, focusing on understanding the nuances of the processes under review. These conversations aim to extract valuable insights from the operational experiences, identify the core challenges faced, draft an initial outline of the current process flow, and provide initial insights that can be used later on when determining organizational readiness for potential HTI improvements. At this initial stage, gaining an understanding of the organization's approach to benchmarking their performance against other organizations is important, as the way organizations define and measure their performance will shape what KPIs they use and how effective these KPIs are as an actual performance assessment.

Supporting Information: Plant personnel will often know potential improvement areas or inefficiencies through experience. When potential WROs are already known, the initial screening process becomes more focused and strategic, aiming to validate and further investigate these opportunities. However, not all WROs will provide easy access to investment returns and must be initially screened for complexity, feasibility, and cost-benefit.

- *Review of Identified WROs.* Start with a detailed review of the preidentified WROs to understand the context and basis of their identification, including the data and assumptions used. This step ensures that each WRO is grounded in accurate and current operational insights.
- *Stakeholder Engagement.* Engage with stakeholders involved in the identified WROs, such as technical staff, process owners, and management, to validate the WROs' relevance and gather

additional details. This engagement helps in refining the understanding of each opportunity and its potential impact on operations.

- *Selection of Process Champions.* For each WRO, appoint process champions who have the necessary expertise and authority to lead the analysis and implementation phases. These champions will be responsible for driving the project forward, ensuring a focused and effective approach to exploring and realizing the work reduction potential.
- *Documentation and Reporting.* Document the outcomes of the initial screening, detailing the validated WROs and the insights gained from stakeholder discussions. This documentation forms the foundation for the next stages of analysis and sets the stage for detailed exploration and planning.

This targeted screening approach ensures that the analysis and subsequent actions are concentrated on the most promising WROs, facilitating a more efficient and effective optimization of the plant's operations.

4.3.2 Step 2. Develop Initial Process Map Outputs

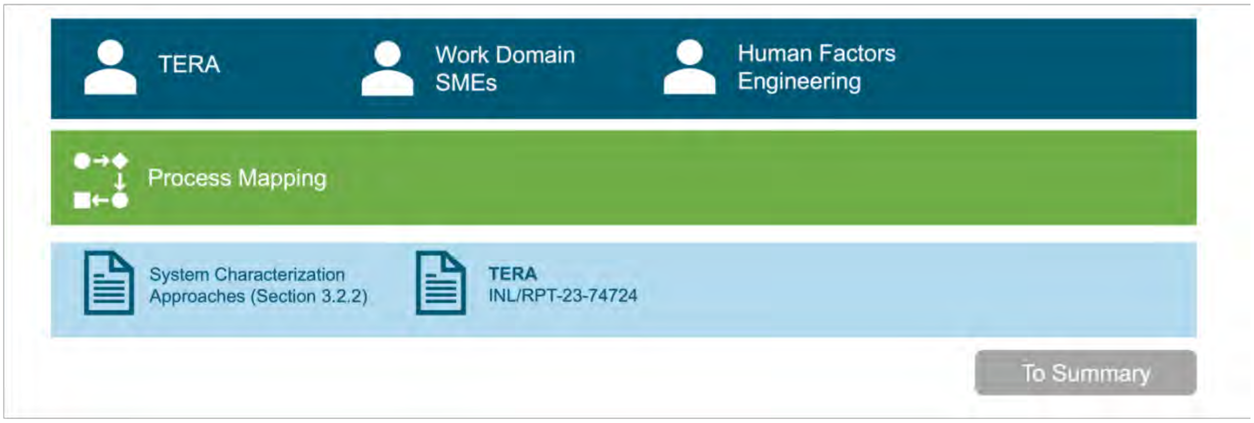

Figure 58. Step 2 of the HITT process.

Practical Guidance: In the second step, the focus shifts to developing initial process map outputs for the screened-in WROs (e.g., Section 3.2.2.3). This involves creating visual representations of the current processes to identify inefficiencies, redundancies, and bottlenecks. The process maps should be detailed enough to facilitate a clear understanding of each process step and its interrelations with other steps.

Supporting Information: Developing initial process map outputs is a critical step to understand the existing workflows and serves as the basis for identifying and prioritizing WROs. These maps not only provide a visual aid for comprehending complex processes but also serve as a communication tool to facilitate discussions among stakeholders. Furthermore, the process maps can help in identifying KPIs that are crucial for monitoring the performance and success of the implemented changes. Benefits include:

- *Creation of Detailed Process Maps*. Utilize the insights and data gathered during the initial screening to construct detailed process maps. These maps should illustrate each step in the process, the flow of information and materials, data sources, and decision points along the process chain.
- *Identification of Inefficiencies*. Analyze the process maps to identify areas of inefficiency, such as unnecessary steps, duplications, or points where delays commonly occur. Highlighting these areas is crucial for pinpointing where improvements can be made.
- *Identification of KPIs*. Define KPIs that are directly linked to the process efficiencies and organizational objectives. These indicators should be specific, measurable, achievable, relevant, and time-bound to effectively monitor and evaluate the impact of implemented WROs.

- *Baseline Performance Measurement*. Establish baseline metrics for the current processes to measure performance and identify areas for improvement. This will facilitate the comparison of pre- and postimplementation performance.

To effectively measure the impact of the work optimization initiatives, it is essential to identify relevant KPIs that align with the organizational goals. These KPIs should follow the SMART format (Doran 1981):

- *Specific*: Clearly defined and related to the process and can be measured and influenced
- *Measurable*: Quantifiable to track progress and compare against benchmarks or targets
- *Achievable*: Realistic in terms of the organization's capabilities and resources
- *Relevant*: Directly related to the operational improvements and organizational goals
- *Time-bound*: Associated with specific time frames to assess performance changes over time.

By establishing KPIs, the organization can monitor the effectiveness of the WROs, make data-driven decisions, and continuously improve process efficiency and effectiveness.

4.3.3 Step 3. Assemble a Multidisciplinary Team

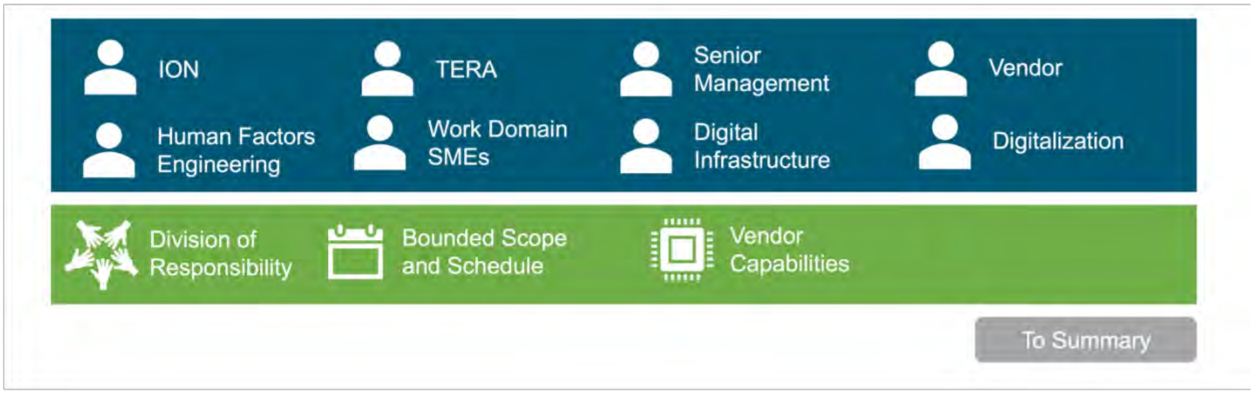

Figure 59. Step 3 of the HITT process.

Practical Guidance: A multidisciplinary, cross-functional team is needed to support the execution of the remaining HITT steps. The team composition should include at least the following stakeholders:

- End users (e.g., operations, training, engineering, maintenance, etc.) of the SOI (i.e., they will participate in verifying the accuracy of technical outputs of HITT)
- An SME in the work domain in question
- Stakeholders in the technical domain(s) of interest (e.g., engineering, AI/ML)
- HFE professionals
- TERA professionals
- Vendors (i.e., if selected).

Supporting Information: The purpose of a multidisciplinary team is to provide a comprehensive view of the SOI such that each technical discipline's unique expertise can be leveraged to assess the accuracy of the process maps, as well as vet that potential solutions are practical and effective. Key points of contact from each stakeholder cohort should be identified. With this, having SMEs with considerable experience in the work domain in question is highly valuable. The SME should work closely with the core team of HFE and TERA professionals. The SME will be able to "talk the talk" with other stakeholders of the work domain, as well as provide useful insights to those less familiar with the work domain.

There should be effective collaboration within the team and a clear division of responsibility between stakeholders (Kovesdi et al., 2022). A final point worth mentioning is that each stakeholder should be aware of the value that the HITT process will provide to them, especially for end users of the SOI. Once its value is communicated and understood by the team, it's likely that there will be greater engagement across key activities, which is important for the success of HITT.

4.3.4 Step 4. Perform DERIVE for Performance Improvement Review

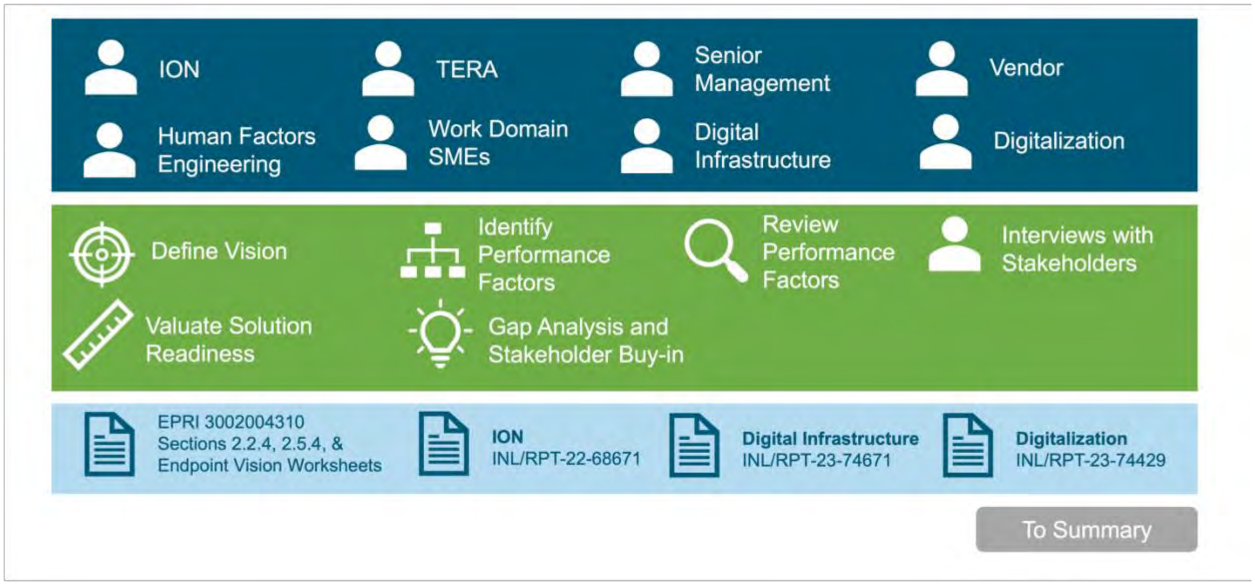

Figure 60. Step 4 of the HITT process.

In order to optimize the HTI of a particular work domain, gaps in excellence or at least in a new state vision in one or more areas need to be identified. These gaps need to be significant enough that there will be adequate ROI for the costs and efforts of the design and implementation of the new improvements. The ROI may be achieved in savings that can be directly measured or in latent gains, such as event avoidance and gains in regulatory margin due to more resilient control structures, and improved equipment reliability.

Therefore, the elicitation of the current status and efficacy of the subject work domain is necessary through a methodical process that reviews all factors that impact or control that work domain. The process that will be used is called DERIVE. The substeps of this process are:

- Define new state vision (Section 4.3.4.1)
- Evaluate department performance factors (Section 4.3.4.2)
- Review relevant performance information (Section 4.3.4.3)
- Interview stakeholders (Section 4.3.4.4)
- Valuate current organization solution readiness (Section 4.3.4.5)
- End-state gap analysis and achieve stakeholder buy-in for gaps identified (Section 4.3.4.6).

Each of these substeps are described next.

4.3.4.1 Define The New State Vision

Practical Guidance: Although facilitated by the HITT process team, the new state vision will ultimately be defined by the stakeholders and validated through the interviews and other steps during the DERIVE process. The new state vision of the stakeholders will vary from improved process efficiency and plant performance and will be instrumental in helping to define the desired new state after HTI improvements through process benchmarking from the experience of the HITT team members.

Supporting Information: There are several tools that may be used to facilitate the new state vision definition. EPRI 3002015797 (2020) provides a suite of worksheets for defining the vision. Either the entire set or subset of these worksheets may be used. The coverage of these worksheets entails defining the vision for the:

- Concept of operations
- Concept of maintenance
- HSI design concepts for the vision
- Simplifications concepts (i.e., expanding on the use of sensors, diagnostics, and other technological strategies to simplify work)
- Additional failure management issues
- Organizational architecture (i.e., including streamlining of organizational and workflow considerations, as well as skills and organizational requirements).

Finally, it is worth noting that the guide provided in Section 2.2.1 (i.e., specifically in Sections 2.2.1.1–2.2.1.4) should be considered here. Specifically, enabling tools like 3D modeling can be applied (if applicable) to communicate physical features of the vision. Impacts to the concept of operations (or expanded to other areas defined by EPRI 3002015797) may be applied to identify key differences between the way work is performed in the existing state compared to the new state; human factors impacts can be readily identified through this approach.

4.3.4.2 Evaluate Department Performance Factors

Practical Guidance: There are many sources of information that can be evaluated to elicit departmental and process performance. Some of these are measured through published KPIs and others can be derived from data sources, such as raw work order performance data. Finally, the team will try to analyze personnel competency data, which will help determine whether the individuals performing the various process duties are optimally suited to perform those functions.

The goal in this step is to identify all potential sources of performance information, including nontraditional indicators of performance, so that the true performance of the process can be fully evaluated. For example, staff quality of life may not be a typical indicator that is published; however, it may be one of the areas with the largest gaps to be addressed.

4.3.4.3 Review Relevant Performance Information

Practical Guidance: Once all of the data sources have been identified, an in-depth review of the data will be necessary to fully assess the process performance. The goal is to accurately assess the current performance against the desired new state to identify potential gaps. Another gap that may be identified could be the gap between the perceived new state and that of high-performing external organizations or nuclear power plants.

The breadth of team experience will help identify these gaps. When this step is complete, the team will have a clearer hypothesis of the gaps and will begin corroborating these hypotheses with the actual employees and stakeholders through discussions and anonymous interviews.

4.3.4.4 Interviews with Stakeholders

Practical Guidance: Surveys and data evaluation are an important source of information; however, interviews can provide a completely different perspective on a process by providing a more humanistic viewpoint of a process and how the end users or stakeholders are affected by the current execution of the process under review. Anonymous interviews will be performed for a good representative sample of employees that encompasses individuals from all levels of the organization that manages the subject process or work domain, as well as the stakeholders that influence or are affected by it. The interview results will be tabulated and compared to the identified gaps. If there is a large disparity between the interviews and the data, the team will evaluate why the data and KPIs were not accurately representative of the actual organizational performance. The team may end up performing more in-depth follow-up interviews to either corroborate the conclusions or clarify the reason for the disparity.

4.3.4.5 Valuate Current Organization "Solution Readiness"

The concept of solution readiness was depicted in Figure 53 and consists of human readiness (Section 2.1.4), organizational readiness, digitalization readiness, technology readiness, and solution effectiveness. The magnitude of the gaps from the desired new state vision will have a direct impact on which HTI improvements will be suggested to help close some of the gaps in performance.

Various tools will be employed to help evaluate aspects of the organization's digital acumen, including data quality, information accessibility, and overall digital quality of life. As previously mentioned, the resilience of the organization to be able to withstand the proposed changes also needs to be assessed to be able to fully determine how ready an organization is to make HTI improvements. Digital infrastructure in terms of the EAM platform used to capture enterprise data is also a significant factor. Typically, commercial off-the-shelf EAM systems, although very robust and dependable, can also be costly to upgrade or to build a customized front end to improve the HSI. Finally, HTI solutions that are already available will also have an impact on the readiness of the organization to accept the solutions, as customized solutions may take a considerable amount of time and resources to design and implement.

At this step in HITT, elements of solution readiness can be evaluated specifically for digitalization readiness and organizational readiness for potentials of resilient performance from the following assessment tools described next.

Digital Quality of Life Survey[8]

Practical Guidance: The goal of the "Digital Quality of Life" survey is to gain a digitalization status snapshot of a plant, as part of a multistage approach to determine a plant's digitalization needs. It is customized, rapid, and user-friendly, consisting mainly of multiple-choice questions. The nature of the information being collected can be summarized as health indicators of a collection of work processes performed at the plant. The information gained will be used to identify optimal candidates for a digitalization deep dive that yield the highest payback in terms of increased process efficiencies. In conjunction with the digitalization guiding principles, these research activities will be used to develop a specific digitalization plan with supporting success metrics.

Resilience Analysis Grid

Practical Guidance: The resilience analysis grid (RAG) was developed by Hollnagel (2017) and originates from resilience engineering literature. Resilience engineering's goal is to ensure that an organization can perform effectively in everyday conditions, as well as cope with unusual and unexpected situations. According to Hollnagel, the purpose of the RAG is to provide a well-defined characterization of an organization's ability to manage and develop *potentials* for resilient performance (i.e., ability to perform everyday work successfully). RAG is a standardized survey that can be administered to stakeholders within the organization who are involved in the work domain of interest. RAG can be administered before and after an HTI improvement to evaluate its effectiveness in terms of enabling potentials for resilient performance. The RAG is presented in Appendix B.

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[8] This work is described by digitalization lead Dr. Anna Hall and is currently an active research area at the time of publication of this technical report.

Supporting Information: Resilient performance can be characterized across four potentials:

- *The ability to respond.* This potential refers to the ability of an organization to know what to respond to in the event of regular changes, irregular changes, disturbances, or opportunities.
- *The ability to monitor.* This potential refers to the ability for an organization to know what to monitor to prepare to respond. Monitoring encompasses internal and external performance factors.
- *The ability to learn.* This potential refers to the ability for an organization to learn from experiences to improve its ability to respond, monitor, and anticipate.
- *The ability to anticipate.* This potential refers to the ability for an organization to predict developments in the future (e.g., disruptions, demands, changing conditions).

The RAG assesses potentials for resilient performance across these four potentials using a standardized set of questions (Appendix B), which can be adapted as needed.

4.3.4.6 End-State Gap Analysis and Achieve Stakeholder Buy-in for Gaps Identified

Practical Guidance: The final step of the DERIVE process is to provide full details on how the gaps were identified, why certain HTI solutions are being proposed (i.e., if certain solutions are currently identified before completing HITT), and the organization's readiness to be able to implement the various proposed solutions. Collaboration with the process owners, and various stakeholders, especially those interviewed, will ensure the elicitation was accurate and proposed improvements are feasible and will ensure maximum acceptance of the conclusions of the elicitation.

4.3.5 Step 5. Update Process Map Outputs

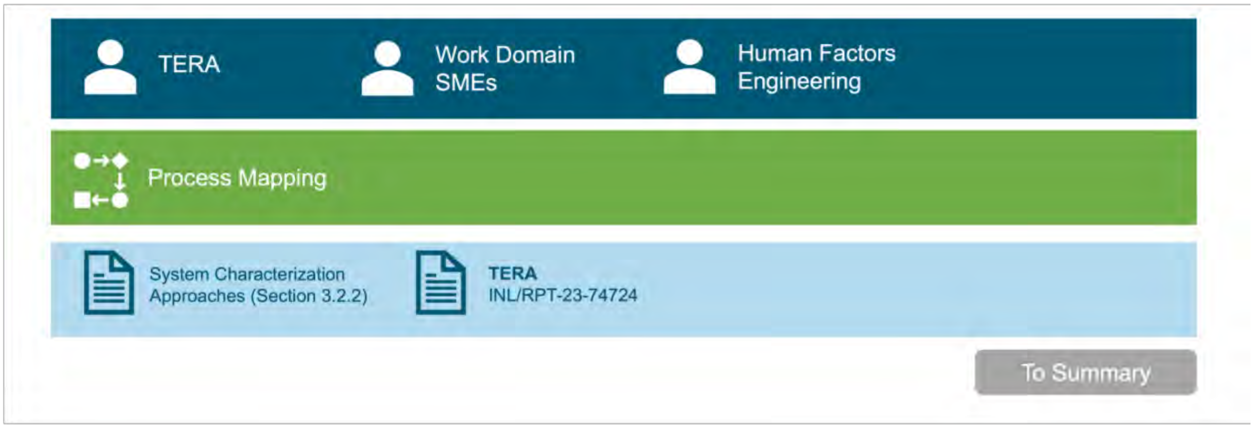

Figure 61. Step 5 of the HITT process.

Practical Guidance: After the DERIVE process, it's crucial to update the initial process map outputs from Step 2 with the newfound insights and data. This step involves revising the process maps to reflect the current understanding of the work processes, including any identified inefficiencies, gaps, and potential areas for improvement that came from DERIVE. The updated process maps should encapsulate the enhanced workflow and illustrate how the proposed WROs can be integrated into the existing processes.

Supporting Information: The updated process map outputs are pivotal for visualizing the future state of the processes after WRO implementation. They serve as a blueprint for the changes to be made and provide a clear path forward for the implementation teams. Furthermore, these updated maps facilitate a continuous improvement cycle, where process efficiencies are regularly monitored and adjustments are made as necessary to optimize performance. By systematically updating the process maps based on the DERIVE insights, organizations can ensure that their operational processes are streamlined, efficient, and aligned with their strategic objectives.

To perform this update systematically, the same steps should be taken as were described in Step 2. However, this time more emphasis should be placed on updating information based on information identified from performing the DERIVE methodology. The steps include:

1) *Incorporate DERIVE Insights*. Integrate the key findings from the DERIVE process into the process maps, ensuring that all identified gaps and improvement areas are clearly represented. This may involve adding new steps, removing redundant ones, or altering the flow to increase efficiency.
2) *Validate with Stakeholders*. Present the updated process maps to the stakeholders involved in the DERIVE process for validation. This ensures that the maps accurately reflect the consensus understanding and that the proposed changes are feasible and aligned with the organizational goals.
3) *Align with KPIs*. Ensure that the updates to the process maps are in sync with the identified KPIs. This alignment is crucial for monitoring the impact of the implemented changes and ensuring that they contribute to the overall performance improvement.
4) *Document and Finalize*. Document the updated process maps comprehensively, detailing the changes made and the rationale behind them. This documentation serves as a reference for the implementation phase and helps in tracking the progress of the WROs.

4.3.6 Step 6. Select Human Factors Impact Assessment Methods

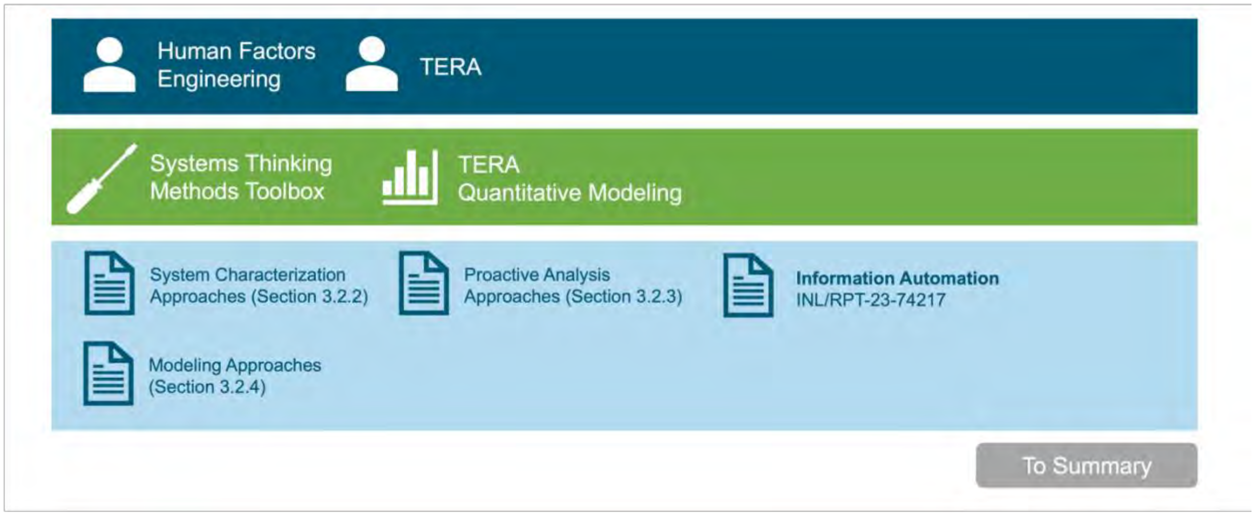

Figure 62. Step 6 of the HITT process.

Practical Guidance: Step 6 pertains to selecting HTI impact assessment methods that will be used to ultimately evaluate the existing work domain (Step 7), identify HTI improvements (Step 8), and support the subsequent analysis of the impacts of proposed improvements on the work domain (Steps 9 and 10). Here, the team may use the systems thinking methods toolbox (Figure 55) to decide what methods to use. The primary inputs for the impact assessment come from the findings collected when performing DERIVE in Step 4 and the process map developed and updated in Step 5.

Supporting Information: Figure 55presents the possible systems thinking methods that can be used, grouped by their type of approach. A summary of these methods is provided in Section 3.2. Moreover, building on Figure 55, Table 9 presents a concise list of tradeoffs for these methods.

Table 9. Tradeoffs of types of impact assessments from the systems thinking methods toolbox.

Type of Approach	**Method**	**Advantages**	**Disadvantages**
System Characterization	Process Map (Section 3.2.2.3)	– Directly used in TERA framework. – Represents the flow of activities in a work process. – Readily interpreted with minimal training.	– Can be unwieldy with complex work processes. – May not clearly show task dependencies. – Does not explicitly show the goals of each activity.
	HTA (Section 3.2.2.2)	– Explicitly provides the goals and subgoals of each activity. – Readily interpreted with minimal training. – Can be extended to other advanced HFE methods.	– Can be unwieldy with complex work processes. – May not clearly show task dependencies. – Does not explicitly show the flow of activities in a work process.
	Cognitive Task Analysis (Section 3.2.2.4)	– Considers cognitive aspects of a task. – Can be used in conjunction with HTA.	– Requires HFE expertise to perform the methodology. – Can be time consuming.
	Cognitive Work Analysis (Section 3.2.2.5)	– Offers the most comprehensive analysis of the work domain in question. – Flexible framework that allows the analyst to apply a subset of phases as appropriate.	– Requires HFE expertise to perform the methodology. – Can be very time consuming if all phases are completed.
Proactive Analysis	STAMP-STPA (Section 3.2.3.1)	– The control structure provides a clear representation of key agents within the system and their interactions. – ICAs can be identified across different layers of the control	– Requires STAMP expertise to perform the methodology. – Does not explicitly consider emergent risks.

Type of Approach	**Method**	**Advantages**	**Disadvantages**
		structure, including at the organizational level, at the user(s) level, or system component(s) level.	– Requires a degree of translation when developing the control structure from a process map or HTA.
	Net-HARMS (Section 3.2.3.2)	– Can be directly extended from a process map or HTA. – Explicitly considers emergent risks. – Offers flexibility in the potential risk mode classification scheme to use.	– Requires expertise in performing HTA and risk identification to perform the methodology. – Can be time consuming to apply, particularly when developing a task network graph and identifying emergent risks.
Modeling	Quantitative Modeling (Section 3.2.4.1)	– Provides quantitative results of system performance. – Results can readily support a business case to modernize.	– Requires expertise in quantitative modeling. – Model accuracy is predicated on having deep knowledge of the system. – Can be time consuming to apply, especially for complex processes.
	Human-in-the-Loop Simulation (Section 3.2.4.2)	– Provides a comprehensive and empirical-based approach to modeling human behavior in a system. – Allows end users to interact with a proposed redesigned system to provide direct feedback.	– Requires access to end users. – Requires access to a prototype of the redesigned system. – Requires access to a test bed of sufficient fidelity.
	Human Performance Modeling (Section 3.2.4.3)	– Provides a means for analyzing human performance in the absence of end users for predefined tasks and cognitive processes.	– Generally limited to evaluate very specific elements of human behavior, which may miss key aspects that human-in-the-loop simulation can address.

4.3.7 Step 7. Perform Impact Assessment on Existing Work System

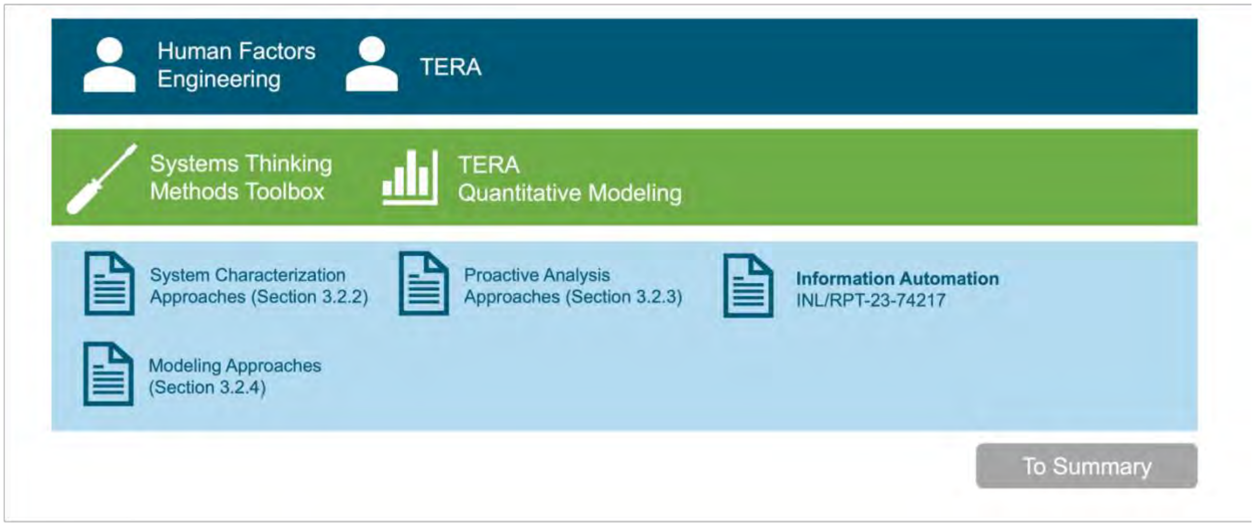

Figure 63. Step 7 of the HITT process.

Step 7 entails performing the impact assessment on an existing work system. Using the results from DERIVE and the evolved process map artifacts, this step entails performing a proactive analysis on the existing work system, developing the quantitative process model of the existing work system, and then quantifying the impacts. Collectively, these substeps address the following questions:

- *What* task-based and emergent risks are plausible in the work system?
- *How* could these risks occur? (e.g., What decisions are made? Who makes these decisions? What are the potential outcomes of each decision?)
- *To what extent* could the impacts of these risks affect the plant's safety, costs, or reputation?

4.3.7.1 Perform Proactive Analysis

Practical Guidance: Using the impact assessment method(s) selected in Step 6, the first substep for Step 7 entails performing the proactive analysis on the existing work system using the methods described in Section 3.2.3. The goal of the proactive analysis is to identify task-based and emergent risks and begin identifying potential WROs or "leverage points" that address these risks to improve performance while ensuring safety and reliability.

Supporting Information: The following example shows the application of Net-HARMS (Section 3.2.3.2) to support the proactive analysis of an example use case for work package preparation under work management. In this example, an initial task analysis was first developed to identify the primary tasks under work management. Next, a task network graph transition matrix was developed to identify interrelated tasks downstream from work package planning. Task risks were then identified for preparing the work package using the risk mode taxonomy from Dallat and colleagues (2018; refer to Table 8). The example is predicated on the work scope being inadequately prepared after inadequate screening. Finally, emergent risks were identified using the outputs of the identified task risks for work package preparation in the task network. These emergent risks used a similar taxonomy as seen in Table 8. Once all plausible risks were identified, potential consequence types (i.e., related to safety, financial, reputational, performance, and legal) were identified and then linked to each risk using guidance in Salmon et al. (2023).

The results of this Net-HARMS demonstration are presented in Figure 64 and Table 10. Figure 64 presents a hierarchical edge bundle (i.e., an alternative format to a network graph) to illustrate the interrelations between the task risks for preparing a work package (i.e., the proximal stems) and plausible emergent risks downstream in the work management process (i.e., the distal branches). Focusing on the emergent risks that propagate from the resulting task risks from preparing the work package, Table 10 then presents each task and emergent risk mode in greater detail, including additional information, such as their consequences, as well as probability of occurrence and criticality of emergent risk mode using a nominal scale (e.g., low, medium, high).

To further illustrate the use of HITT in this example, we focus on the emergent risks associated with ordering parts. This is illustrated by the colored rectangles over the associated emergent risks in Figure 64, as well as the colored rows in Table 10. The Net-HARMS outputs can then be used for two purposes:

- As inputs to develop the quantitative process model for the existing work system, illustrated next in Section 4.3.7.2.
- To begin identifying HTI improvements that will mitigate potential risks identified (i.e., see Step 8 in Section 4.3.8).

A final point to mention is that additional systems thinking methods can be applied if desired to identify potential risks and WROs. For instance, STPA could also be used here to provide an alternative lens into the SOI, based on STAMP. Its application may provide additional insights and potentially unique WROs or potential risks. For example, while Net-HARMS provides insights into potential emergent risks that can propagate, a STAMP-based STPA provides a means to analyze the interactions between components within the SOI and shows a clear hierarchy across the control structure. Combined, both approaches may provide a more comprehensive perspective of the SOI to ensure a more complete set of WROs and potential risks.

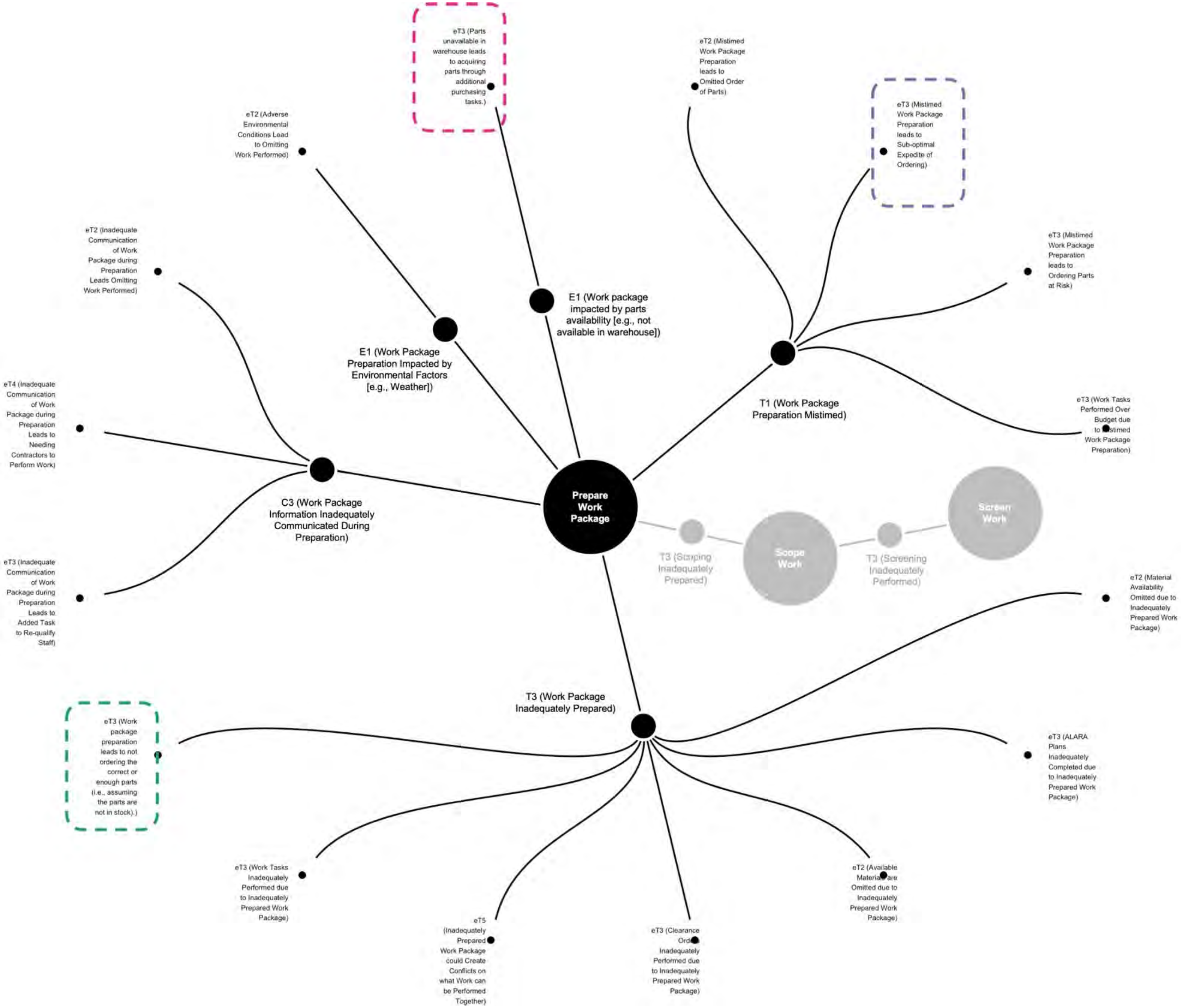

Figure 64. Example of Net-HARMS risk mode network using a hierarchical edge bundle.

Table 10. Example of Net-HARMS risk mode table for work package preparation.

Task	Task Risk Mode	Task Risk Description	Task Risk Consequence Category	Linked Tasks	Emergent Risk Mode	Emergent Task Risk Description	Probability of Occurrence	Criticality	Emergent Risk Consequence Category
(Planning Phase) Begin Work Package Preparation	T1	Work package preparation is mistimed. A consequence of this risk is that it could completely underestimate the importance of planning the task and could wait too long. If one waits too long to plan fully, then timing can become a significant factor.	Financial	(Planning Phase) Order Obsolete Parts	eT2	Mistimed work package preparation leads to omitted order of parts.	Medium	Medium	Financial
					eT3	Mistimed work package preparation leads to suboptimal expediting of ordering.	Medium	High	Financial
					eT3	Mistimed work package preparation leads to ordering parts at risk.	Medium	Medium	Financial
				(Execution Week) Perform/Complete Work Tasks	eT3	Work tasks performed over budget due to mistimed work package preparation.	Medium	Medium	Financial
	T3	Work package is inadequately prepared. An inadequately prepared work package may entail missing any number of considerations, details, steps, or other pertinent information.	Safety, Financial	(Planning Phase) Order Obsolete Parts	eT3	Work package preparation leads to not ordering the correct or enough parts (i.e., assuming the parts are not in stock).	Medium	High	Financial
				(Scheduling Phase) Material Availability Confirmation	eT2	Material availability omitted due to inadequately prepared work package.	Medium	Medium	Financial
				(Post-Schedule Freeze) ALARA Plans Complete	eT3	ALARA plans inadequately completed due to inadequately prepared work package. An inadequate ALARA plan may not adequately identify where the work is going to be performed and the dose estimates could be different, which affects resources needed to complete the work.	Medium	Medium	Safety, Financial
				(Post-Schedule Freeze) Verify Materials Available	eT2	Available materials are omitted due to inadequately prepared work package.	Medium	Medium	Financial
				(Post-Schedule Freeze) Clearance Orders Approved	eT3	Clearance orders inadequately performed due to inadequately prepared work package.	Medium	Medium	Financial
				(Execution Week) Check in with Operation for Task Start Approval	eT5	Inadequately prepared work package could create conflicts on what work can be performed together.	Medium	Medium	Financial
				(Execution Week) Perform and Complete Work Tasks	eT3	Work tasks inadequately performed due to inadequately prepared work package.	Medium	Medium	Safety, Financial
	C3	Work package information is inadequately communicated during preparation. Inadequate communication may entail not having the level of detail needed for the workers to perform the work.	Safety, Financial	(Execution Week) Perform and Complete Work Tasks	eT3	Inadequate communication of work package during preparation leads to added task to requalify staff.	Medium	Medium	Financial
					eT4	Inadequate communication of work package during preparation leads to requiring additional contractors to perform work.	Medium	Medium	Financial
					eT2	Inadequate communication of work package during preparation leads to omitting work performed.	Medium	Medium	Safety, Financial
	E1	Work package preparation is impacted by external or	Financial	(Execution Week) Perform and Complete Work Tasks	eT2	Adverse environmental or other external conditions lead to omitting work performed.	Low	Medium	Financial

Task	Task Risk Mode	Task Risk Description	Task Risk Consequence Category	Linked Tasks	Emergent Risk Mode	Emergent Task Risk Description	Probability of Occurrence	Criticality	Emergent Risk Consequence Category
		environmental factors (e.g., adverse weather).							
	E1	Work package impacted by parts availability (e.g., not available in warehouse).	Financial	(Planning Phase) Order Obsolete Parts	eT3	Parts unavailable in warehouse leads to acquiring parts through additional purchasing tasks.	Medium	High	Financial

4.3.7.2 Develop Process Model

Practical Guidance: The purpose of this substep is to develop a process model that can be used to quantify the impacts of the identified risks in the next step. While the proactive analysis (e.g., using Net-HARMS or STPA) is applied to broadly analyze the SOI to identify potential risk modes, this step begins to develop a more specified model of the identified risks. Key elements of the process model that must therefore be succinctly described to develop a comprehensive quantitative model include characterizing the tasks, decisions, data and information flows, and information of the SOI (Spangler et al., 2023).

The approaches described in Section 3.2.2 can be applied to enable data mapping, decision mapping, task mapping, and performance metric identification in this substep to inform the development of the quantitative model in the next substep following guidance in Section 3.2.4.1. To enable the development of the quantitative model, it may be necessary to further specify the process beyond what was developed for the process map in Step 5; for example, additional decisions within the process may need to be further analyzed using a decision tree (Section 3.2.2.3).

Supporting Information: The supporting information provided here describes the basis and approach for modeling the work package planning process, following the Net-HARMS analysis. In this case, work package planning is one of the cornerstone processes in completing work at a nuclear power plant. The outcome of the work package affects many different facets of the work management process utilized to schedule and complete work. As such, issues or problems that affect the quality or accuracy of the work package can have a significant impact on one or more downstream processes, as well as the scope of work that the work package is being planned to address.

One of the elements of planning a work package is to determine which supplies, materials and parts will be needed to complete the work. The work order history for the equipment being worked on can provide valuable information to the work planners about which parts may be needed for the upcoming work. If a previous work package has been created for similar work, many of the spare parts may have been identified in the previous work package, and this will assist the work planner in selecting the correct parts to reserve for the next work to be performed. Also, the list of actual parts used during the previous work will be helpful in selecting which parts to acquire for the upcoming work.

There are many factors that can affect the list of parts reserved if a recent work package has not been planned for similar work. One of the factors is whether a business goal of the nuclear power plant is to reduce inventory growth. This goal—if enforced—will put pressure on the work planners to be very specific about which parts they reserve. Often, if the equipment is inaccessible, and a walkdown is limited or not possible, the work planner must review drawings and use the Bill of Material to identify the potential parts needed. This will also have an impact on which parts are reserved for the work and could result in too few parts being identified.

If the work planner reserves the parts for the work order, and they are in stock and not allocated for other work, the parts will be ear marked for that particular job in the inventory system, and no further actions are needed. However, if the parts are not in stock for the upcoming work, a decision tree is necessary to ensure that the parts will be available for work and that the acquisition of the parts not in stock will be as optimal as possible to make sure that inventory growth is minimized but that the work can be completed as scheduled. Another factor that will affect part acquisition is the priority of the work order and whether the work management organization has the latitude to push the work out into the future until the parts can all be received and their quality verified. If the work is considered a high priority to the operating organization, this will significantly influence the decision tree for part acquisition. Figure 65 demonstrates a typical decision tree that a utility would use to acquire parts that are not in inventory to support upcoming work.

The decision tree begins with reporting the equipment defect (green). The decisions (diamonds) and actions (blue rectangles) are indicated using standard notation for a decision tree (e.g., Kirwan and

Ainsworth, 1992). Terminal activities that are not considered for modeling are indicated as gray ovals. Further, the emergent risks identified from Net-HARMS are overlaid onto the decision tree, following the color conventions in Figure 64 and Table 10. The decision tree terminates at the decision of whether the part passes the bench test or not.

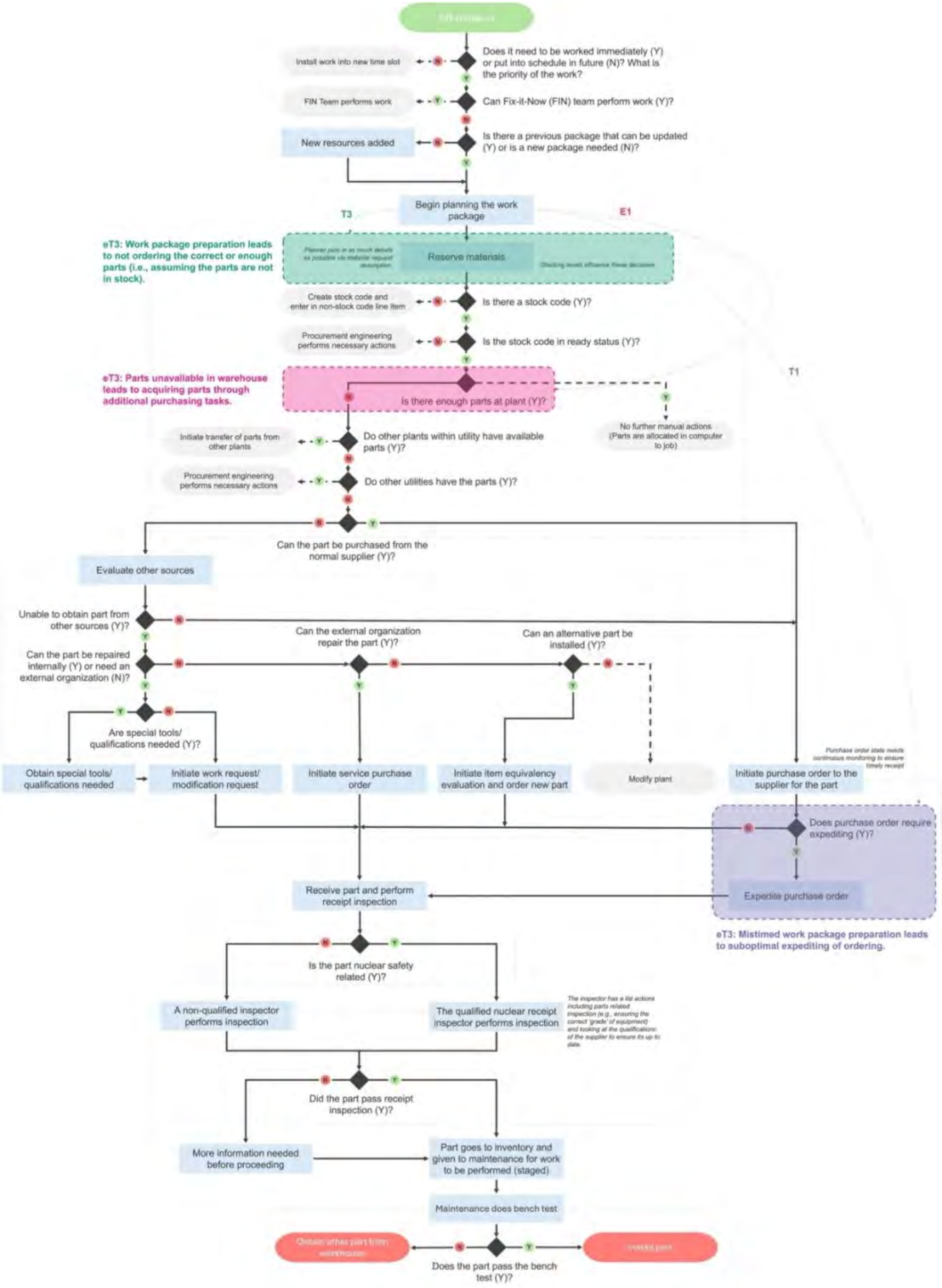

Figure 65. Example process chart for ordering parts with emergent risks highlighted.

4.3.7.3 Quantify Impacts

Practical Guidance: This substep involves quantifying the impacts of the decisions and actions identified in the process model. The objective is to understand the probabilistic outcomes of different decisions and actions within the system, especially in terms of cost, time, resource allocation, and risk. This will involve developing a quantitative model that integrates the data flows, decisions, tasks, and performance metrics identified in the previous steps.

Supporting Information: Quantifying the impacts of decisions and actions within the work package planning process is essential for the effective management and optimization of resources at a nuclear power plant. The quantitative model developed in this substep will provide a comprehensive view of how different decisions and actions affect the overall efficiency and effectiveness of the work management process. By integrating the decision tree with probabilistic outcomes and cost implications, the model allows for a detailed analysis of the tradeoffs involved in each decision. This enables decision makers to make informed choices that balance cost, risk, and performance objectives, leading to improved operational efficiency and reduced inventory costs.

Turning the process and decision model into a quantitative model (i.e., here an influence diagram is used), follows these steps:

1) *Identify Decision Nodes.* Begin by identifying the decision points within the process. These are the points where choices are made and different paths can be taken. In the influence diagram, these will be represented as decision nodes, typically depicted by rectangles or squares.
2) *Determine Chance Nodes.* Identify the points in the process where uncertainty or variability occurs. These are events or outcomes that cannot be controlled but have a probability of occurring and will impact subsequent stages of the process. In the influence diagram, these are represented as chance nodes, usually shown as circles or ovals.
3) *Define Outcome and Value Nodes.* Determine the endpoints or objectives of the process that need to be achieved or optimized. These outcomes are what the decision maker aims to influence through their decisions and are affected by the chance events. In the influence diagram, these are represented as value nodes, often depicted as diamonds or hexagons.
4) *Map the Information Flow.* Draw arrows to connect these nodes, showing the flow of information and the cause-and-effect relationships. Arrows from decision nodes to chance nodes represent how decisions influence uncertain outcomes. Arrows between chance nodes can represent how one uncertain event affects another. Arrows to value nodes show how both decisions and chance events impact the final outcomes.
5) *Assign Probabilities and Utilities.* For each chance node, assign probabilities to the different outcomes based on historical data, expert judgment, or statistical models. For each value node, assign utilities or values that reflect the desirability or importance of each outcome.
6) *Analyze Influences and Dependencies.* Review the diagram to ensure it accurately represents all significant influences and dependencies in the decision-making process. This includes ensuring that the diagram shows how information available at the time of a decision influences that decision and how earlier decisions or events might influence later decisions or uncertainties.

By following the above steps, the influence diagram shown in Figure 66 was created. When performing these steps for the process shown in Figure 65, simplification was required to reduce the number of steps in the process to reduce the modeling burden but still retain important KPI influences. The diagram starts with a condition report that initiates the process. The process continues until the issue is resolved on time (green states) or late (red states). While the actual process continues past ordering parts from suppliers and continues until a plant modification may occur, the created quantitative model only includes a subset of the entire process. In this model, costs are only accrued after an action or when the new state of being late is reached. The costs for being late are due to several undesirable outcomes that have been aggregated into one cost or "consequence." The parameters that dictate the dynamics and outcome of this model are shown in Table 11.

In addition to the main financial cost drivers, there are "Quality of Life" cost nodes that help evaluate the working conditions of the managers and staff that are part of this process. The quality of life for individuals managing the work planning process can be significantly impacted due to the demanding nature of their roles. The need to put in extra hours and miss family events to recover the schedule performance leads to a poor quality of life for these professionals. This situation can be attributed to several causes:

- *Excessive Workload*. High demands and expectations to meet strict deadlines often result in extended working hours, contributing to burnout and stress.
- *Inflexible Scheduling*. The rigidity of the work schedule, with little to no flexibility, forces individuals to prioritize work over personal or family time, leading to work-life imbalance.
- *Resource Constraints*. Insufficient staffing or resources to effectively manage and execute the planning process can increase the burden on existing staff, exacerbating stress and fatigue.
- *Inadequate Support Systems*. Lack of support, whether in terms of technology, management, or colleague assistance, can leave individuals feeling isolated and overwhelmed by their responsibilities.
- *High-Pressure Environment*. The critical nature of work planning in maintaining operational efficiency often creates a high-pressure environment, where the stakes for errors are high, contributing to anxiety and decreased job satisfaction.

These factors collectively degrade the quality of life for work planning managers, necessitating interventions to improve work conditions, enhance support mechanisms, and promote a healthier work-life balance. By including quality of life in the model, we can quantify how changes to the system can improve work-life balance and can help alleviate issues like worker retention.

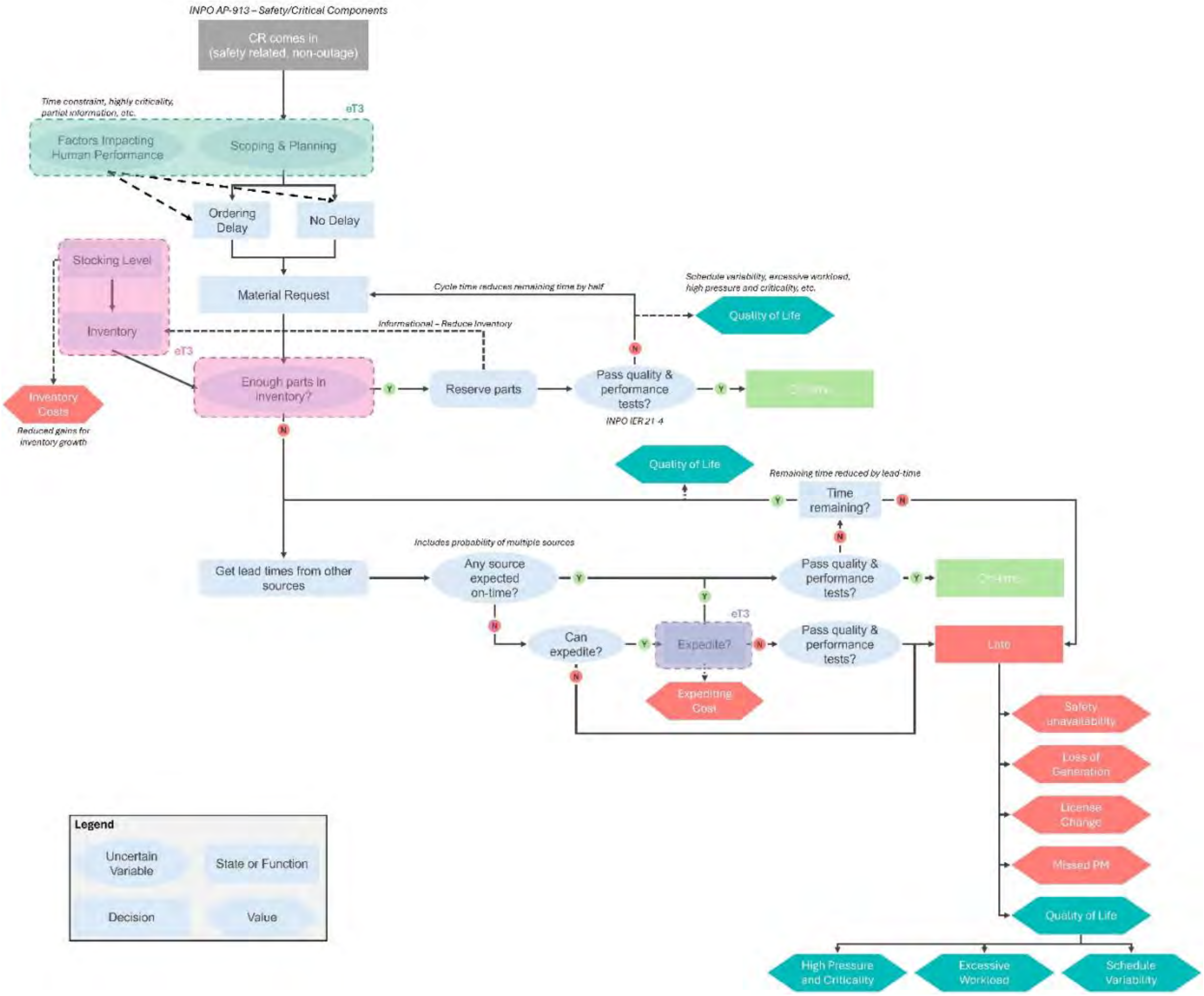

Figure 66. Simplified process model (influence diagram) for quantifying impacts.

Table 11. Parameters for influence diagram.

Parameter	Nominal	Min, Max
Consequence	10^6	0.9×10^6 → 1.1×10^6
Inventory	1	0 → 3
Lead Time (mean)	25%	15 → 40
Leads (#)	1	0 → 2
Expediting Factor	2	1.5 → 3
Human Performance Index	0.95	0.8 → 0.99
Error—Delayed Order Time (mean)	40%	30 → 50%
Critical Part Reliability Rate	0.9	.8 → 0.99

Nominal System Cost

To evaluate the cost of the system under the nominal parameters, 10^7 Monte Carlo simulations were performed. The nominal expected cost of the system was $51,919, and the expected quality of life index was -14.75. A summary of these results can be seen in Table 12.

Table 12. Summary of nominal system results.

Expected Value	**Nominal**
Overall Cost	$51,919
Quality of Life (max is 0)	−14.75

Sensitivity Analysis

To identify the parameters that have the largest influence on the expected cost of the system, a sensitivity analysis[9] was performed. The sensitivity analysis was performed by changing a parameter of interest while holding the remaining parameters constant at their nominal values. Each parameter was changed to the high and low values as listed in Table 11 and compared to the nominal. The results of the sensitivity analysis can be seen in Figure 67 and Figure 68.

The sensitivity analysis results show two features: the influence of each parameter and the impact of uncertainty from each parameter. Although the parameter change amount was not normalized, it is easy to see that some parameters have greater impacts on the expected cost and quality of life. Additionally, the sensitivity analysis shows which parameters have a significant impact due to uncertainty and where more information is needed. If the range of some parameters can be reduced (gathering more information regarding the true value of that parameter), we can reduce the uncertainty in the expected output of the system. For example, the quality pass rate for a component is considered stochastic (any component may pass or fail) but the degree to which the components pass is uncertain without significant testing (sometimes performed by the manufacturer). Many components may have a quality assurance guarantee from the manufacturer and a known pass/fail rate. In this case, the quality pass rate will have less variability and will therefore cause less variability on the system outcome. As long as the quality pass rate is known, even if it is low, inventory levels can be adjusted to minimize the resulting cost.

It should be noted that the sensitivity analysis was performed around the nominal operating point for the system. Due to the nonlinear effects of decision-making and states of the model, the sensitivity of each parameter will change at different operating points. For example, lead time will have a much more significant impact on being late when inventory levels are low or below their nominal value. This effect will be discussed in more detail in the following sections.

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[9] Note: The sensitivity analysis was performed using nominal parameters, which means it only accounts for changes around the nominal operating region.

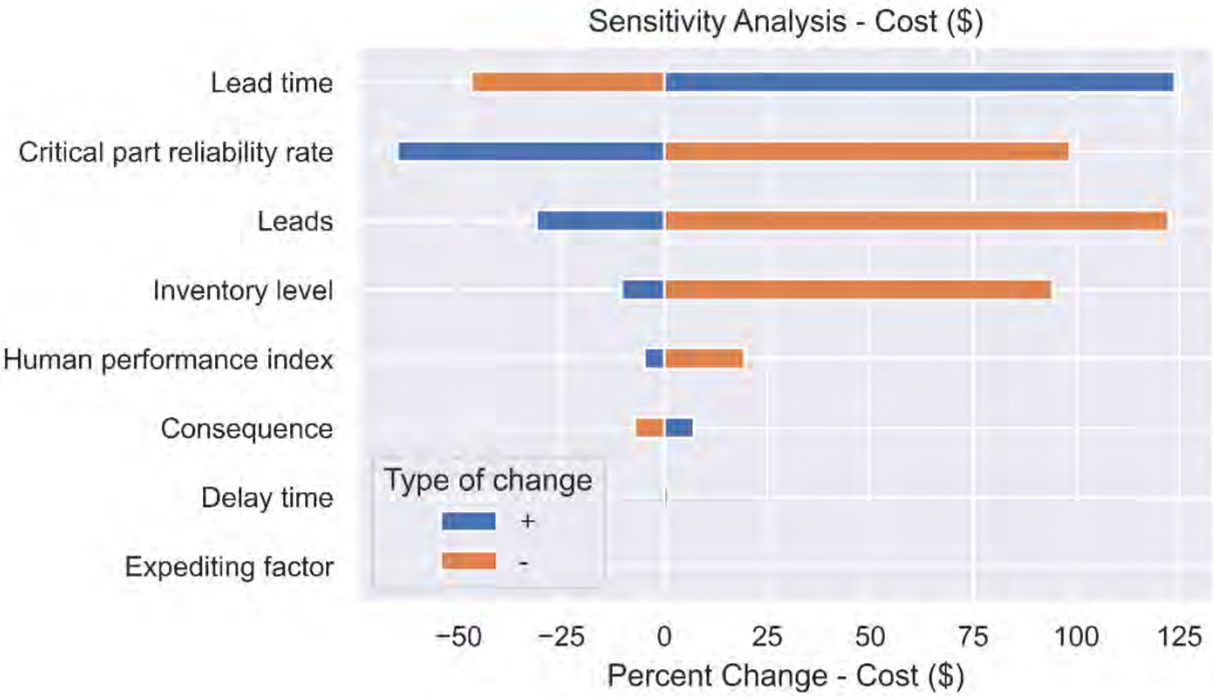


Figure 67. Sensitivity analysis results summary from impact assessment (complete dataset).

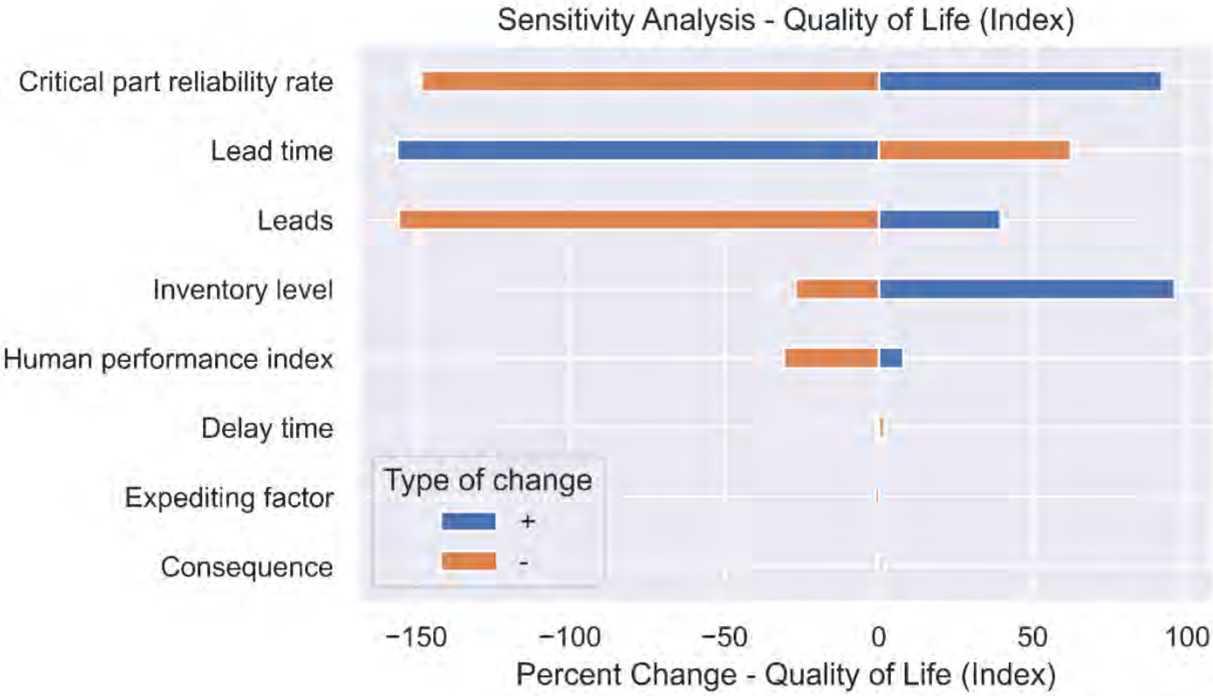


Figure 68. Sensitivity analysis results summary from quality of life impact assessment (complete dataset).

4.3.8 Step 8. Identify HTI Improvements

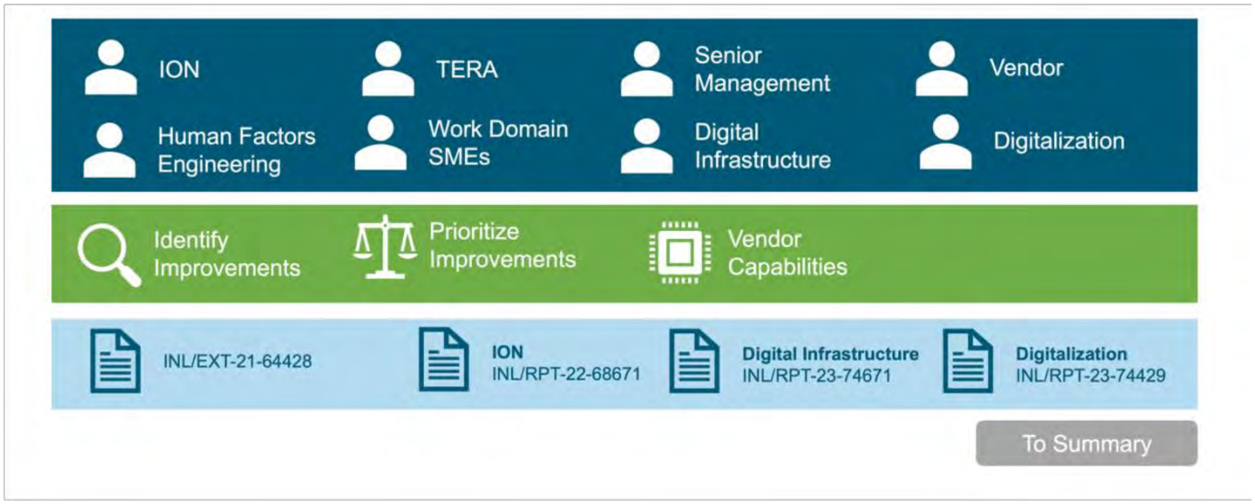
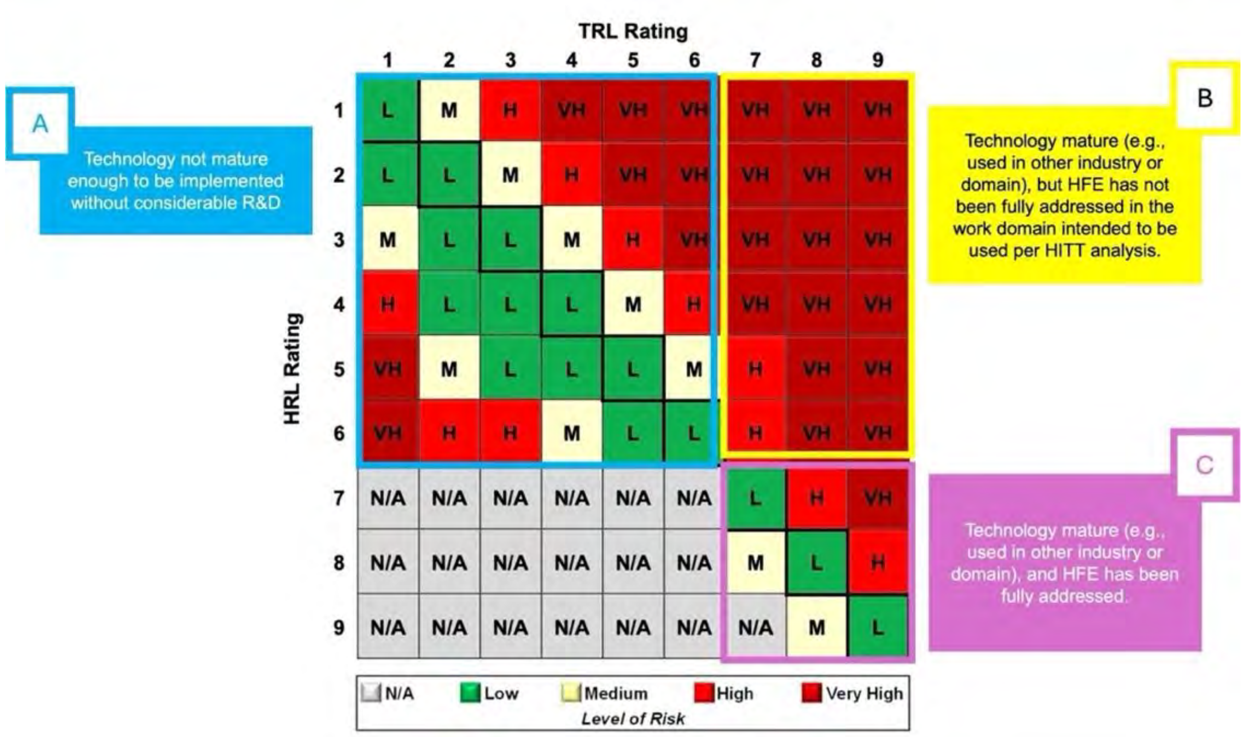


Figure 69. Step 8 of the HITT process.

Practical Guidance: Using the results of the impact assessment in Step 7, ION-informed HTI improvements are then identified. To do so, guidance from INL/EXT-21-64428 can be applied. Specifically, the HITT team identifies potential innovations that will reduce or eliminate the probability and criticality of the identified risks from Step 7. Identified innovations can then be prioritized by the team based on the following criteria (adapted from INL/EXT-21-64428):

- *High Priority*. Expectation that implementation would result in significant cost reductions (or improvements to safety)
- *Medium Priority*. Expectation that implementation would result in important cost reductions (or improvements to safety) but not as much as innovations prioritized as high priority
- *Low Priority*. Expectation that implementation would result in some cost reductions (or improvements to safety) but not as much as innovations assigned medium or high priority.

Supporting Information: A starting point for identifying HTI improvements begins with considering any innovations already identified by the organization and considering any innovations part of associated WROs that were screened in during Step 1 (i.e., also refer to Attachment A of INL/RPT-23-74671). Further, identifying HTI improvements may begin with the simplest and lowest cost design controls (e.g., administrative controls) before systematically considering more expensive improvements. As seen in Figure 56, the feedback loops between Step 10 and Step 8 represent this systematic review of potential HTI improvements. A final point worth highlighting is to consider any identified HTI improvement's TRL and HRL (i.e., refer to Appendix A to determine an innovation's HRL). Figure 70 presents three potential situations that may be seen when identifying potential improvements.



A: Technology not mature enough to be implemented without considerable R&D

B: Technology mature (e.g., used in other industry or domain), but HFE has not been fully addressed in the work domain intended to be used per HITT analysis.

C: Technology mature (e.g., used in other industry or domain), and HFE has been fully addressed.

HRL Rating \ TRL Rating	1	2	3	4	5	6	7	8	9
1	L	M	H	VH	VH	VH	VH	VH	VH
2	L	L	M	H	VH	VH	VH	VH	VH
3	M	L	L	M	H	VH	VH	VH	VH
4	H	L	L	L	M	H	VH	VH	VH
5	VH	M	L	L	L	M	H	VH	VH
6	VH	H	H	M	L	L	H	VH	VH
7	N/A	N/A	N/A	N/A	N/A	N/A	L	H	VH
8	N/A	N/A	N/A	N/A	N/A	N/A	M	L	H
9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	M	L

Level of Risk: ⬜ N/A 🟩 Low 🟨 Medium 🟥 High 🟥 Very High

Figure 70. Project risk due to TRL-HRL misalignment (adapted and enhanced from ANSI/HFES-400:2021).

In one situation, a potential innovation may be immature in terms of its TRL and HRL (i.e., Situation “A” in blue from Figure 70). An example of such a case would entail a solution that is being developed and is not in a production state, for instance, a first-of-a-kind technology (e.g., a new sensor technology or AI-enabled application) being developed in collaboration with an organization for the specific use case identified. The implementation therefore would require significant R&D from a technical maturity and human readiness standpoint.

Situation “B” in yellow presents a second situation in which the innovation is technically mature but the human readiness is lagging. A likely scenario that could create Situation “B” may be a technology that deployed in a different use case being leveraged for a new use case identified from HITT. In this case, the specific differences in the context of use, tasks the innovation supports, and user’s competencies may be different from what the innovation was originally designed for. Consequently, unforeseen risks could be manifested from these differences if proper HFE is not appropriately applied, including fully testing the innovation through V&V using a high-fidelity simulator or actual environment. This situation is likely in cases where commercially available technology is identified and considered, but is applied for a new use case (e.g., an electronic work package platform used at a chemical plant now being considered for a nuclear power plant). This is not to say that such innovations should be avoided but rather that adequate HFE should be applied (e.g., by applying task analysis, usability tests, human-in-the-loop simulations, and human performance modeling) in implementing the innovation in its new use case.

Lastly, Situation “C” in magenta presents the third situation where the innovation is technically ready and has been thoroughly tested from a human readiness perspective. An example of this situation may be a scenario where a utility has already implemented a solution at one of their plants and is now considering implementing the same solution in another of their plants. In this example, the two plants are sufficiently similar as well. Such a scenario may be enabled if the utility has strategically defined their new vision and identified the impacts to their sites’ concept of operations.

For purposes of the example, the following HTI improvements may be considered:

- Virtual resource manager
- Dynamic work execution platform
- Work planning auto-assist or AI software
- Process automation
- Failure mode tracking software
- Data integration of the above capabilities
- Improved administrative controls and OE.

The potential of these HTI improvements provides data of part availability in the inventory ahead of scoping, and planning is used to demonstrate the impact assessment in Step 10. This HTI improvement would provide information to the planner ahead of scoping and planning, which reduces the risk of uncertainties that require the planner to go through the series of decisions shown in Figure 65, thereby eliminating the necessity of these downstream decisions.

4.3.9 Step 9. Develop Process Map Outputs for New State

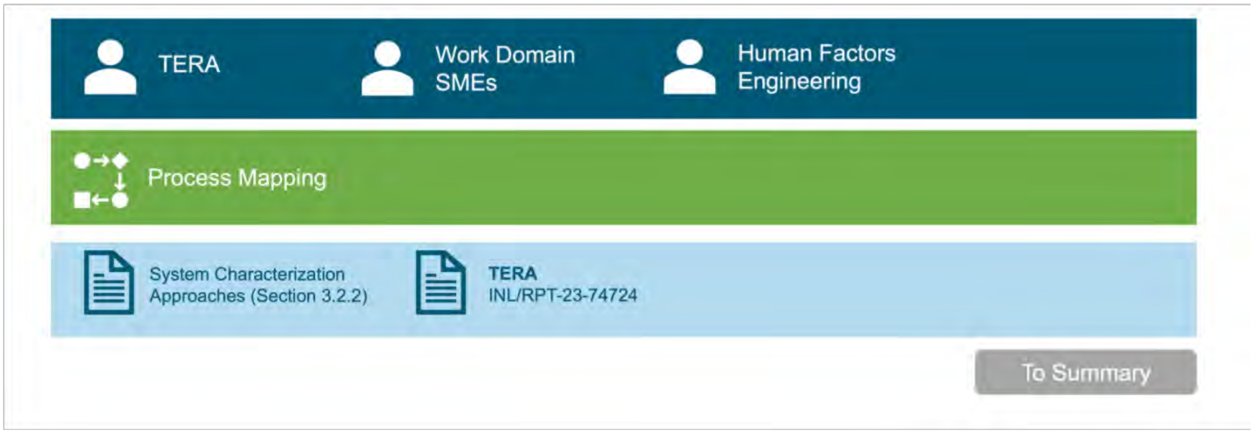


Figure 71. Step 9 of the HITT process.

Practical Guidance: This step involves developing the process map outputs for the new state of the system after the identified HTI improvements have been conceptually integrated. The new state process maps will illustrate how the system will function with the improvements in place, providing a detailed view of the revised workflows, decision points, and information flows. The reuse of the proactive analysis in Step 7 may be performed if there are notable changes to the work process with the identified innovations.

Supporting Information: Developing the process map outputs for the new state is crucial for visualizing the future operations of the system with the HTI improvements in place. These maps serve as a blueprint for the implementation phase, guiding the integration of the improvements into the existing system. They also provide a basis for training and communication about the new workflows and processes across the organization. Additionally, the updated process maps can be used as a tool for monitoring and evaluating the effectiveness of the HTI improvements, facilitating continuous system improvement and optimization.

To systematically develop a new process model with HTI improvements, the following steps should be considered:

1) *Integrate HTI Improvements*. Start by integrating the HTI improvements identified in Step 8 into the process maps. This should reflect changes in workflow, elimination or addition of tasks, modification of decision points, and updates to information flows.

2) *Reevaluate Workflow Efficiency*. With the HTI improvements integrated, assess the efficiency of the new workflows. Look for further opportunities to streamline processes, reduce redundancies, and eliminate unnecessary steps.

3) *Update Decision Points and Pathways*. Reflect the changes in decision-making processes that result from the HTI improvements. This might involve adding new decision nodes, modifying existing ones, or changing the pathways between them based on the new operational logic.

4) *Align with Updated KPIs*. Ensure that the process map for the new state aligns with the updated KPIs. This alignment will facilitate measuring the improvements' impact on the system's performance and ensure they are driving the desired outcomes.

4.3.10 Step 10. Perform Impact Assessment on Modernized Work System

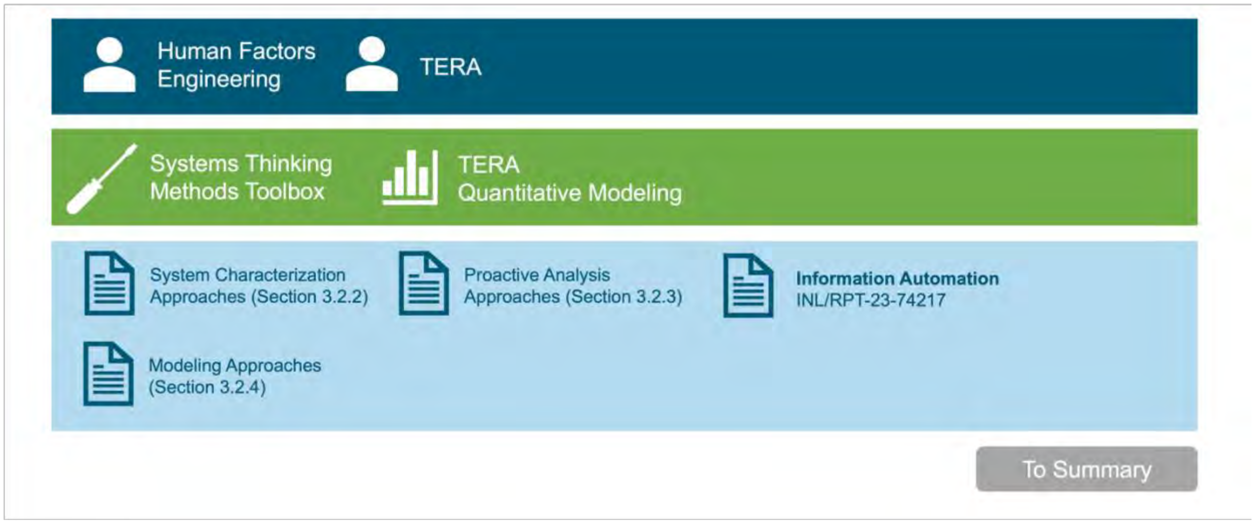


Figure 72. Step 10 of the HITT process.

The final HITT step captures the comparative assessment of the existing work system to the redesigned work system. Using the process map developed in Step 9, Step 10 first begins with performing the impact assessment for the redesign work system to enable a cost-benefit analysis of the proposed innovation(s) identified in Step 8. If the benefits are favorable, a design decision can be made to consider the innovations and begin implementing them.

4.3.10.1 Quantify Impacts and Compare to Existing Work System

Practical Guidance: In this substep, the aim is to assess the impact of the redesigned work system following the implementation of HTI improvements. This involves a comprehensive evaluation to quantify and compare the effects of the new system against the existing one. The assessment should focus on a range of criteria, from efficiency and cost-effectiveness to safety, reliability, and employee satisfaction, ensuring alignment with the organization's broader goals and KPIs.

Supporting Information: The impact assessment of the redesigned work system is a critical step in validating the effectiveness of the HTI improvements. It provides objective evidence of how the changes have affected the overall performance and efficiency of the work system. This assessment helps to justify the investments made in the HTI improvements and guides future decisions on process optimization and system design. Additionally, it offers insights into how well the redesigned system meets the operational goals and objectives of the organization, facilitating continuous improvement and strategic planning.

- *Quantify Improvements*. Using the redesigned work process map, identify the impacts of the new system. This could involve calculating cost savings, time reductions, improvements in safety records, or other relevant metrics.
- *Compare with Baseline*. Compare the quantified improvements against the baseline data from the existing work system before the HTI improvements were implemented. This comparison will highlight the actual impact of the changes made.
- *Assess ROI*. Calculate the ROI of the HTI improvements by comparing the benefits gained (e.g., cost savings, improved efficiency) against the investment made in implementing the changes.

The final part of this step is preparing an impact assessment report. This document should summarize the methodologies employed, the analysis conducted, key findings, and actionable recommendations. This report not only validates the effectiveness of the HTI improvements but also serves as a critical tool for informed decision-making and strategic planning in future process optimization initiatives.

Scenario 1: Human Performance

The evaluation of human performance rate on cost with varying inventory levels demonstrates a clear relationship where improved human performance, reflecting the accuracy and dependability of human performance in the system, causes a cost reduction. As human performance is improved, there is a noticeable decrease in the cost tied to being late and expected consequences. In this scenario, inventory acts as a critical buffer or safeguard. At zero inventory, the system's vulnerability is at its peak, with a reliance on human performance in the scoping and planning phase to order components on time to mitigate cost. However, increasing the inventory levels introduces an additional layer of security, thus diminishing the overall cost. This connection between human performance and inventory level shows the significance of refining human performance and inventory management to mitigate costs effectively.

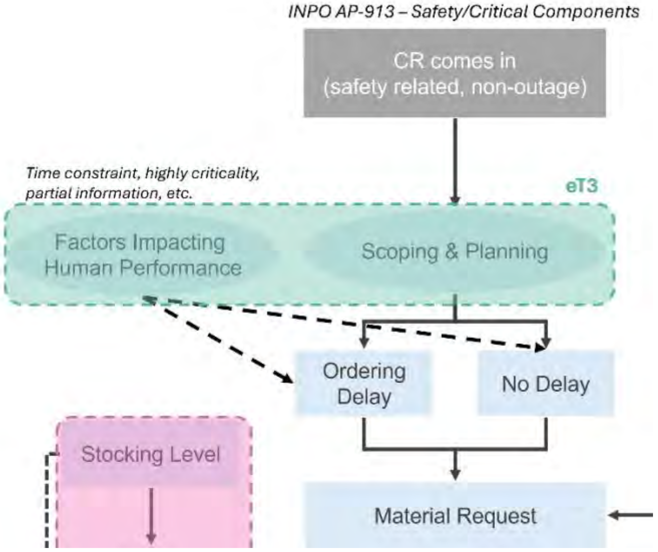


Figure 73. Examination of scoping and planning emergent risk mode from an influence diagram.

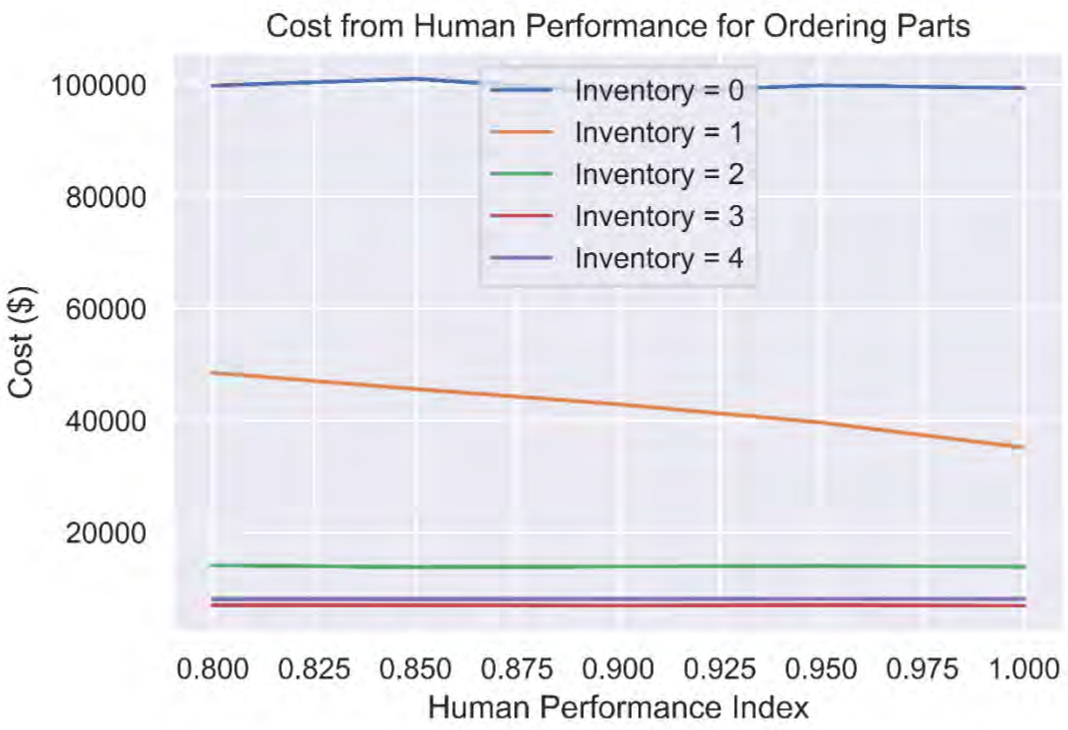


Figure 74. Costs for ordering parts as a function of human performance rate and available inventory.

Scenario 2: Inventory Levels

The impact of inventory level on cost, assessed across a spectrum from zero to five, significantly shifts between scenarios of perfect human performance and constant human error while the inventory is low. In a state of perfect human performance, the influence of inventory on cost diminishes, as the system's reliance on inventory for mitigating errors decreases. Beyond an inventory level greater than three, human performance emerges as a nonfactor in cost contribution, allowing the system to function effectively without increasing cost. On the contrary, under constant human error, inventory level is more important within risk management, where a higher inventory acts as a cushion against human mistakes, thus mitigating cost. In such circumstances, the system's dependency on an ample inventory intensifies to counterbalance the escalated cost stemming from human errors.

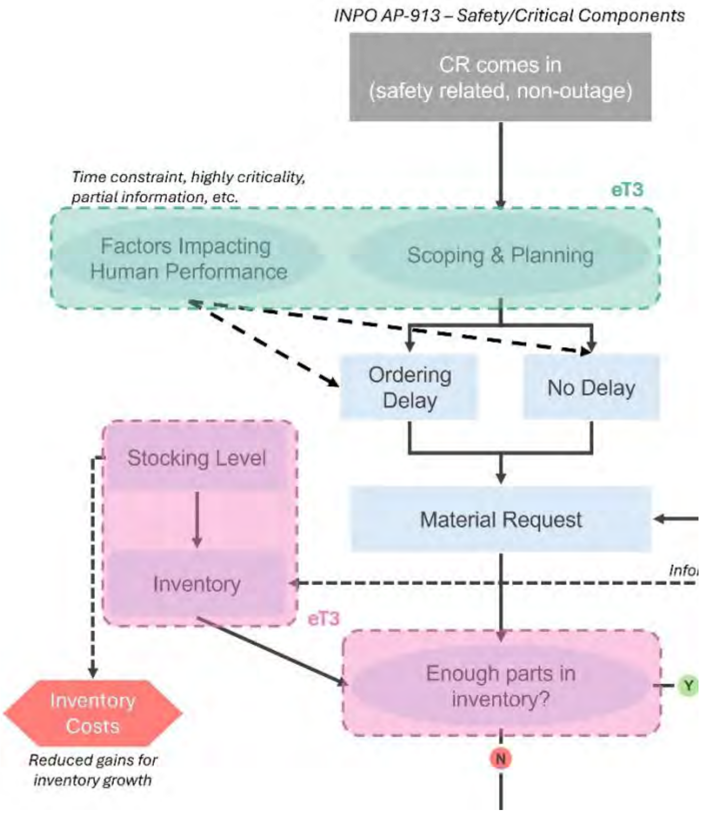


Figure 75. Examination of stocking level and inventory emergent risk mode from an influence diagram.

Figure 76. Cost for ordering parts as a function of mistiming ordering and available inventory.

Under all inventory levels, human error consistently introduces additional cost into the system, emphasizing the critical role of human performance in operational risk management. Regardless of how much inventory is available, errors made by personnel can lead to unforeseen complications, disruptions, and increased likelihood of failure, thereby amplifying the overall cost profile of the operation. The impact of a mistimed event can significantly increase the cost (as shown in Figure 77). It should be noted that this increase in cost must be accounted for every time this process takes place. Due to the weekly nature of this process (work week planning), the risk factors will be multiplied by the number of safety-critical components that require this process as specified by the Institute of Nuclear Power Operations report titled "Equipment Reliability Process Description AP-913."

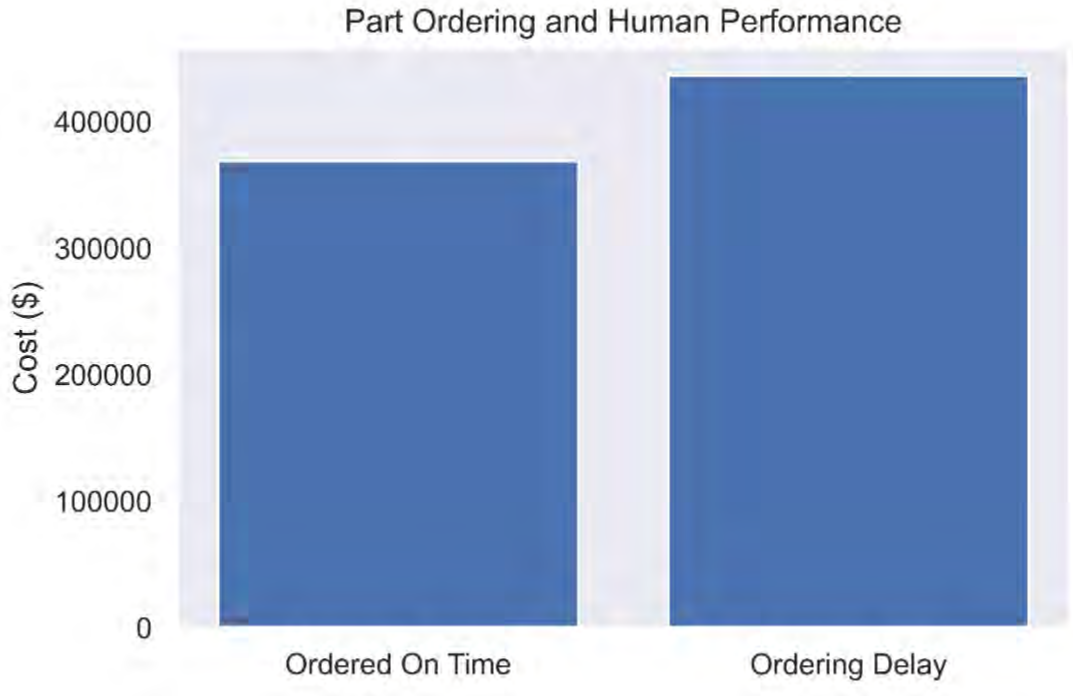


Figure 77. Overall cost comparison of no mistiming error versus mistiming error when ordering parts.

Scenario 3: Quality and Performance Test Pass Rate—Cost

The impact of the quality and performance test pass rate on the overall cost was evaluated for changing levels of pass rate. The result reveals a direct correlation between the pass rate of quality and performance tests and the system's risk level, with an increased pass rate signifying enhanced quality and performance standards, leading to a decreased cost. This relationship can be explained by the fact that higher pass rates are indicative of improved system reliability, reduced defects, and elevated operational standards. As a result, a higher pass rate enhances the system's overall risk profile by diminishing the likelihood of failures or performance issues. This emphasizes the critical need for upholding high-quality performance standards as a means to effectively manage and mitigate risks within operational processes.

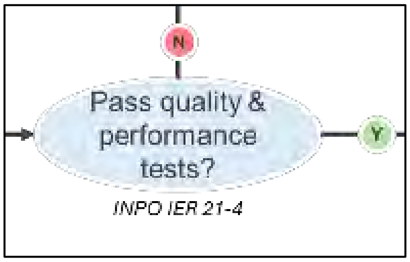


Figure 78. Examination of pass quality and performance test decision point from an influence diagram.

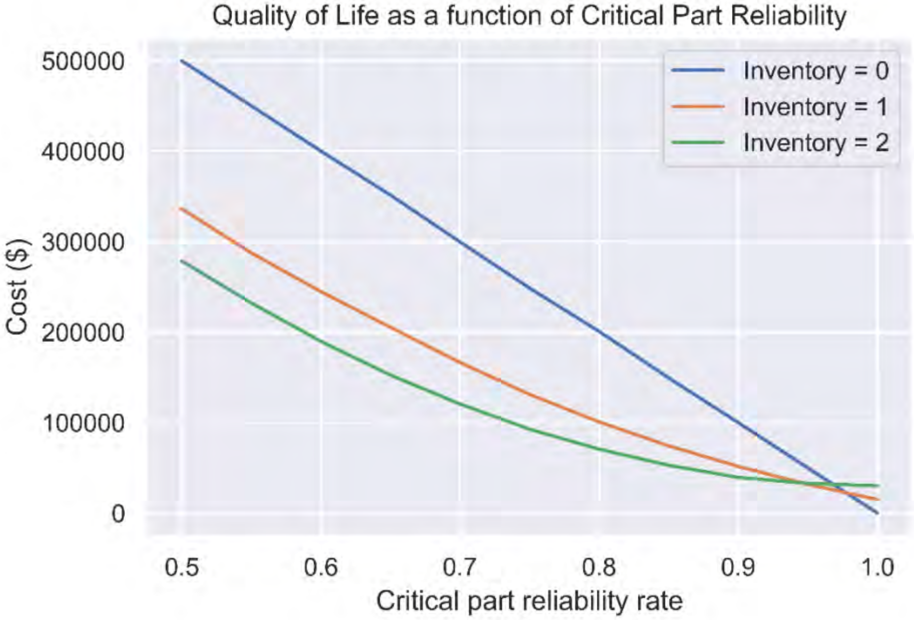


Figure 79. Overall costs for ordering parts as a function of quality and performance test pass rate and available inventory.

Scenario 4: Quality and Performance Test Pass Rate—Quality of Life

The last scenario evaluated is the quality of life impacts as a function of the "Critical Part Reliability Rate." The results (Figure 80) indicating that an increase in the pass rate leads to an improved quality of life for workers can be understood in the context of operational efficiency and predictability. When tests are consistently passed, it implies a stable and reliable work environment, reducing the frequency of urgent, stress-inducing interventions. Workers benefit from a more predictable schedule and decreased pressure from emergency problem-solving, contributing to better work-life balance and overall job satisfaction.

Interestingly, the scenario with an inventory level of 0 presents an anomaly where, contrary to what one might expect, the quality of life is reported to be the best when reliability is low. This can be attributed to the clear, immediate action required in such cases—calling suppliers and ordering parts. This direct response eliminates uncertainties and provides a straightforward path, reducing the stress associated with decision-making and unexpected problem-solving after assuming the inventory would be reliable.

Conversely, when there is inventory and a component fails the quality test, it leads to a significant decrease in quality of life. This situation represents an unexpected failure, disrupting planned activities and schedules, and necessitating immediate and unplanned problem-solving efforts. The presence of an inventory in this context may create a false sense of security, making the sudden need for action following a failed test more jarring and stressful, thereby negatively impacting the quality of life for the workers involved. In such cases, oftentimes work planners may order an excess of parts; however, these parts may degrade when in the warehouse for long periods and therefore degrade in quality or performance.

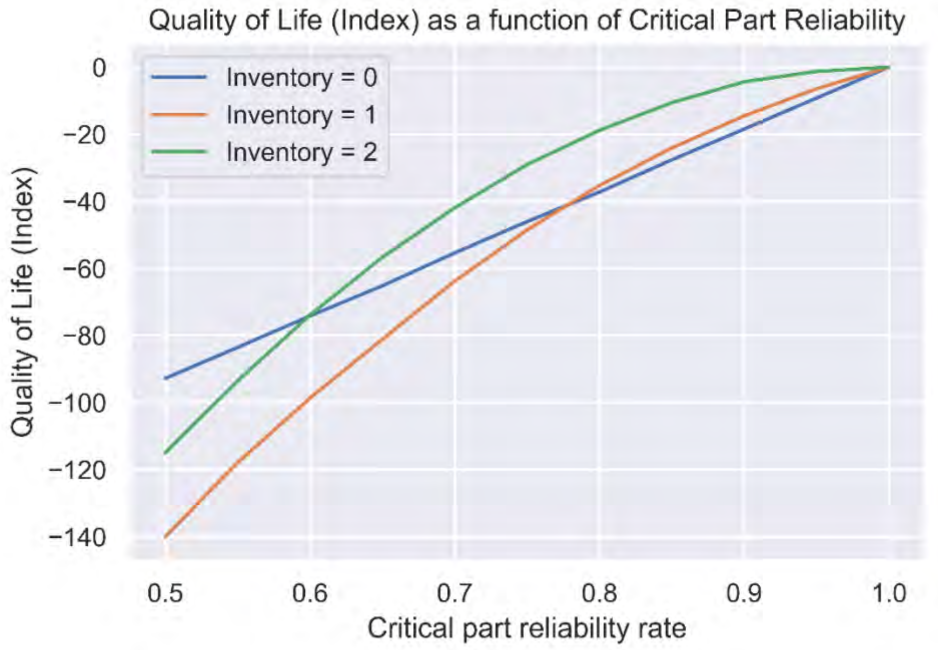


Figure 80. Quality of life improvement as a function of the critical part reliability rate.

4.3.10.2 Determine if Cost/ Benefit is Acceptable and Iterate on Work System as Needed

Practical Guidance: In this section, the focus is on evaluating the financial viability of the redesigned work system through a discounted cash flow (DCF) analysis. This analysis is performed by calculating cost savings and the investment to calculate the NPV to determine if the cost/benefit ratio is acceptable. This evaluation will guide whether further iterations on the work system are needed to optimize the balance between costs and benefits.

Supporting Information: To evaluate the financial benefits of HTI improvements, it's essential to calculate both direct and indirect cost savings. Direct cost savings may include decreased expenditures on materials, labor, and operational activities. Conversely, indirect savings arise from enhanced efficiency, improved regulatory margin, reduced equipment downtime, improved productivity, and improved quality of life. These savings should be quantified over an appropriate timeframe to gauge the total financial impact of the enhancements. Subsequently, performing an NPV analysis assesses the profitability of the work system redesign. This analysis involves estimating the present value of future cash flows generated by the improvements, discounting them to their current value. A positive NPV, where projected earnings surpass the costs, signals the financial viability of the investment.

The assessment of the cost/benefit ratio involves comparing the derived cost savings and NPV with the costs of implementing the HTI improvements. An acceptable ratio is where the financial gains outweigh the investment and operational costs, justifying the economic feasibility of the redesign. If the cost/benefit analysis indicates insufficient financial return or highlights a potential for further efficiency gains, an iterative approach to refining the work system may be necessary. This could entail revising the HTI enhancements, conducting additional impact assessments, or introducing new improvements to boost both performance and financial outcomes. Through a systematic evaluation of the cost/benefit ratio and ongoing refinement of the work system, organizations can ensure that their investment in system redesign and improvements is not only financially prudent but also strategically aligned with their broader goals.

To evaluate the cost/benefit analysis for eliminating human error through eliminating the decisions tied to them via HTI improvements, the system NPV was calculated using the yearly cost savings as the net cash flow. A discount rate of 10% was used in the DCF calculations. In this scenario, the potential yearly cost savings are known by evaluating the nominal system and comparing that to a system with perfect human performance. The yearly cost savings come out to be about $164,580 (this is taking human performance from the assumed 95% to 100%). What is important in this analysis is to identify what the maximum amount of investment is that could support this improvement in reliability. To do that, we evaluate various levels of investment and find where the NPV is equal to zero. In this scenario, a 5% improvement in human performance is worth a $634,890 investment to receive positive returns in 5 years. The results of this analysis can be seen in Figure 81 and Figure 82. It should be noted that, although these returns seem small, the values selected for the model do not represent an actual system financial structure. The returns for a real system financial structure would be expected to be much greater.

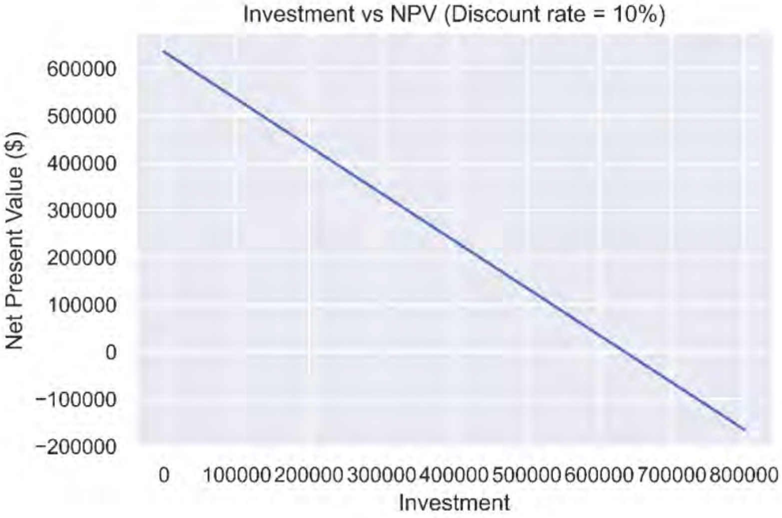


Figure 81. Evaluating DCFs to identify the maximum investment to achieve an NPV equal to zero.

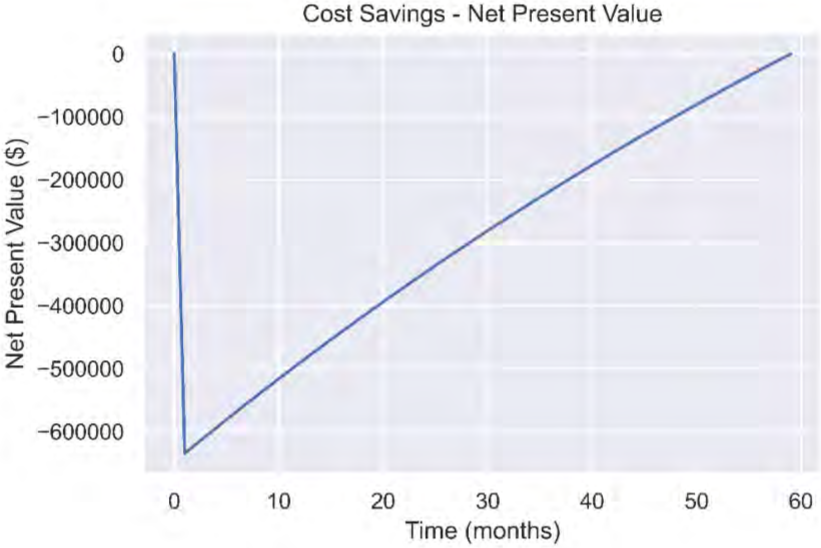


Figure 82. The results of the DCF calculation for the investment that equals a zero NPV.

4.3.11 HTI Design Synthesis: Prototyping and Testing

The HITT process described from the 10 steps enables an informed decision on whether to proceed in implementing a specific HTI improvement, as well as inputs into requirements that drive human readiness for the identified solutions. As these improvements begin to be implemented through conceptual and detailed design activities, HTI continues to have an active role to ensure the human readiness of these changes. The next phase is design synthesis.

HTI is an important consideration to ensure human readiness during conceptual design activities (Kovesdi, Mohon, and Pederson-San Miguel, 2023). Here, HTI is involved in the synthesis of HTI requirements into design solutions. This process entails supporting the specification and integration of the identified solutions into the work environment. In this process, *tests and evaluations* are key HTI activities (i.e., refer to Section 2.2.3 activities).

Design tests can then be applied to collect design feedback and evaluate aspects of human-system performance with these concepts. Here, human-in-the-loop simulation (Section 3.2.4.2) and human performance modeling (Section 3.2.4.3) techniques can be used for evaluating and validating aspects of the HTI design synthesis.

SMEs are essential to the planning, executing, and analyzing for human-in-the-loop simulation activities. Semi-structured interviews with SMEs can be used to understand the potential issues and challenges that users encounter when using the new innovations, offering areas where further refinements and improvements can be made during implementation. Human-in-the-loop simulations can be performed on prototypes or the as-built technology. For prototyping, HTI researchers develop mockups, functional prototypes, or 3D models that represent characteristics of the envisioned solution.

Human performance models can also be used to evaluate the proposed innovations. An advantage of these models is that they do not require SMEs directly, which can be advantageous when SME availability is limited. CogTool and Cogulator are two human performance modeling tools that use GOMS and are used to storyboard and evaluate new technologies early. For instance, work system planning tasks can be broken down into primitives using cognitive modeling software to understand users' cognitive processes and time required to perform these processes. Human performance can then be modeled with Cogulator or CogTool to simulate the work system to evaluate workload levels, response times, visual inputs, decision-making, and other measures with current work processes and changes to the work processes for comparative assessments.

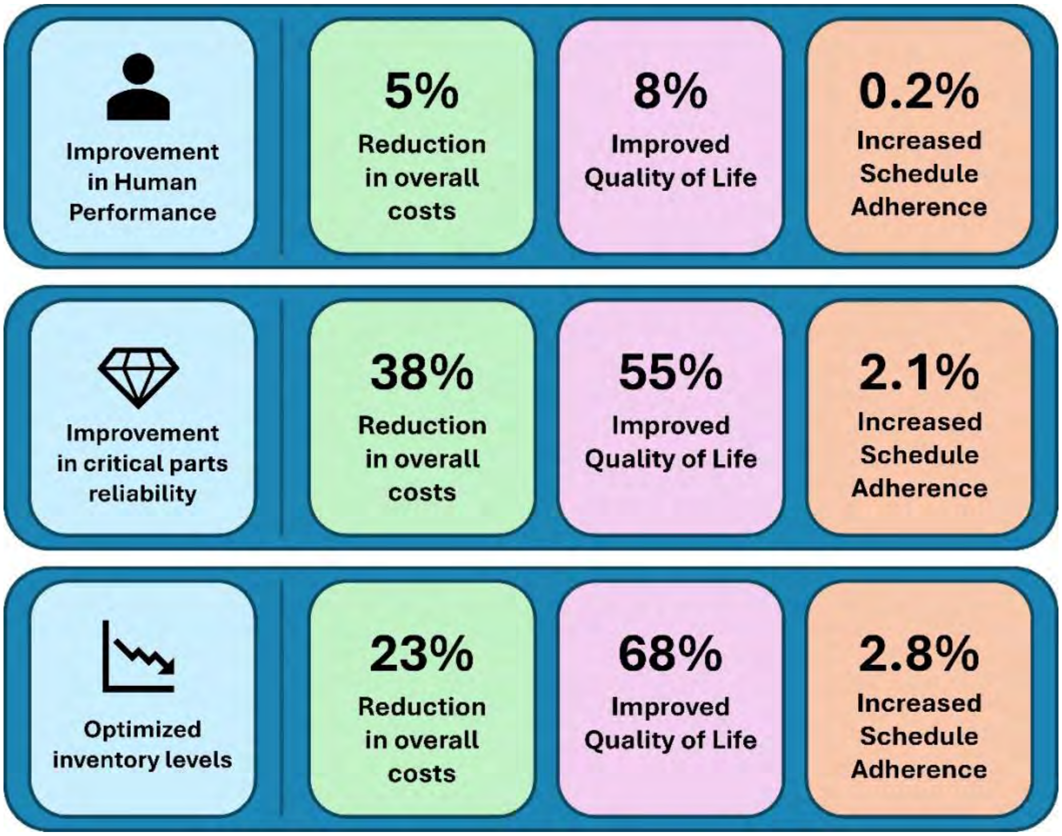
Finally, the HTI improvements can be evaluated using HFE methods like *heuristic evaluation* and *cognitive walkthroughs* that apply HFE design guidelines and principles to evaluate the proposed solutions against. Details of these approaches are discussed in INL/RPT-23-74346. When used together, these approaches provide a comprehensive toolset for tests and evaluations during design synthesis.

5. CONCLUSIONS

The existing nuclear power plant fleet in the United States is in imminent need to reduce O&M costs through a strategic transformation in the way work is performed. Advanced digital technology and automation has a major role in enabling this transformation. However, to effectively integrate digital technology and automation in the existing nuclear power plant operating model, a multidisciplinary approach is needed that addresses technological and sociotechnical (i.e., HTI) considerations.

This report describes an extension to the HTI methodology described in INL/EXT-21-64320 to support the safe, reliable, and efficient use of proposed innovations identified through ION with the intended users in their intended environment to perform their intended tasks. By effectively incorporating HTI into a plant modernization effort using HITT, we believe a utility can significantly improve work performance and overall workforce quality of life.

For instance, if performed to optimize work management, scheduling performance and scope stability can be significantly improved (Figure 2).



Improvement in Human Performance	5% Reduction in overall costs	8% Improved Quality of Life	0.2% Increased Schedule Adherence
Improvement in critical parts reliability	38% Reduction in overall costs	55% Improved Quality of Life	2.1% Increased Schedule Adherence
Optimized inventory levels	23% Reduction in overall costs	68% Improved Quality of Life	2.8% Increased Schedule Adherence

Figure 2 (repeated). Key benefits of the HITT process.

Other significant benefits include:

1) Improved quality of life for all plant workers
2) Improved safety system performance and availability
3) Improved plant reliability (e.g., reduced unplanned corrective work orders)
4) Reduced project management demands
5) Surveillance modifications and obsolescence backlogs

6) Reduced O&M costs.

HITT enables these benefits through developing a rich understanding of the work being performed, the utility's vision, and the opportunities that provide greatest value to optimize performance through a 10-step process that leverages a combination of knowledge elicitation methods that use a diverse set of data sources via DERIVE, the systems thinking methods toolbox, and quantitative modeling. The next step in this research entails continued collaboration with partnering industry collaborators to demonstrate and evaluate the effectiveness of HITT. Key outputs of future work include lessons learned and updates to HITT, as well as technical bases for integrating advanced digital capabilities for both commercially available and future technologies.

6. REFERENCES

Agarwal, V., J. Joe, A.V. Gribok, J.A. Smith, J. Oxstrand, and C. Primer. 2022. “Data Architecture and Analytics Requirements for Artificial Intelligence and Machine Learning Applications to Achieve Condition-Based Maintenance.” INL/RPT-22-70350. Idaho National Laboratory. https://lwrs.inl.gov/Advanced%20IIC%20System%20Technologies/DataArchitectureAnalyticsRequirementsAI.pdf.

Al Rashdan, A., M. Griffel, and L. Powell. 2019. “Automating Fire Watch in Industrial Environments through Machine Learning-Enabled Visual Monitoring.” INL/EXT-19-55703, Idaho National Laboratory.

Al Rashdan, A., J. Oxstrand, and V. Agarwal. 2016. “Automated Work Package: Conceptual Design and Data Architecture.” INL/EXT-16-38809, Idaho National Laboratory. https://doi.org/10.2172/1364774.

ANSI/ISA 101.01. 2015. “Human Machine Interfaces for Process Automation Industries.” International Society of Automation, Research Triangle Park. https://webstore.ansi.org/preview-pages/ISA/preview_ANSI+ISA+101.01-2015.pdf.

ANSI/HFES. 2021. “Human Readiness Level Scale in the System Development Process.” ANSI/HFES-400-2021. https://www.hfes.org/Portals/0/Documents/DRAFT%20HFES%20ANSI%20HRL%20Standard%201_2_2021.pdf.

Bini, D., G. Latouche, and B. Meini. 2005. Numerical methods for structured Markov chains. OUP Oxford.

Boring, R. L. 2014. “One size does not fit all: Human failure event decomposition and task analysis.” INL/CON-14-32870, Idaho National Laboratory. https://www.osti.gov/biblio/1166041.

Boring, R. L., and M. Rasmussen. 2016. “GOMS-HRA: A method for treating subtasks in dynamic human reliability analysis.” In Proceedings of the 2016 European Safety and Reliability Conference: 956–963.

Boring, R., T. Ulrich, and M. Rasmussen. 2018. “Task level errors for human error prediction in GOMS-HRA.” In Safety and Reliability–Safe Societies in a Changing World, edited by Stein Haugen, Anne Barros, Coen Gulijk, Trond Kongsvik, and Jan Erik Vinnem, 433–439. London: CRC Press. https://www.taylorfrancis.com/chapters/oa-edit/10.1201/9781351174664-54/task-level-errors-human-error-prediction-goms-hra-boring-ulrich-rasmussen.

Bremaud, P. 2001. Markov chains: Gibbs fields, Monte Carlo simulation, and queues. Springer Science & Business Media.

Brown, C. 2018. “Why and how to employ the SIPOC model.” Journal of Business Continuity & Emergency Planning, 12 (3): 198–210. https://www.henrystewartpublications.com/sites/default/files/JBC12.3Whyandhowtoemploythe%20SIPOCmodel.pdf.

Burns, C. M., and J. Hajdukiewicz. 2017. Ecological Interface Design. CRC Press. https://doi.org/10.1201/9781315272665.

Center B.P. 2023. Annual Energy Review 2023. U.S. Energy Information Administration.

Clefton, G., J. Joe, and C. Kovesdi. 2018. "Connecting LWRS Human Factors Engineering R&D to NUREG-0711 Elements and Modification Activities in Nuclear Power Plants." INL/EXT-18-45149, Idaho National Laboratory. https://www.osti.gov/biblio/1468638.

Crandall, B., G. Klein, and R. Hoffman. 2006. Working Minds: A Practitioner's Guide to Cognitive Task Analysis. MIT Press. https://doi.org/10.7551/mitpress/7304.001.0001.

Csardi, G., and T. Nepusz. 2006. "The igraph software package for complex network research." InterJournal, Complex Systems, 1695. https://igraph.org.

Dainoff, M., L. Hettinger, L. Hanes, and J. Joe. 2020. "Addressing Human and Organizational Factors in Nuclear Industry Modernization: An Operationally Focused Approach to Process and Methodology." INL/EXT-20-57908, Idaho National Laboratory. https://doi.org/10.2172/1615671.

Dainoff, M.J., et al. 2022. "Using System-Theoretic Accident Model and Processes and Causal Analysis to Manage Organizational Information to Enable Digitalization and Information Automation." INL/RPT-22-69058, Idaho National Laboratory. https://doi.org/10.2172/1894897.

Dallat, C., P. M. Salmon, and N. Goode. 2018. "Identifyings and emergent risks across sociotechnical systems: the NETworked hazard analysis and risk management system (NET-HARMS)." Theoretical Issues in Ergonomics Science, 19 (4): 456–482. https://doi.org/10.1080/1463922X.2017.1381197.

Dekker, S. 2016. Drift into failure: From hunting broken components to understanding complex systems. CRC Press.

Doran, G. T. 1981. "There's a SMART way to write management's goals and objectives." Management review, 70 (11): 35–36. https://community.mis.temple.edu/mis0855002fall2015/files/2015/10/S.M.A.R.T-Way-Management-Review.pdf.

Düzgün, H. S., and N. Leveson. 2018. "Analysis of soma mine disaster using causal analysis based on systems theory (CAST)." Safety Science, 110 (A): 37–57. https://doi.org/10.1016/j.ssci.2018.07.028.

EPRI. 2015. "Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification: Guidelines for Planning, Specification, Design, Licensing, Implementation, Training, Operation, and Maintenance for Operating Plants and New Builds." Report 3002004310, Electric Power Research Institute. https://www.epri.com/research/products/000000003002004310.

EPRI. 2020. "Digital Systems Engineering: Modernization Guide for Practitioners." Report 3002015797, Electric Power Research Institute.

EPRI. 2021a. "Digital Engineering Guide: Decision Making Using Systems Engineering." Report 3002011816, Electric Power Research Institute. https://www.epri.com/research/products/000000003002011816.

EPRI. 2021b. “HAZCADS: Hazards and Consequences Analysis for Digital Systems, Revision 1.” Report 3002016698, Electric Power Research Institute. https://www.epri.com/research/programs/065093/results/3002016698.

EPRI. 2021c. “HFAM - Human Factors Analysis Methodology for Digital Systems: A Risk-Informed Approach to Human Factors Engineering.” Report 3002018392, Electric Power Research Institute. https://www.epri.com/research/programs/065770/results/3002018392.

France, M. E. 2017. “Engineering for Humans: A New Extension to STPA.” Ph.D. Thesis, Massachusetts Institute of Technology. http://hdl.handle.net/1721.1/112357.

Fuld, R. B. 2000. “The fiction of function allocation, revisited.” International Journal of Human-Computer Studies, 52 (2): 217–233. https://doi.org/10.1006/ijhc.1999.0286.

Gideon, O., and R. Boring. 2023. “A Graded Approach to Simulators: Feature Requirements Mapping to Simulator Types for Nuclear Plant Control Room Research Use Cases.” Augmented, Virtual and Mixed Reality Simulation, 118 (1): 196–208. https://doi.org/10.54941/ahfe1004454.

Guastello, S. J. 2015. Human Factors Engineering and Ergonomics: A Systems Approach. CRC Press. https://industri.fatek.unpatti.ac.id/wp-content/uploads/2019/03/102-Human-Factors-Engineering-and-Ergonomics-A-Systems-Approach-Stephen-J.-Guastello-Edisi-2-2013.pdf.

Hall, A., T. Miyake, J.C. Joe, Z.A. Spielman, and J.H. Oxstrand. 2023. “Digitalization Guiding Principles and Method for Nuclear Industry Work Processes.” INL/RPT-23-74429, Idaho National Laboratory. https://www.osti.gov/servlets/purl/2251507.

Hollnagel, E. 2017. Safety-II in Practice: Developing the Resilience Potentials. Routledge.

Hugo, J. 2015. “Work Domain Analysis Methodology for Development of Operational Concepts for Advanced Reactors.” INL/EXT-15-34783, Idaho National Laboratory. https://doi.org/10.2172/1179386.

Hunton, P., and R. England. 2019. “Addressing Nuclear I&C Modernization Through Application of Techniques Employed in Other Industries.” INL/EXT-19-55799, Idaho National Laboratory. https://doi.org/10.2172/1567848.

Hunton, P. and R. England. 2021. “Digital Infrastructure Migration Framework.” INL/EXT-21-64580. Idaho National Laboratory. https://doi.org/10.2172/1822876.

Hunton, P., C. Kovesdi, and J. Joe. 2023. “Limerick Safety-Related Instrumentation and Control Upgrade Human Factors Engineering Conceptual Verification Report.” INL/RPT-23-71063, Idaho National Laboratory.

Hunton, P., C. Kovesdi, J. Joe., and J. Mohon. 2023. “Limerick Safety-Related Instrumentation and Control Upgrade Human Factors Engineering Preliminary Validation Report.” INL/RPT-23-71903, Idaho National Laboratory.

Hunton, P., R. England, D. Herrell, S. Lawrie, S., and M. Samselski. 2022. “Safety-Related Instrumentation and Control Pilot Upgrade: Initial Scoping Phase Implementation and Lessons Learned.” Nuclear Technology, 209 (3): 366–376. https://doi.org/10.1080/00295450.2022.2053808.

Hunton, P., R. England, J. Segner, M. Samselski, G. Bonanni, S. Schumacher, and P. Krueger. 2023. “Safety-Related Instrumentation and Control Pilot Upgrade: Conceptual – Detailed Design Phase Report and Lessons Learned.” INL/RPT-23-72105, Idaho National Laboratory. https://doi.org/10.2172/1983868.

Hunton, P., and S. Lawrie. 2023. “Integrated Operations for Nuclear: Work Reduction Opportunity Demonstration Strategy.” INL/RPT-23-74671, Idaho National Laboratory. https://www.osti.gov/biblio/2000859.

IAEA. 2007. “Safety of Nuclear Power Plants: Specific Safety Requirements.” Safety Standard [SSR-2/2 (Rev.1) Requirement 24; 5.28] [IAEA Safety Guideline SSG-50; 2.40]. International Atomic Energy Agency.

IAEA. 2021. “Human Factors Engineering Aspects of Instrumentation and Control System Design.” NR-T-2.12. International Atomic Energy Agency. https://www.iaea.org/publications/13589/human-factors-engineering-aspects-of-instrumentation-and-control-system-design.

IEC. 2000. “Nuclear Power Plants - Design of Control Rooms - Functional Analysis and Assignment.” IEC 61839, International Electrotechnical Commission. https://webstore.iec.ch/publication/6002.

IEEE. 1999. “Guide for the Evaluation of Human-System Performance in Nuclear Power Generating Stations.” IEEE-845, Institute of Electrical and Electronics Engineers. https://ieeexplore.ieee.org/document/798774.

IEEE. 2017. “Guide for Incorporating Human Reliability Analysis into Probabilistic Risk Assessment for Nuclear Power Generating Stations and Other Nuclear Facilities.” IEEE 1082, Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/IEEESTD.2018.8332121.

IEEE. 2018. “Standard Criteria for Safety Systems for Nuclear Power Generating Stations.” IEEE-603, Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/IEEESTD.2018.8573235.

IEEE. 2020. “Recommended Practice for the Application of Human Factors Engineering to Systems, Equipment, and Facilities of Nuclear Power Generating Stations and Other Nuclear Facilities.” IEEE-1023, Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/IEEESTD.2021.9361514.

IEEE. 2021. “Guide for Human Factors Engineering for the Validation of System Designs and Integrated Systems Operations at Nuclear Facilities.” IEEE-2411, Institute of Electrical and Electronics Engineers. https://ieeexplore.ieee.org/document/9690140.

International Council on Systems Engineering. 2015. Systems Engineering Handbook: A Guide for System Life Cycle Processing and Activities Version 4. https://www.incose.org/publications/products/se-handbook-v4.

ISO/ IEC. 1998. “Ergonomic Requirements for Office Work with Visual Display Terminals (VDT)s- Part II Guidance on Usability.” ISO/IEC 9241-11:1998(E), International Organization for Standardization. https://www.iso.org/standard/16883.html.

Joe, J., L. Hettinger, M. Dainoff, P. Murray, and Y. Yamani. 2023. “Optimizing Information Automation Using a New Method Based on System-Theoretic Process Analysis.” INL/RPT-23-73099, Idaho National Laboratory. https://www.osti.gov/biblio/1988134.

Joe, J., L. Hettinger, Y. Yamani, P. Murray, and M. Dainoff. 2023. “Optimizing Information Automation Using a New Method Based on System-Theoretic Process Analysis: Tool Development and Method Evaluation.” INL/RPT-23-74217, Idaho National Laboratory. https://lwrs.inl.gov/Advanced%20IIC%20System%20Technologies/OptimizingInformationAutomation.pdf.

Kirwan, B., and L. Ainsworth. 1992. A Guide to Task Analysis: The Task Analysis Working Group. London: CRC Press. https://doi.org/10.1201/b16826.

Kovesdi, C. 2022. “Addressing Function Allocation for the Digital Transformation of Existing Nuclear Power Plants.” Human Factors in Energy: Oil, Gas, Nuclear and Electric Power, 54: 49–55. https://doi.org/10.54941/ahfe1002220.

Kovesdi, C., and K. Le Blanc. 2021. “A tool for performing link analysis, operational sequence analysis, and workload analysis to support nuclear power plant control room modernization.” In Advances in Artificial Intelligence, Software and Systems Engineering: Proceedings of the AHFE 2020 Virtual Conferences on Software and Systems Engineering, and Artificial Intelligence and Social Computing, 1213: 597–604. Springer International Publishing. https://doi.org/10.1007/978-3-030-51328-3_81.

Kovesdi, C., et al. 2022a. “Human Factors Engineering Combined Functional Requirements Analysis, Function Allocation, and Task Analysis for the Limerick Control Room Upgrade: Results Summary Report.” INL/RPT-22-68995, Idaho National Laboratory.

Kovesdi, C., P. Hunton, J. Mohon, J. Joe, T. Miyake, and S. Whitmore. 2022b. “Demonstration and Evaluation of the Human-Technology Integration Function Allocation Methodology.” INL/RPT-22-68472, Idaho National Laboratory. https://doi.org/10.2172/1881859.

Kovesdi, C., and J. Joe. 2019. “Exploring The Use of Cognitive Models for Nuclear Power Plant Human-System Interface Evaluation.” In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 63 (1): 2190–2194. Sage CA: Los Angeles, CA: SAGE Publications. https://doi.org/10.1177/1071181319631136.

Kovesdi, C., J. Joe, and R. Boring. 2018. “A Guide for Selecting Appropriate Human Factors Methods and Measures in Control Room Modernization Efforts in Nuclear Power Plants.” In Proceedings of the International Conference on Applied Human Factors and Ergonomics, 441–452. Springer, Cham. https://doi.org/10.1007/978-3-319-94229-2_43.

Kovesdi, C., J. Mohon, and C. Pedersen-San Miguel. 2023. “Demonstration of the Human and Technology Integration Guidance for the Design of Plant-Specific Advanced Automation and Data Visualization Techniques.” INL/RPT-23-71395, Idaho National Laboratory. https://doi.org/10.2172/1963680.

Kovesdi, C., J. Mohon, and K. Wilhite. 2023. “Human and Technology Integration Evaluation of Advanced Automation and Data Visualization.” INL/RPT-23-74346, Idaho National Laboratory. https://lwrs.inl.gov/Advanced%20IIC%20System%20Technologies/HumanTechnologyIntegrationEvaluation.pdf.

Kovesdi, C., et al. 2021. “Nuclear Work Function Innovation Tool Set Development for Performance Improvement and Human Systems Integration.” INL/EXT-21-64428, Idaho National Laboratory.

Kovesdi, C., et al. 2020. “Development of an Advanced Integrated Operations Concept for Hybrid Control Rooms.” INL/EXT-20-57862, Idaho National Laboratory. https://lwrs.inl.gov/Advanced%20IIC%20System%20Technologies/Development_of_an_Advanced_Integrated_Operations_Concept_for_Hybrid_CR.pdf.

Kovesdi, C., Z. Spielman, R. Hill, J. Mohon, T. Miyake, and C. Pedersen. 2021. “Development of an Assessment Methodology That Enables the Nuclear Industry to Evaluate Adoption of Advanced Automation.” INL/EXT-21-64320, Idaho National Laboratory. https://doi.org/10.2172/1822880.

Kovesdi., C., Z. Spielman, R. Hill, K. Le Blanc, and J. Oxstrand. 2018. “Development and Evaluation of the Conceptual Design for a Liquid Radiological Waste System in an Advanced Hybrid Control Room.” INL/EXT-18-51107, Idaho National Laboratory. https://doi.org/10.2172/1495183.

Le Blanc, K. et al. 2018. “Control Room Modernization End-State Design Philosophy.” INL/EXT-18-44798, Idaho National Laboratory. https://doi.org/10.2172/1495035.

Lee, J. D., C. Wickens, Y. Liu, and L. Boyle. 2017. Design for People. An Introduction to Human Factors Engineering. Createspace, 3rd Edition. https://www.researchgate.net/publication/319402797_Designing_for_People_An_introduction_to_human_factors_engineering.

Leveson, N., and J. Thomas. 2018. “STPA Handbook.” http://psas.scripts.mit.edu/home/get_file.php?name=STPA_handbook.pdf.

Liao, H., K. Groth, S. Stevens-Adams, and J. Xing. 2014. “Leveraging existing human performance data for quantifying the IDHEAS HRA method.” In Safety, Reliability and Risk Analysis: Beyond the Horizon-Steenbergen et al.(Eds), 563–569. https://www.taylorfrancis.com/chapters/edit/10.1201/b15938-87/leveraging-existing-human-performance-data-quantifying-idheas-hra-method-liao-groth-stevens-adams-xing.

McCormack, P., G. Read, A. Hulme, B. Lane, S. McLean, and P. Salmon. 2023. “Using systems thinking-based risk assessment methods to assess hazardous manual tasks: A comparison of Net-HARMS, EAST-BL, FRAM, and STPA.” Ergonomics, 66 (5): 609–629. https://doi.org/10.1080/00140139.2022.2105959.

Mohon, J., and C. Kovesdi. 2022. “Demonstrating the Value of 3D Models to Support Large-Scale Digital Modifications at Nuclear Power Plants.” InDigital Human Modeling and Applied Optimization. AHFE (2022) International Conference, 46. http://doi.org/10.54941/ahfe1001894.

Mohon, J., C. Kovesdi, P. Hunton, and J. Joe. 2023. “3D Modeling of Safety-Related Upgrade Pilot Project.” Proceedings of 13th Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, NPIC and HMIT 2023: 111–119. American Nuclear Society. https://doi.org/10.13182/NPICHMIT23-40999.

Naikar, N., A. Brady, G. Moy, H.W. Kwok. 2023. “Designing human-AI systems for complex settings: Ideas from distributed, joint, and self-organising perspectives of sociotechnical systems and cognitive work analysis.” Ergonomics, 66 (11): 1669–1694. https://doi.org/10.1080/00140139.2023.2281898.

Oxstrand, J., K. Le Blanc, and A. Bly. 2016. “Design Guidance for Computer-Based Procedures for Field Workers.” INL/EXT-16-39808, Idaho National Laboratory. https://doi.org/10.2172/1344173.

Read, G. J., P. M. Salmon, M. G. Lenne, N. A. Stanton, C. M. Mulvihill, and K. L. Young. 2016. "Applying the prompt questions from the cognitive work analysis design toolkit: A demonstration in rail level crossing design." Theoretical Issues in Ergonomics Science, 17 (4): 354–375. https://doi.org/10.1080/1463922X.2016.1143987.

Remer, S. J., et al. 2023. "Integrated Operations for Nuclear Business Operation Model Analysis and Industry Validation." INL/EXT-22-68671, Revision 1, Idaho National Laboratory. https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_64103.pdf.

Remer, J., K. Thomas, S. Lawrie, K. Martin, and C. O'Brien. 2021. "Process for Significant Nuclear Work Function Innovation Based on Integrated Operations Concepts." INL/EXT-21-64134, Idaho National Laboratory. https://lwrs.inl.gov/Advanced%20IIC%20System%20Technologies/ProcessSignificantNuclearWorkFunctionInnovation.pdf.

Roth, E. M., C. Sushereba, L. Militello, J. Diiulo, and K. Ernst. 2019. "Function allocation considerations in the era of human autonomy teaming." Journal of Cognitive Engineering and Decision Making, 13 (4): 199–220. https://doi.org/10.1177/1555343419878038.

Salmon, P., Hulme, A., Walker, G. H., Waterson, P., and Stanton, N. A. 2020. "The Accident Network (AcciNet): A new accident analysis method for describing the interaction between normal performance and failure." In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 64 (1): 1676–1680. Los Angeles, CA: SAGE Publications. https://doi.org/10.1177/1071181320641407.

Salmon, P. M., and G. J. Read. 2019. "Many model thinking in systems ergonomics: A case study in road safety." Ergonomics, 62 (5): 612–628. https://doi.org/10.1080/00140139.2018.1550214.

Salmon, P. M., et al. 2023. Handbook of Systems Thinking Methods. CRC Press. https://doi.org/10.1201/9780429281624.

Schmid, D., B. Korn, and N. A. Stanton. 2020. "Evaluating the reduced flight deck crew concept using cognitive work analysis and social network analysis: Comparing normal and data-link outage scenarios." Cognition, Technology & Work, 22: 109–124. https://doi.org/10.1007/s10111-019-00548-5.

Scholtes, P. R., B. L. Joiner, and B. J. Streibel. 2003. The Team Handbook. Oriel incorporated.

Sergio, L.-M., P. Vassiliadis, and J. Trujillo. 2004. "Data mapping diagrams for data warehouse design with UML." 23rd International Conference on Conceptual Modeling. Shanghai, China. http://dx.doi.org/10.1007/978-3-540-30464-7_16.

Shahbaz, Q. 2015. Data Mapping for Data Warehouse Design. Elsevier. https://doi.org/10.1016/C2015-0-04423-9.

Skraaning Jr, G., and G. A. Jamieson. 2023. "The failure to grasp automation failure." Journal of Cognitive Engineering and Decision Making. https://doi.org/10.1177/15553434231189375.

Spangler, R., et al. 2023. "Development of a Technical, Economic, and Risk Assessment Framework for the Evaluation of Work Reduction Opportunities." INL/RPT-23-74724, Idaho National Laboratory. https://doi.org/10.2172/2008364.

Spielman, Z., J. Mohon, C. Pedersen-San Miguel, and C. Kovesdi. 2022. “Demonstration and Evaluation of the Human-Technology Integration Guidance for Plant Modernization.” INL/RPT-22-70538, Idaho National Laboratory. https://doi.org/10.2172/1963677.

St Germain, S., J. Masterlark, R. Priddy, and S. Beck. 2019. “Methods to Automate Assessing Outage Risk and Technical Specification Compliance for Planned Work and Current Plant Conditions.” INL/EXT-19-55308, Idaho National Laboratory. https://doi.org/10.2172/1560376.

Stanton, N. A., P. M. Salmon, L. A. Rafferty, G. H. Walker, C. Baber, and D. P. Jenkins. 2013. Human Factors Methods: A Practical Guide for Engineering and Design. CRC Press. https://doi.org/10.1201/9781315587394.

Stanton, N. A., P. M. Salmon, G. H. Walker, D. P. Jenkins, Eds. 2017. Cognitive Work Analysis: Applications, Extensions and Future Directions. CRC Press. https://doi.org/10.1201/9781315572536.

Stuster, J. 2019. Task analysis: How to develop an understanding of work. Washington DC: Human Factors and Ergonomics Society. https://www.hfes.org/Publications/Books/Task-Analysis-How-to-Develop-an-Understanding-of-Work.

Thomas, K. D., J. Remer, and C. Primer. 2020. “Analysis and Planning Framework for Nuclear Plant Transformation.” INL/EXT-20-59537, Idaho National Laboratory. https://doi.org/10.2172/1668293.

Ulrich, T., R. Lew, T. Mortenson, J. Park, H. Medema, and R. Boring. 2020. “An Integrated Energy Systems Prototype Human- System Interface for a Steam Extraction Loop System to Support Joint Electricity-Hydrogen Flexible Operations.” INL/EXT-20-57880. Idaho National Laboratory. https://doi.org/10.2172/1608624.

“Appendix B to Part 50—Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants.” Code of Federal Regulations, Section 10, Part 50, Criterion 16 (2021). https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-appb.html.

“Protection of digital computer and communication systems and networks.” Code of Federal Regulations, Section 10, Part 73.54 (2015). https://www.nrc.gov/reading-rm/doc-collections/cfr/part073/part073-0054.html.

U.S. NRC. 2018. “Digital Instrumentation and Controls Interim Staff Guidance.” DI&C-ISG-06, 6, Rev. 2, U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML1826/ML18269A259.pdf.

U.S. NRC. 1983. “Methodology for Allocating Nuclear Power Plant Control Functions to Human or Automatic Control.” NUREG/CR-3331, U.S. Nuclear Regulatory Commission.

U.S. NRC. 2007. “Demonstrating the Feasibility and Reliability of Operator Manual Actions in Response to Fire.” NUREG-1852, U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML0730/ML073020676.pdf.

U.S. NRC. 2012. “Human Factors Engineering Program Review Model.” NUREG-0711, Rev. 3, U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML1228/ML12285A131.pdf.

U.S. NRC. 2012. “NRC/EPRI Draft Report on Integrated Decision-Tree Human Event Analysis System (IDHEAS).” U.S. Nuclear Regulatory Commission.

U.S. NRC. 2002. “Human-System Interface Design Review Guidelines.” NUREG-0700, Rev. 2., U.S. Nuclear Regulatory Commission. https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0700/r2/index.html.

U.S. NRC. 2016. “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants - Human Factors Engineering.” NUREG-0800, Chapter 18, Rev. 3, U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML1612/ML16125A114.pdf.

Underwood, P., P. Waterson, and G. Braithwaite. 2016. “Accident investigation in the wild’–A small-scale, field-based evaluation of the STAMP method for accident analysis.” Safety Science, 82: 129–143. https://doi.org/10.1016/j.ssci.2015.08.014.

Urbanic, R., G. Bacioiu. 2013. “Using a systems dynamics model to assess skill level impact.” In IIE Annual Conference.

Vazquez J. A., B. D. Green, and D. R. Desaulniers. 2022. “Regulatory Considerations for the Potential Use of a Multi-Stage Validation Testing Approach to Support Human Factors Engineering Technical Reviews for Proposed Nuclear Power Plant Control Room Design Modifications.” In Proceedings in the Human Factors and Ergonomics Society Annual Meeting, 66 (1): 1381–1385. https://journals.sagepub.com/doi/10.1177/1071181322661492.

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APPENDIX A
HUMAN READINESS LEVELS

(ANSI/HFES-400:2021)

	HRL Level	Description	HFE Approaches
Research and Development	*HRL 1:* Basic principles for human characteristics, performance, and behavior observed and reported	– This first level of human readiness observes and reports basic principles for human characteristics, performance, and behavior. – It is a broad, high-level exploration of human capabilities and limitations and basic human-centered issues and risks relevant to a developing concept or proposed application.	– Literature Reviews – Operating Experience Reviews – High-Level Function/ Task Analysis
	HRL 2: Human-centered concepts, applications, and guidelines defined	– As practical applications are being invented or identified, implications for human involvement are analyzed concurrently. – Relevant human-centered concepts, applications, and guidelines are developed to begin identifying human use requirements and provide inputs for preliminary conceptual designs. – Human systems experts begin establishing objective and subjective metrics that will signal accomplishment of successful human performance for the developing technology. – While HRL 2 focuses on applied research, basic human research begun at HRL 1 may continue.	
	HRL 3: Human-centered requirements to support human performance and human- technology interactions established	– Critical characteristics and functions of the initial proof of concept are demonstrated analytically or experimentally; however, individual components are not yet integrated or representative. – Analyses of human operational, environmental, functional, cognitive, and physical needs to understand requirements for supporting human user roles and meeting expected operational and system demands have been completed.	– Initial Function Allocation – Detailed Function/ Task Analysis – Personnel Competencies Identified – Human Factors Risk Assessment
Technology Demonstration	*HRL 4:* Modeling, part-task testing, and trade studies of human systems design concepts and applications completed	– Human systems design concepts and applications are evaluated in basic laboratory environments or controlled field settings, using ad hoc modeling and part-task testing with low-fidelity prototypes and mockups that begin integrating key elements. – Trade studies to analyze and identify viable human systems design options have been completed.	– Part-Task/ Formative Usability Testing – Updated Function Allocation and Task Analysis – Human Factors Risk Assessment
	HRL 5: Human-centered evaluation of prototypes in mission-relevant part-task simulations completed to inform design	– Human performance is evaluated via prototypes in mission-relevant part-task simulations or actual environments. – The fidelity of key elements has increased significantly, and users participating in testing are independent from the design team and more representative of the target population. – HRL 5 is the latest level to begin engaging more representative users during testing.	
	HRL 6: Human systems design fully matured and demonstrated in a relevant high-fidelity, simulated environment or actual environment	– Human performance is evaluated with objective metrics in relevant high-fidelity simulated or actual environments, with a functional prototype and representative users. – HRL 6 represents a major step up in demonstrated human readiness. – The human-centered design is essentially finished, though minor modifications may still be made at subsequent levels.	– Part-Task/ Formative Usability Testing – Updated Function Allocation and Task Analysis – Human Factors Risk Assessment – Procedure Development – Training – Human Factors Issue Tracking
Deployment	*HRL 7:* Human systems design fully tested and verified in operational environment with system hardware and software and representative users	– Human performance is evaluated for the full range of usage scenarios and tasks with the final development system in an operational environment. – Recommended strategies to support human use and resolve human performance issues have been satisfactorily incorporated. – The final development system conforms to key human-centered guidance and requirements.	– Human Factors Validation Testing – Human Factors Issue Tracking
	HRL 8: Human systems design fully tested, verified, and approved in mission operations, using completed system hardware and software and representative users	– Human performance is verified with the production system in a representative environment before full-rate production and final system fielding. – HRL 8 represents the final opportunity to identify and incorporate elements to support human readiness before fielding and operational use. – Any remaining human use issues are satisfactorily resolved.	
	HRL 9: System successfully used in operations across the operational envelope with systematic monitoring of human- system performance	– The qualified system is fielded in the operational environment and operated by the intended users. – Human systems experts continue to monitor the fielded system and resolve emerging issues. – Human performance issues, errors, and accidents are systematically analyzed to identify enhancements.	– Human Factors Monitoring

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APPENDIX B
RESILIENCE ASSESSMENT GRID QUESTIONNAIRE

The formative questions from RAG presented below are grouped around the four key elements of resilient performance (Hollnagel, 2017). These questions are adapted from Hollnagel (2017) and can be applied in their current form or tailored. The questions are meant to be presented in rating form, using a standardized Likert scale:

Missing	Deficient	Unacceptable	Acceptable	Satisfactory	Excellent

- **Excellent** – the system meets and exceeds the criteria for the required ability.
- **Satisfactory** – the system fully meets all reasonable criteria for the required ability.
- **Acceptable** – the system meets the nominal criteria for the required ability.
- **Unacceptable** – the system does not meet the nominal criteria for the required ability.
- **Deficient** – there is insufficient ability to provide the required ability.
- **Missing** – there is no ability to provide the required ability.

Key Definitions

The ability to respond. Knowing what to do, or being able to respond to regular and irregular changes, disturbances, and opportunities by activating prepared actions or by adjusting current mode of functioning.

The ability to monitor. Knowing what to look for, or being able to monitor that which is or could seriously affect the system's performance in the near term – positively or negatively. The monitoring must cover the system's own performance as well as what happens in the environment.

The ability to learn. Knowing what has happened, or being able to learn from experience, in particular to learn the right lessons from the right experience.

The ability to anticipate. Knowing what to expect, or being able to anticipate developments further into the future, such as potential disruptions, novel demands or constraints, new opportunities, or changing operating conditions.

Questionnaire

Ability to Respond

Q1. *Event List.* Is there a prepared list of potential conditions for which the organization should be ready to respond?

Q2. *Relevance of Event List.* Has the list been verified and/ or is it revised on a regular basis?

Q3. *Response Set.* Have responses been planned and prepared for every event in the list?

Q4. *Response Set.* Do people know what to do when one of these event occur?

Q5. *Relevance of Response Set.* Does the organization check that the responses are adequate? How, and how often is this done?

Q6. *Response Start and Stop.* Are the triggering criteria or threshold well-defined? Are they relative or absolute?

Q7. *Response Start and Stop.* Are there clear criteria for ending the response and returning to a normal state?

Q8. *Activation and Duration.* Can an effective response be activated fast enough?

Q9. *Activation and Duration.* Can it be sustained as long as needed?

Q10. *Response Capability.* Are there sufficient support and resources to ensure response readiness (people, material, equipment)?

Q11. *Verification.* Is the readiness to respond (response capacity) adequately maintained?

Q12. *Verification.* Is the readiness to respond verified regularly?

Ability to Monitor

Q1. *Indicator List.* Does the organization have a list of regularly used performance indicators?

Q2. *Relevance.* Is the list verified and/or revised on a regular basis?

Q3. *Validity.* Has the validity of indicators been established?

Q4. *Delay.* Is the delay in sampling indicators acceptable?

Q5. *Sensitivity.* Are the indicators sufficiently sensitive? Can they detect changes and developments early enough?

Q6. *Frequency.* Are the indicators measured or sampled with sufficient frequency?

Q7. *Interpretability.* Are the indicators/ measurements directly meaningful or do they require some kind of analysis?

Q8. *Organizational support.* Is there a regular inspection scheme or schedule? Is it properly resourced? Are the results communicated to the right people and put into use?

Ability to Learn

Q1. *Selection Criteria.* Does the organization have a clear plan for which events to learn from?

Q2. *Learning Basis.* Does the organization try to learn from things that go well or does it only learn from failures?

Q3. *Learning Style.* Is learning event driven (reactive) or continuous (scheduled)?

Q4. *Categorization.* Are there any formal procedures for data collection, classification, and analysis?

Q5. *Responsibility.* Is it clear who is responsible for learning?

Q6. *Delay.* Does learning function smoothly, or are there significant delays in the learning process?
Q7. *Resources.* Does the organization provide adequate support for effective learning?
Q8. *Implementation.* How are 'lessons learned' implemented? (Regulation, procedure, training, instructions, redesign, reorganization, etc.)

Ability to Anticipate

Q1. *Corporate Culture.* Does the corporate culture encourage thinking about the future?
Q2. *Acceptability of Uncertainty.* Is there a policy for when risks/ opportunities are considered acceptable or unacceptable?
Q3. *Time Horizon.* Is the time horizon of the organization appropriate for the kind of activity it does?
Q4. *Frequency.* How often are future threats and opportunities assessed?
Q5. *Model.* Does the organization have a recognizable and articulated model of the future?
Q6. *Strategy.* Does the organization have a clear strategic vision? Is it shared?
Q7. *Expertise.* What kind of expertise is used to look into the future (inhouse or outsourced)?
Q8. *Communication.* Are there expectations about the future known throughout the organization?