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Light Water Reactor Sustainability Program

Digitalization Guiding Principles and Method for Nuclear Industry Work Processes

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Digitalization Guiding Principles and Method for Nuclear Industry Work Processes

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EXECUTIVE SUMMARY

The commercial U.S. light-water reactor fleet has been operating at historical efficiency, reliability, and safety over the last decade. Nuclear power has the highest capacity factor of any other power generation technology while also serving as the largest baseload source for carbon-free energy. Despite this remarkable achievement, continued operations for many plants are threatened due to fierce electricity market competition and rising operations and maintenance costs of which continued maintenance of obsolete analog equipment is a contributor.

The digital age and associated technologies are where the future lies in process control, and nuclear has yet to take full advantage of the capabilities offered therein. The Light Water Reactor Sustainability Program (LWRS) at Idaho National Laboratory (INL), sponsored by the Department of Energy, has a mission to help the light-water reactor fleet manage its foundational capabilities to continue providing safe and reliable carbon-free power. LWRS helps support that mission by providing scientific, technology-based solutions for advanced concepts of operations with a more viable business model that will allow the fleet to continue to operate at peak levels through extended plant operation.

The LWRS Digitalization Project at INL seeks to leverage digital technologies to synthesize and transform work processes. We provide a state-of-the-art analysis of digitalized work processes in nuclear power and investigate ways in which researchers at INL and the nuclear industry can work together to identify what data to access, how to access it, what to do with the data, and most importantly, how to use the insights for decision-making across all levels within the business. Borne from these considerations, we present four guiding principles for digitalization: develop a coherent digitalization plan, apply human factors engineering, establish data governance, and anticipate unintended consequences. Together, these principles form a method that plants can use to effectively to digitalize nuclear industry work processes.

Our guiding principles are informed by multiple knowledge sources. First, we document activities from the Work Digitalization Initiative, which was conceived as a means for nuclear organizations to help define and standardize the industry's approach to digitalizing work. Second, we detail primary research conducted with industry professionals regarding drivers and barriers to digitalization adoption. We present survey results that demonstrate what the industry hopes to get out of digitalization and the ways that INL can continue to support the industry's digital transformation. Third, we present a digitalization use case with industry partners NextAxiom Technology and Xcel Energy. The project objective was to transform the current condition report work process from paper to digital, incorporating digitalized principles. We report the development of the application and lessons learned.

The accomplishments achieved by this research and development serve to identify critical needs for plant guidance in support of digitalization implementation and contribute to the knowledge and strategies available for utilities considering or undertaking digitalization.

ACKNOWLEDGEMENTS

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ACRONYMS

AI/ML	artificial intelligence / machine learning
CBP	computer-based procedure
CDIM	common dynamic instruction model
CDO	chief data officer
CR	condition report
DI	dynamic instructions
DIRECTOR	dynamic instructions editing tool requirements
DOE	Department of Energy
DWEP	dynamic work execution platform
EWP	electronic work package
FRA	functional requirements analysis
HFE	human factors engineering
HMI	human-machine interface
I&C	instrumentation and controls
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Laboratory
ION	integrated operations in nuclear
IoT	internet of things
LWR	light water reactor
LWRS	Light Water Reactor Sustainability Program
NEWPER	nuclear electronic work packages–enterprise requirements
NITSL	Nuclear Information Technology Strategic Leadership
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
OCR	object character recognition
PPA	Procedure Professionals Association
PTPG	people, technology, process, and governance
SDE	seamless digital environment
SRO	senior reaction operator
STT	speech to text
UX	user experience
VRMF	Virtual Resource Manager Framework
WDI	work digitalization initiative

DIGITALIZATION GUIDING PRINCIPLES AND METHOD FOR NUCLEAR INDUSTRY WORK PROCESSES

1. INTRODUCTION

The commercial U.S. light water reactor (LWR) nuclear fleet has been operating at historical levels of reliability and safety. Nuclear power has the highest capacity factor of any other power generation method while also serving as the largest baseload source for carbon-free energy in the United States. As it stands, nuclear power is key to achieving our nation's net zero initiatives while providing safe and reliable power. However, while the LWR fleet is performing at peak levels, two primary factors threaten the continued operation of nuclear power in the United States. One is that the plant business model is not as viable as it was several decades ago when nuclear power was developed (Thomas et al., 2020). Secondly, the cost to maintain current analog systems continues to increase as the supply for such equipment becomes costlier due to obsolescence of these systems.

The digital age and associated technologies are where the future lies in process control, and nuclear has yet to take full advantage of the capabilities offered therein. The Light Water Reactor Sustainability (LWRS) Program at Idaho National Laboratory (INL), sponsored by the Department of Energy (DOE), has a mission to help the LWR fleet manage the foundational capabilities of the LWR fleet that include the systems, structures, and components and continue providing safe and reliable carbon-free power. LWRS helps support that mission by providing scientific, technology-based solutions that create a foundation for the advanced concept of operations that can enable the LWR fleet to operate at the same peak levels and with a more viable business model through their operational lifetime. This shift in mindset from helping nuclear survive and maintain status quo to thrive and transform the business model to better match the current economical and sociotechnical landscape is embodied the Integrated Operations in Nuclear (ION) approach.

The ION approach uses a transformative business process model that shifts the focus of plant modernization activities from survival today to creating profitable, competitive operations tomorrow. Currently, the actions and initiatives LWR plants have taken to improve the reliability of their operations, improve safeguards, reduce human error, and address obsolescence issues have added more complexity to plant processes while realizing fewer returns in these areas for their efforts. The focus of ION is developing new capabilities that allow plants to rethink how processes are performed by removing the ossified way of performing work and allow room for advanced technologies and utilization of plant resources to create a new way of performing reliable, safe, and efficient work.

The advanced capabilities ION embodies are developed by restructuring the way people and technology add value to the business. How these two resources add value is typically structured by a process. Plant governance dictates what a process must achieve and therefore it can influence how people and technology are combined to add value. The four domains: people, technology, process, and governance (PTPG), form the pillars by which ION approaches transformation. A fully integrated operation defines the characteristics of these four domains as listed in Figure 1. As LWRS works toward providing scientific, technology-based solutions, ION provides the approach that influences the development of the solutions and measures how those solutions move plant operations towards the characteristics defined under each domain (bullet points in Figure 1). Synthesizing how PTPG work to achieve plant goals creates the capabilities within a plant that, once combined, deliver the performance goals needed for competitive nuclear plant operation (Reegård et al., 2014).

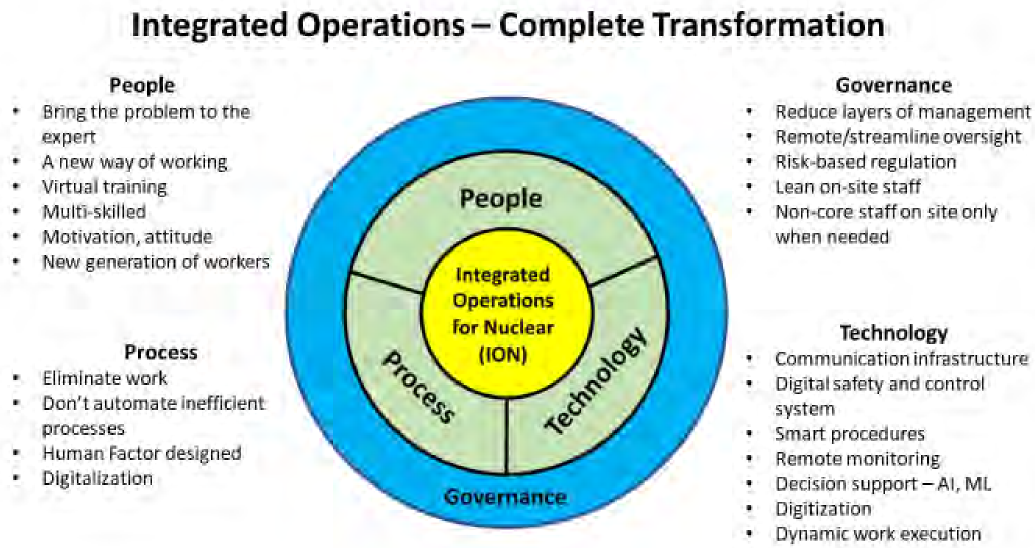


Figure 1. The relationship between PTPG. As viewed by ION, the characteristics envisioned for each in a transformed design are enumerated around the outside (image from Kovesdi et al., 2020).

The synthesis of PTPG requires a holistic method that can analyze candidate work processes through the PTPG lens and accomplish two goals. First, create immediate results for the plant that help justify the modernization effort. Second, curate the solution in harmony with other plant modernization processes, to ensure smooth transition from how work is done now to how work can be done in an integrated fashion. The Advanced Concept of Operations, a research area within LWRS, refers to such a method as digitalization, the use of information to optimize or transform work processes.

Using information to optimize and transform work processes is simple only by definition. It requires framing a work process by the governance dictating the outcomes of such a work process, identifying what data is available to create applicable information, curating such information to meet the needs of the intended recipient, identifying the technology that can perform such analytics and curation, and then structuring the process through the lens of the ION PTPG model.

All LWRS research projects seek to transform the business model for nuclear operations, to ensure the long-term sustainability and economic viability of the fleet. Digitalization occupies a unique space within the pathway because its focus is on using improved digital infrastructure to transform work processes. For example, whereas ION takes a broad view to rethink entire business processes and how they are performed, digitalization aims to rethink how day-to-day work tasks are performed with the help of digital technology. Whereas the Human and Technology Integration Project seeks to better understand how plant personnel will use new digital technologies, and to optimize its safe and reliable use, digitalization expands this perspective and aims to optimize interactions between systems, between people, and between systems and people using digital communications. Thus, the Digitalization project complements the other pathway approaches and provides a new format that yields insights and possibilities by restructuring daily processes around digital technology. Too often solutions look to mitigate only the symptoms of a deeper challenge at a plant. Digitalization has a focus on addressing the root challenge within a work process by using advanced technology to restructure how people and technology cooperatively carry out a process. The restructuring is focused on achieving the characteristics defined by the people, process, and technology characteristics in the ION approach.

Furthermore, these solutions can, at times, be singular in that they are not intended to contribute to general plant knowledge or improve capabilities outside the work process they were designed for. This is not ideal. A digitalized process is designed with capabilities to synthesize, collect, and distribute data-driven information that can be used by other digitalized processes. Doing so creates solutions that can easily and quickly provide information to other plant organizations, breaking down information silos and streamlining work. The capability to share information across organizations brings plants closer to the ION governance domain characteristics (listed as bullet points in Figure 1).

A successful digitalization effort empowers the people performing the work with exactly the information they require to be successful. That information could be in the form of virtual training, real-time access to experts, historical information, and advanced decision aids. The technology brings capabilities to collect and distribute data and information to need-to-know personnel, it offers insight into the work being performed, and it automates administrative, clerical, or often tedious tasks that allow the worker to focus more on the process at hand. This creates a process that is more efficient, generates knowledge for the plant, streamlines data gathering and distribution across work groups, and, by automating the clear, tedious, or administrative tasks, frees up time for the user to perform other duties.

As more processes are digitalized, the plant transitions to a more networked mode of operations. The ease of disseminating useful information across plant organizations through a networked business structure can enhance distributed plant awareness across work groups. Each organization, instead of operating with tunnel vision on the tasks passed down through line management may begin to develop holistic insight into how the plant is operated. These emergent capabilities are part of ION and can be harvested to develop further innovations regarding how work is done or to identify multiskilled personnel. It is imperative that the nuclear industry takes advantage of these digital capabilities imminently and becomes aligned with other energy sectors such as North Sea Oil and Gas industries, which adopted the integrated operations concept nearly two decades ago resulting in positive business transformation.

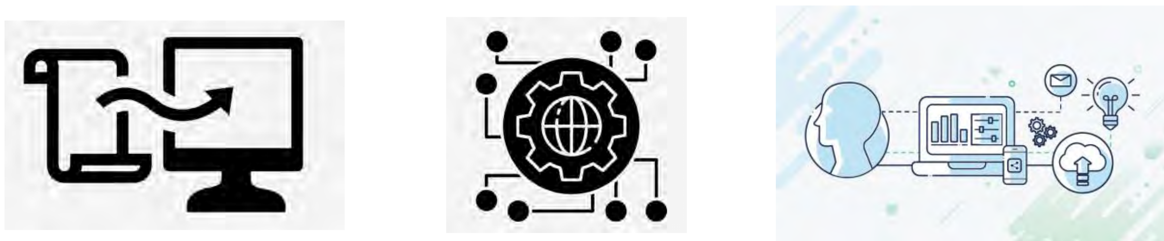
1.1 The Digital Revolution

The first and second industrial revolutions were marked by mechanization in the late 1700s and by manufacturing in the late 1800s, respectively. Digitalization is a function of the third industrial revolution—the digital revolution – which, in the late 1960s was largely brought about by the rise of electronics and computers. The emergence of the internet in the 1980s was a key milestone of the digital revolution because it connected people in various locations beyond what previously existed. With smart system interconnectivity, an internet of things (IoT) has emerged. Now, any system or human can be connected to another at any time. In the IoT, physical and virtual agents can interact and host a range of functions including data capture, data storage, and communications. As the IoT matures along with advancements in big data, this will give rise to the fourth industrial revolution, with smart factories and smart plants —i.e., coordinated cyberphysical systems that seamlessly collect and share digital data to optimize operations.

1.2 Digitalization in Industry

Most are familiar with the terms digitize and digitization but not as familiar with digitalize and digitalization. Hence, it is essential to clarify their distinction. To digitize is to render information into a digital format, such as the conversion of paper files to PDF, or cassette tapes and vinyl records into mp3 files. To digitalize is to incorporate digital technologies into new processes and human interactions. With digitalization of the music industry, this took the form of new ways users would come to listen to music (i.e., songs on demand via streaming services). Curating albums and B-sides became far less important processes in the music industry. Hence, digitalizing is a step beyond digitizing. Incorporating digital technologies offers transformative effects for industry practices, the business model and user experience (see Figure 2).

Digitization	Digitalization	Digital Transformation



Converting analog information and control to digital	The restructuring of processes around digital technology	The transformation of how industries think due to digitization and digitalization

Figure 2. Industry pathway to digital transformation (image from Alivisatos, 2023).

Digitalization involves the incorporation of information and communications technology. Consider an everyday task such as ordering a ride (e.g., Uber). To complete this task:

- The person must have the necessary personal technology device (e.g., smartphone)
- The person must know how to use the smart device
- The person must know how to navigate the internet or use the application
- The person must trust that all connections (e.g., internet, global positioning system) will operate properly
- The physical systems must operate properly
- Real-time data must be available to be used within the system.

The information communicated from the person to the receiver within the interconnected system must be conveyed accurately and quickly or people will not perceive the value in the long term. Uber used digitalization to transform both the taxi business model and how people used transport in everyday life, by matching passengers to empty seats in private cars traveling in the same direction. Uber created a digital application that improved efficiency and provided door-to-door service regardless of where a person lived (SanchezArmas, 2020). Prior to Uber's entrance into the market, time, location, and local phone number influenced whether a consumer could access taxi services. The digital application also created a more transparent and easier method of payment. Through digitalization innovation, throughout the 2010s Uber was able to capture commanding rates of the global taxi market, without owning any vehicles. In process control industries such as nuclear power, digitalization can improve efficiency in planning, scheduling, work management activities and other functions.

1.3 Digitalization in Energy

Digital technologies have already led to transformative change in the energy sector. For example, the oil and gas industry has enhanced their exploration capabilities in remote and harsh locations by incorporating digital technologies into the industry (International Energy Agency, 2017). Analysis of large seismic datasets in land and oceans, dynamic steering of drill bits in real-time, and the use of advanced sensors for wellbores placement have all helped optimize resource exploration. Digitalization affords additional cost-savings via optimized production processes from digitally connected remote operations centers (Figure 3). In the longer term, this digitalization infrastructure can be used to shift focus to improvements in data analysis, smart systems and the use of artificial intelligence and machine learning (AI/ML) as a way to decrease labor costs, improve equipment reliability, and increase safety.

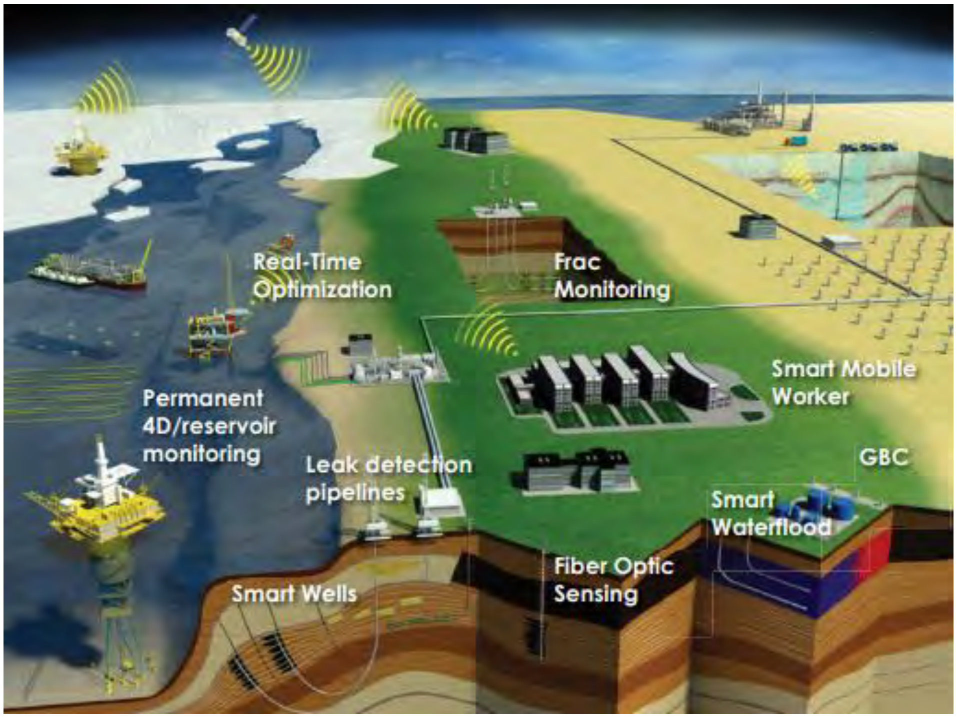


Figure 3. Digitally connected remote operations in oil and gas fields (image from International Energy Agency, 2017).

There are several challenges to future digitalization efforts in the oil and gas industry. Projects tend to spend years in development and are relatively inflexible once approved. In contrast, digital technologies advance quickly. Thus, once a project finally gets underway, the digital technology to be installed may no longer be cutting edge. This lag means that the software is much closer to being obsolete. On the other hand, it also allows time for other industries to detect and report system bugs to the software developers. Other challenges include older facilities lacking the necessary infrastructure to accommodate digital innovations, the significant costs to upgrade, fragmentation in the supply chain, and long-term trends impacting demand.

As we will see in Chapter 3, the challenges faced by oil and gas in its bid for increased digitalization are similar to the challenges the nuclear industry is now facing. Nonetheless, within the existing fleet, digitalization is underway.

1.4 Digitalization of the Nuclear Industry

Nuclear stakeholders are envisioning the digitalization of the industry, and this vision is predicted to deliver a high rate of return. In recent years, the amount of plant data accessible to nuclear power plants (NPPs) has increased drastically. This has been made possible due to instrumentation and controls (I&C) upgrades, smart gauges, electronic work packages (EWPs), and dynamic instructions (DIs). The industry now has the potential to access highly valuable insights to support planning and work management as well as high-level business decisions. Through the Plant Modernization Pathway in the LWRS Program, researchers at INL and the nuclear industry are working together to identify what data to access, how to access it, what to do with the data, and most importantly how to best use the insights for decision-making across all levels within the business.

One area that is currently undergoing digital upgrade in the nuclear industry is work packages. A critical component of the work management process is planning work packages (Agarwal et al., 2014). As can be seen from Figure 4, a work package includes a cover sheet, pre-job brief, contingency plan, work instructions, necessary parts, special tools and equipment, a feedback mechanism, and references. The work instructions—highlighted in green—provide the information on what must be completed in the task.

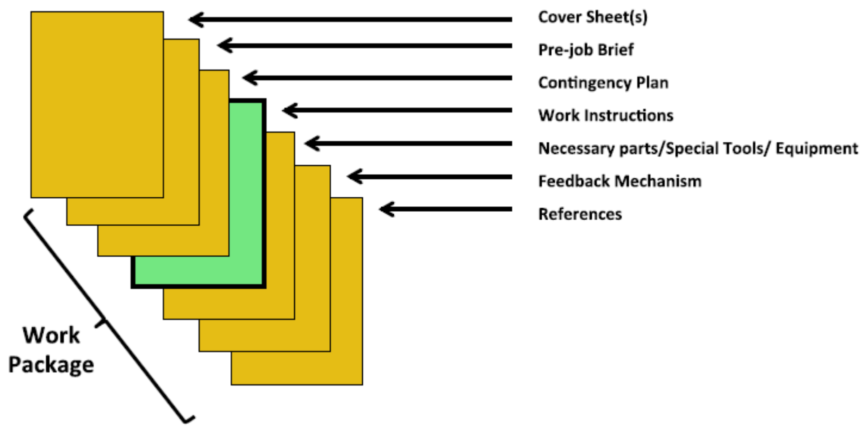


Figure 4. Elements of a work package (image from Agarwal et al., 2014)

EWP solutions used in the nuclear industry are an example of digitization in work management. In other words, the information in the work package and instructions that was once hard copies (i.e., printed on paper) has been digitized: it is now available as electronic paper (i.e., PDFs) on handheld devices. Tools for smart planning, scheduling and DIs are examples of work digitalization. These technologies pull and use data and information from EWPs and other applications, and push new insights forward to appropriate decision makers.

Digitalization, and by extension, work digitalization, is realized using a seamless digital environment (SDE), which integrates information from process systems and delivers it to workers through an array of related technologies. That is, data from digital I&C components in plant systems can be fed to various plant processes and applications, which are then used by plant staff to execute work. The information integration afforded via digitalization saves time, creates significant work efficiencies, and reduces system and human errors. The integration of information via an SDE includes:

- Plant systems. Beyond centralized monitoring and awareness of plant conditions, deliver plant information to digitally based systems that support plant work and provide it directly to workers performing these activities.
- Plant processes. Integrate plant information into digital fieldwork devices, automate many manually performed surveillance tasks, and manage risk through real-time centralized oversight and awareness of fieldwork.
- Plant staff. Provide plant workers with immediate and accurate plant information needed to conduct work at plant locations using assistive devices that minimize radiation exposure, enhance procedural compliance and proper work execution, and enable collaborative oversight and support even in remote locations.

In the context of work digitalization, an SDE is the mechanism that brings all the equipment data, processes, and staff together to ensure the correct plant operation or maintenance is conducted by the necessary craftsperson, with the correct tools, at the optimal time.

1.5 Summary

Commercial U.S. NPPs are vital in the generation of highly efficient, safe, and non-carbon emitting electricity. However, their continued operation is threatened because of an outdated business model and the high costs associated with legacy equipment and systems. The nuclear industry has lagged behind in taking full advantage of digital technologies and the powerful, cost-saving capabilities offered as a result of digitalization. The LWRS Digitalization Project at INL seeks to support utilities in effectively digitalizing their work processes. Thus, the purpose of this report is to communicate guiding principles and methods to digitalization (Section 2) with a focus on sustainability of the existing fleet (although this guidance can also be applied to advanced reactor and small modular reactor design). Beyond interrogation of the relevant scientific literatures, these principles and methods to digitalization were developed by integrating knowledge from multiple industry sources. In Section 3 we document activities from the Work Digitalization Initiative (WDI), which was conceived as a means for individuals from varied nuclear organizations to help define and standardize the industry's approach to digitalizing work processes. Section 4 details survey research conducted with industry professionals outlining insights into the realized and potential benefits of work digitalization in the nuclear industry, and importantly, drivers and barriers to digitalization adoption. Importantly, these data demonstrate the hope that industry has for INL to develop best practices and processes in developing a digitalization implementation plan, and ways to support the industry's digital transformation. In Section 5 we present a digitalization use case with a utility partner. The project objective was to transform the current condition report work process from paper to digital. Last, in Section 6 we conclude with paths forward for the digitalization of the nuclear industry, including the increased functionality brought about by new data-driven insights, and new day-to-day operational possibilities with optimized decision-making.

2. GUIDING PRINCIPLES AND METHOD TO DIGITALIZATION

Today, becoming more data-driven is a priority for most companies. However, over half of business decisions are not based on quantitative data and are instead made by gut instinct, experience, or opinion (Belissent, 2020). While these factors are important, the quality of decision-making can vastly improve with the inclusion of real-time, data-driven insights.

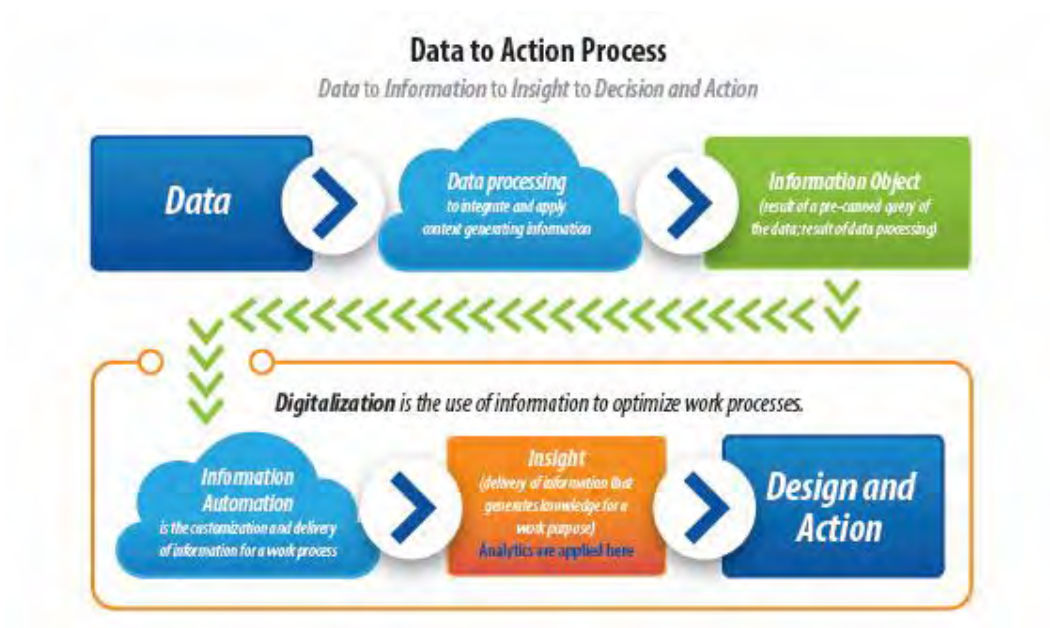


Figure 5. Data to action process of digitalization.

We define digitalization as the use of digital technologies and information to synthesize work processes. Digitalization incorporates PTPG as part of the ION approach to transformation. Just as a catalyst in chemistry increases the rate of a reaction without itself being consumed, digitalization is a catalyst to improve overall human-system performance. It does this by enhancing both equipment reliability and human reliability, which together drive industry to cost-effective solutions.

Data collected from digital technologies is the bedrock of digitalization, because data leads to information and information leads to new insights. Figure 5 illustrates that, once new insights are gained, this leads to better, streamlined decisions which in turn produce optimized actions, via information automation. The transformative effects of digitalization afford new day-to-day operational possibilities that give rise to fundamental changes to the way work processes are carried out.

Table 1. Levels of digitalization in reactors according to Boring et al. [6].

	Level	Description
0	No digitalization	Entirely analog I&C or digital I&C without added functionality
1	Hybrid digitalization	Some digital instrumentation and control that maintains basic functionality while some features offer enhanced functionality
2	Full digitalization	A fully digital system that uses advantages of digital technology to enhance performance
3	Integrated digitalization	Multiple distal digitalized systems are integrated to allow synthesized functionality

Digitalization is intimately connected to automation, and especially information automation—defined as assisting with gathering information (Boring et al., 2019; Parasuraman et al., 2000)—but it is useful to consider them as distinct concepts even though at times, the terms are used interchangeably. Boring et al. (2023) parsed out this distinction and documented levels of each within nuclear reactors. Table 1 lists descriptions of the levels of digitalization. According to this definition, increasing levels of digitalization increases functionality and shifts it to the control system, away from the human.

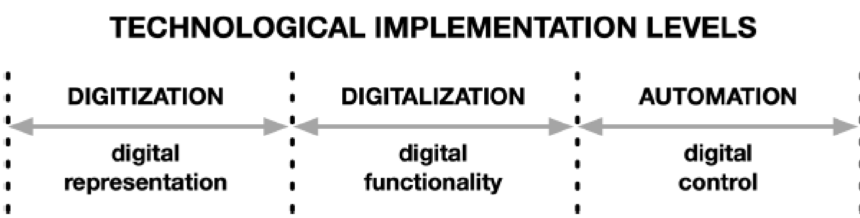


Figure 6. Relationship between different ways of grading digital implementations (image from Boring et al., 2023).

The authors point out that many industries perceive digitalization to sit between digitization and automation on a continuum (see Figure 6). This highlights their interconnectedness and presents a technological advancement whereby intelligent and smart agents may be placed beyond automation (on the right-hand side) and represent a digital action. The overlap and unique characteristics of digitization, digitalization and automation will be important points we will return to throughout this report.

Plants wishing to take advantage of digitalization benefits must carefully consider not just the quality of the technology, but also the implementation strategy, which is just as important (Barroso & Ramos, 2023). Indeed, our survey research detailed in Section 4.1.6 indicates the industry's desire for INL to develop best practices for digitalization implementation. The implementation strategy must necessarily address the challenges associated with a culture shift toward this new concept of operations. A recent survey indicated that 55% of chief data officers (CDOs) perceived the lack of a data-driven culture within organizations as a top challenge to meeting business objectives (Davenport, 2023).

Thus, in this section, we provide guiding principles and methods necessary to effectively digitalize nuclear industry work processes. These principles were developed as the result of engagement with multiple scientific and business disciples and with industry stakeholders. The purpose is not to provide comprehensive design recommendations. Instead, we offer guidance and important considerations that together provide a methodology for the development and implementation of digitalization in nuclear power work processes.

We begin with the principle that plants should develop a coherent digitalization plan and consider their end-state vision for digitalization *and* their implementation approach at the same time. In other words, the standard incremental approach to digital technology upgrades should be conducted with a grander, interconnected vision in mind. These macro- and micro-philosophies to digital transformation should be balanced.

We then consider the principle of human factors engineering (HFE) in the digitalization process. Integrating HFE early on adds tremendous value to the business case by way of technical improvements, operations improvements, and performance improvements, such as a higher capacity factor. Other foundational considerations of this principle include function allocation, user experience (UX), and the tension between user-centered design and data security. As seen in Figure 7, digitalization catalyzes human-system performance by facilitating the joint optimization of workload demands and improving individual, team, and organizational situation awareness. The application of HFE is a critical component in achieving these ends.

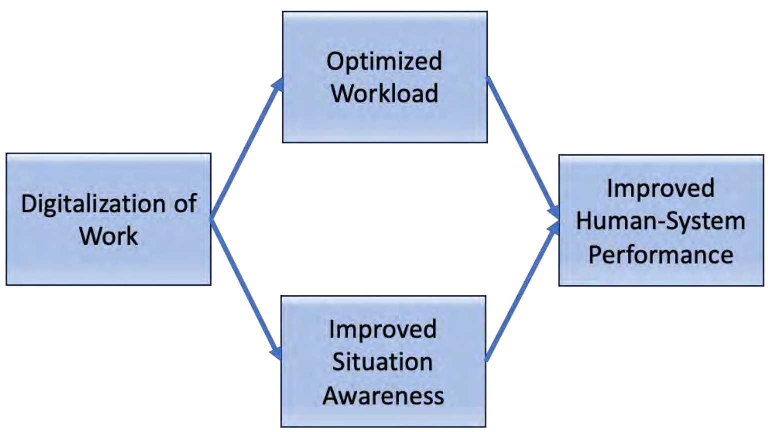


Figure 7. The digitalization benefits.

Our next digitalization principle is to establish data governance. This includes data accessibility, data quality, ascribing meaning to the data, and importantly, cybersecurity concerns. Our last guiding principle is to anticipate unintended consequences. We explore balancing the benefits of digital transformation with the introduction of potential new vulnerabilities and liabilities, such as loss of situation awareness and possible de-skilling of the workforce.

Together, these guiding principles form a methodology with a focus on digitalization implementation within the existing fleet as a means to drastically improve cost efficiency and optimize safe and effective operations. Digitalization considerations for advanced reactor designs are also discussed. Throughout, we demonstrate the overlapping nature of these principles and posit that a successful digitalization methodology will require a high degree of integration and coupling of perspectives from multiple stakeholders.

2.1 Principle #1: Develop a Coherent Digitalization Plan

2.1.1 Vision

It is important for NPPs to develop an end-state vision for their digitalized modernization plans. This must occur before designing a digitalization roadmap. Plants must first envisage what they want their work processes to look like in the future and how they conceive of a new concept of integrated operations to deliver a higher rate of return. Further, the level of human-system performance desired must be stipulated and success metrics formed so that the desired level of achievement can be measured and optimized with time.

The reason for this grand vision is to ensure that altogether, synthesized, and applicable solutions across multiple plant systems are put in place, even if the digital upgrades do not necessarily occur all at once. When considering digitalization solutions for an advanced reactor design, Boring et al. (2023) note that, while the digitized control room translates analog information into digital signals, there will be no expansion of functionality. Thus, the vision is to create digitized information that is seamlessly accessible to the people, processes, and systems to achieve enhanced functionality: a digitalized control room.

The end-state vision should be created with data communications as a guiding principle, front and center. In other words, implementing digitalized instrumentation with an end-state vision in mind avoids merely addressing the symptoms of one inefficient work process in one plant system and instead helps create interconnected data streams that generate plantwide insights. It also helps identify whether the felt need might have an underlying root cause upstream. Moreover, a vision encourages plants to consider vendor selection for the digitalization tools early on, such that digital engineering projects can be consistent and designed to communicate in a collaborative fashion (Hunton & England, 2020).

The strength of the end-state vision is that the resulting knowledge and enhanced information produced by one digitized system will lead to efficiency gains beyond the system at hand. For example, digitized records of corrective action reports can produce integrated historical trend data that can be used to make better decisions about component health as well as better operational decisions. This point cannot be stressed enough, because increased capabilities via information restructuring is the linchpin of the digitalization business case.

A key concept within the vision for digitalization is that it must be flexible and capable of evolution. This is because new insights and new work processes brought about by digitalization will grow over time. This task may seem daunting, and the impulse to focus on immediate, bite-sized needs is strong. However, taking the time to map out ways to leverage networked information into new ways of working will pay dividends. Among industry professionals, our research revealed a need for greater understanding of the end-state digitalization vision and how to attain it.

Importantly, the plants are not alone in this endeavor. This vision should be formulated with a cadre of industry experts across utilities, government, industry, academia, and the regulator. Notwithstanding, it may not be immediately shared across all levels of the organization. There will be some change skeptics, and careful consideration must be given to the rollout of the vision within the organization. The vision should contain a variety of inputs, and business management personnel, LWRS scientists, software engineers and technology developers should liaise and offer perspectives as to how distributed information can raise plant awareness in ways that are useful to the business case and staff. Al Rashdan and St Germain (2018) present an example of how the LWRS Pathway can create a flexible roadmap to end-state vision that is specified to a utility's needs.

2.1.2 Approach

While an end-state vision for modernization is an important north star within a plant's business development landscape, the approach to digitalization must necessarily start small, and with caution. This might be thought of as micro-digitalization. There are several important reasons that the industry typically takes a conservative approach to technological upgrades. The plants themselves were designed to operate for several decades at a time, with highly complex builds that were not necessarily designed with flexibility in mind. Further, as producers of baseload electricity, the plants are generally more cost-effective to the extent that they can operate 24/7. Thus, the price tag must include not only the cost of the upgrades themselves, but loss of revenue during the remodel, as well as any regulatory inspection the upgrade might attract. Other factors that contribute to an incremental approach include a potential lack of in-house expertise, personnel training requirements and licensure issues with the new digital technologies. Taken together, digital upgrades are technically challenging and costly, and the considerable resources necessary to complete them has historically been one of the industry's chief barriers to modernization (Hall & Joe, 2023). Management must conceive of long-term benefit and an amenable regulatory environment to offset the initial investment.

In addition, public opinion about the safety of the technology plays a role in the speed with which nuclear can innovate. Nuclear power has occupied a unique space in the public's consciousness since its inception, which coincided with World War II and the creation of the atomic bomb. Its acceptance by society is a main driver in policy decisions, including investment in technological advancement. The peaceful application of atomic energy saw rapid growth and innovation in the years leading up to Three Mile Island in the late 1970s. However, this event, coupled with Chernobyl in the mid-1980s plummeted the industry into a culture of extreme caution and intense regulatory oversight. Together, these events brought about the nuclear industry's safety culture which dominates the industry, and technological advancement has been slow (Thomas et al., 2020). Since Three Mile Island, plants have operated incredibly safely and reliably, but their I&C have essentially ossified, and the buildings have become tombs of 1970s technology.

Notwithstanding, in the most recent decades, changing political landscapes, including pledges to decarbonize energy, have produced what some have termed a nuclear renaissance (William, 2022), and with the support of the DOE and LWRS researchers, several nuclear power utilities in the United States have been undergoing different types of technical advancements (Joe & Kovesdi, 2021; Joe et al., 2018). Although not without delays and growing pains, recent developments are encouraging. Updates central to digitalization efforts have included smart sensors and gauges, data tracking devices, EWPs, and DIs (Ma et al., 2022; Oxstrand, 2022). These efforts now provide information that was either previously manually recorded or not recorded at all.

European researchers (Barroso & Ramos, 2023) recently documented lessons learned and experiences implementing a digitalization process at two nuclear sites. The upgrade was to replace paper-based procedures with DIs in the main control room in a bid to reduce the number of required tasks and improve supervision, compliance, and performance. Their approach was to identify procedures with the highest administrative burden and those that lent themselves to being blocked to minimize deployment times and risks. Other considerations included procedure complexity. Throughout the process, they identified several key lessons that may be generalized to broader digitalization efforts:

- Identify and engage all stakeholders involved with the upgrade, including finding a champion of the digitalization effort who will coordinate and offer encouragement to keep moving forward
- Conduct a pilot test to strengthen the business case
- Start small and with lesser-used systems, to configure and solidify the process
- Add more processes to the digital system as revisions to the process are captured
- Build interfaces between upgraded system and other management systems *after* the process is solid.

In the near term, plants should decide what data is needed as both an input and output to digitalization in service of optimal decisions. Data output should be considered first, because once choices have been made about what the generated data must look like, deciding which data streams would be helpful to digitize (if they are not already) becomes more straightforward. Discussions among personnel regarding the utility's imperative and identifying precisely the information that the engineer or operator is looking for will determine what is most important for each specific use case. The following questions might apply:

- What is the current state of your digitized records—is there an inventory?
- Which records are currently time-consuming to produce?
- Which records are currently error prone?
- Are there manual processes that would lend themselves to an electronic format?
- Which combination of records would help generate heightened plant awareness?

In terms of immediate pain points, plants might consider looking at their list of significant events to determine whether digitalization opportunities will help the business case. For advanced reactor designs, information management and document control for processes may take the form of a passive approach because digitalization will require less active investment.

2.1.3 Organizational Barriers

The purpose of digitalization is to have a transformative effect on work processes and so will necessarily change the way people structure their workdays. Before tangible improvements are felt, there may be organizational resistance to change. Digital transformation is a disrupting force in an organization, and there is a natural tendency for employees to be skeptical of change. This sentiment is evidenced in our research in Section 4.4.1.2 in which digitalization vendors stated that when deploying new technology, there is still a strong urge to perform the work exactly the same way as it has always been done.

In a recent survey of individuals employed in nuclear power industry and utilities, approximately half the respondents indicated that they did not believe control room modernization to be essential to the industry's survival (Hall & Joe, 2023). Thus, it is critically important that everyone across the organization, from craftsmen to human resources to upper management, understand and are on board with the roadmap to transformation. A multidisciplinary approach to ensure organizational unity is necessary. Together, a combination of perspectives should form the digitalization objectives, goals, and importantly, the settled timescales. Often, synthetic ideas arise from multidisciplinary teams as well as many different topics and priorities, depending on the vantage point. Care and time will have to be taken to create a balanced approach that appeals to as many stakeholders as possible. A comprehensive discussion of the barriers to advanced technology adoption in nuclear power operations is provided in Walker et al. (2023).

In their lessons learned implementing DIs, Barroso and Ramos (2023) highlight that finding a champion at each level of the organization would be extremely beneficial to help coordinate, meet deadlines, and drive the innovation. These key individuals would also manage organizational expectations regarding the transformation. It is almost a certainty that, during the digitalization initiative, plants will experience speedbumps and hurdles along the way, and even once successfully installed, there will be growing pains while workers adapt to new states and optimization occurs. Users may grow impatient, possess unrealistic expectations, or grow discouraged with the transition. Having a champion that can mitigate some of these frustrations will be key.

It is also necessary to understand that digitalization cannot overcome bad organization in the first place. Systems should first be optimized in their current format, or at least a plan for overcoming this limitation should be in place before embarking on the digital transformation. This will be critical when attempting to scale case-by-case digitalized efforts more broadly.

2.1.4 Summary

Both the vision and approach must coexist as a digitalization strategy. Digitalization is by nature visionary but cannot exist without the underlying digitized approach to nuclear operations. Moving too quickly towards a grand vision that is a departure from the current state of affairs might lead to failure, significant unintended outcomes, and system collapse. This will likely carry with it severe consequences. On the other hand, advance too slowly and the industry will likely die a slow death. One is dramatic and the other is death by a thousand cuts.

Lessons learned in the DIs space include starting out by validating a few use cases that are in alignment with the vision and then broadening the plan for wider adoption. Organizational barriers and workplace culture should be carefully incorporated into the digitalization initiative. Digital obsolescence should be considered, and tools that are upwardly compatible favored.

In Section 2.2, we will discuss the importance of HFE in the digitalization strategy and how both vision and approach must comport with immediate and prominent improvements to UX. In other words, a small change from standard runs the risk of not carrying enough of a wow factor to win over users. One thing is clear, however, those in the energy industry must modernize or be left behind. Digitalization has been identified as imperative for sustainability (Patel, 2023).

2.2 Principle #2: Apply Human Factors Engineering

Human factors is a branch of psychology with roots in cognitive science that seeks to harmonize the relationship between a machine and its human user. This is accomplished by modifying either the technology, environment, or in some instances, the user. In a complex sociotechnical environment like nuclear power operations and maintenance, all approaches are used, although modifying the technology is more commonplace. HFE describes the approach in which tools, machines, and technological systems are designed according to psychological competencies and limitations (Gosbee, 2002). In other words, the purpose of HFE is to make machines work better for humans by using knowledge about the ways that humans think and make sense of information and embedding that into the system's modus operandi. In nuclear power, one of the ways that HFE has been applied is to the design of human-machine interfaces (HMIs) to support safe and efficient operations.

The importance of the human user cannot be overstated in the digitalized tools and methods of implementation. Engineer historian David A. Mindell eloquently demonstrates this point in his book "Digital Apollo: Human and Machine in Spaceflight":

> The sociotechnical system, including the engineers, flight controllers, and programmers on the ground, as well as pieces of machinery, was impressive, precise, even wondrous, achieving a successful landing on all six attempts. But it was not perfect. Programs alarmed, guidance over-shot, boulders appeared, people misspoke, and buttons failed. In each case, human abilities intervened in unplanned ways, made decisions and landed the spacecraft on the Moon.

Thus, human factors implications and risks are critical considerations. It should be recognized that, when the plants perform digitalization initiatives, the systems will continue to rely on humans as a backup if, and when, the technology fails. Further, although highly automated environments can produce significant cost reductions, caution should be exercised regarding the difficulties human users face being able to effectively monitor and intervene in systems with which they rarely interact (McLeod, 2022).

2.2.1 NUREG-0711

Digitalized technology serves to furnish plant personnel with heightened knowledge and insights that ultimately produce better decision-making. The LWRS Pathway recognizes that information automation is a core aspect of digitalization (Dainoff et al., 2022). Nonetheless, even with automated digital systems, the human element must be ever-present in the technology's design, deployment, and usage.

The U.S. Nuclear Regulatory Commission (NRC) has developed general HFE criteria and recommendations to satisfy their safety review of applicants wishing to make modifications to I&C, such as digitalization (NUREG-0711; O'Hara et al., 2012). The program is evaluated within 12 elements to ensure that personnel performance and reliability are appropriately supported (see Figure 8). Especially relevant for digitalization efforts is function analysis and allocation, which falls within the planning and analysis stage.

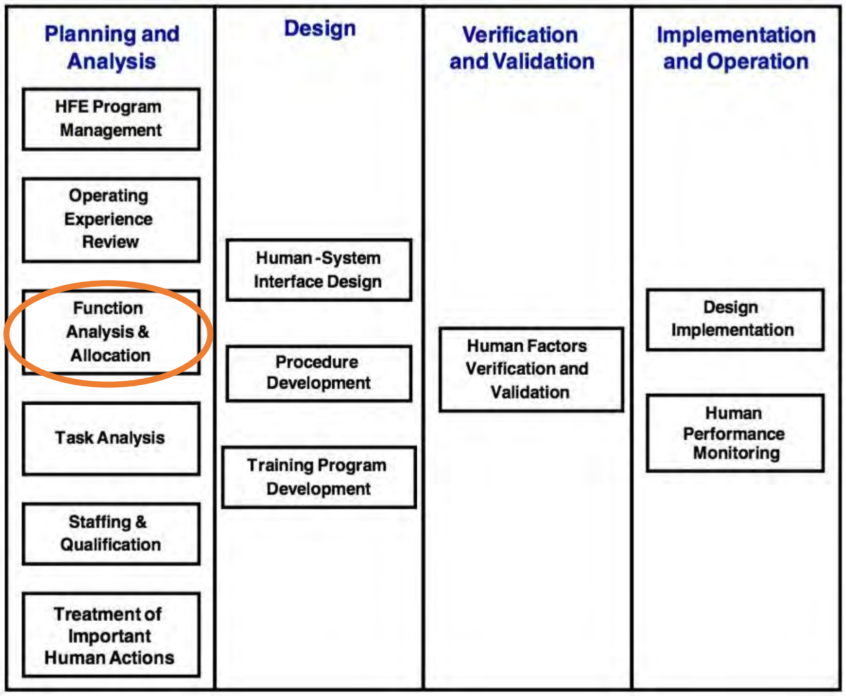


Figure 8. Function analysis and allocation from the NRC's HFE program review (NUREG-0711).

Function allocation is the assignment of functions to either personnel, automatic systems, or a combination of both. These function allocations should be founded upon the functional requirements analysis (FRA) and known HFE principles in a structured, well documented methodology that produces clear roles and responsibilities for personnel. As can be seen from Figure 9, FRA is about deciding *what* needs to be done, and function allocation is about deciding *who* or *what* should do it (humans or automation). Function analysis and allocation answers the question: What's the best design for human interaction with automation to achieve the plant's goals (generating power and supplying electricity to the grid, while ensuring the health and safety of the public)?

Figure 9. FRA and function allocation.

Function allocation has roots in the famous "Men Are Better At, Machines are Better At" formula (Fitts et al., 1951), based on the characteristics and limitations of both (see Figure 10). Although this list is still informative and widely cited some 70 years later, new models of function allocation have since emerged that address degrees of human-machine interactions, in which tasks are completed by a combination of both in concert and not just one or the other.

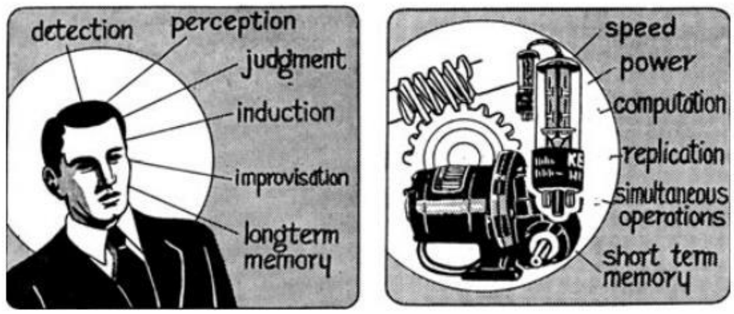


Figure 10. Fitts et al. (1951) "Men Are Better At, Machines are Better At" list.

In their technical report (TR 1011851), the Electric Power Research Institute provides a list of questions to guide function allocation decisions:

- Is automation essential?
  - For example, if the manual performance of the function raises health or safety concerns or the function features high human error rates and high consequences.
- Is automation desirable?
  - For example, if the function requires many repetitive actions that may be fatiguing or boring to operators or the function creates high cognitive workload.
- Is human involvement essential?
  - For example, if human reliability exceeds machine reliability.

Taken together, digitalization will transform the ways in which NPPs are operated and maintained away from mechanical toward digital work processes, and every function the initiative impacts must be carefully evaluated. Correctly assigning tasks to humans, digital technologies, or a combination of both, and with HFE principles applied, will be necessary for the success of the program.

2.2.2 Lessons from Automated Systems

In their white paper titled "Human Factors in Highly Automated Systems," HFE experts from aerospace, defense, nuclear power, and basic and applied research, produced nine guiding principles for HFE in automation. Given digitalization's intimate relationship with automation, a simplified list of these principles is adapted here (from McLeod, 2022):

- Understand the influence of other elements of the system on the automated components.
- Recognize that automation nearly always changes, rather than removes, the role of people in a system
- Decide the core functions of the automation (i.e., either acquiring or extracting meaning from information, making decisions or taking action, or a combination of these)
- Introduce and support the automation such that people can maintain awareness of the system's state because they will still hold ultimate responsibility for the automation performance
- Ensure effective, transparent, and unambiguous communication between the automation and the human
- Be explicit where the balance between authority, responsibility, and control lies
- Ensure the people relied on to support the automation understand what the system is doing and why

- Avoid making unrealistic assumptions about the ability of people to monitor and effectively intervene in any system where there is little for them to do over sustained periods
- Recognize that automated systems can increase the levels of task difficulty and workload imposed on the human.

Many of these core HFE principles for automation boil down to maintaining human situation awareness, which is supported in the basic and applied sciences. This applies not only to the design but to the introduction and ongoing staff support of the new digitalized technology.

2.2.3 Situation Awareness

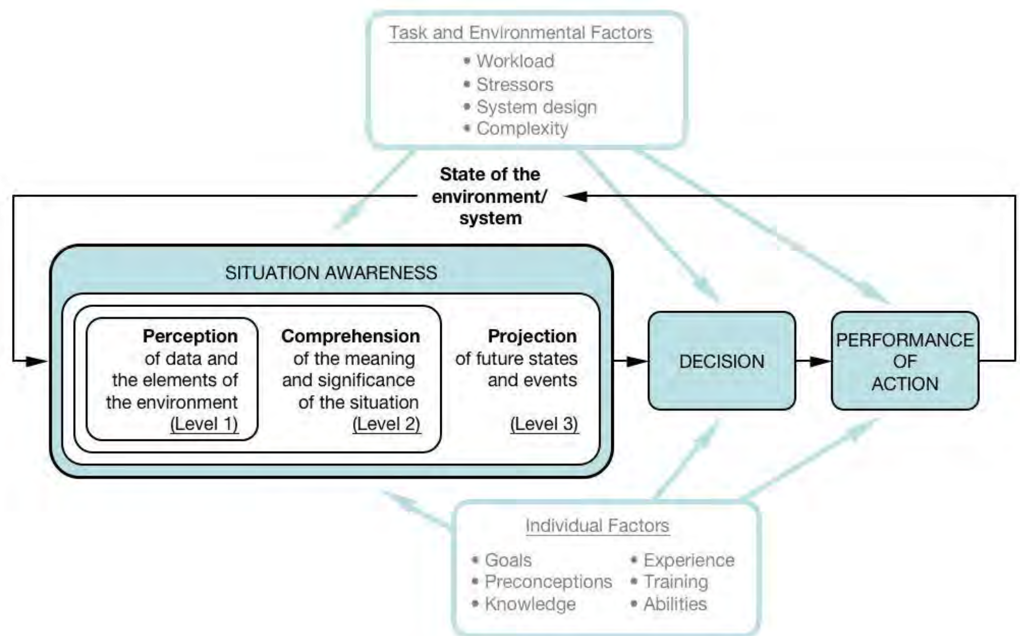


Figure 11. Endsley et al. (2003) model of situation awareness.

Situation awareness is a fundamental principle in HFE because it is so central to effective system performance across all industries, including process control (Burns et al., 2008). The applied psychology and HFE science literatures are authorities on the properties of situation awareness, such as how people proactively monitor, control, and allocate their limited attentional resources. There is also a plethora of research that documents how to design systems that support situation awareness (Bolstad et al., 2006; Diao et al., 2009; Taylor, 2017).

Endsley, considered the grandmother of situation awareness, conceived of three levels that are relevant for digitalization (see Figure 11). Of particular relevance to nuclear operations, she warns of the *automation conundrum*—a negative correlation between autonomy reliability and human situation awareness (Endsley, 2017). Further, a bad decision based on poor situation awareness has trickle effects in that it can propagate throughout a system and lead to more serious problems. McLeod (2022) recommends that humans must remain *proactive* in their engaging behaviors with the system as opposed to *reactive* to combat dissociation and withdrawal and to maintain awareness. HFE researchers at INL have studied situation awareness within the context of nuclear operations extensively (Le Blanc et al., 2015; Oxstrand & Le Blanc, 2014; Spielman et al., 2017).

2.2.4 Apply Human Factors Engineering Early On

As noted in NUREG-0711, the NRC requires early HFE application in the digital upgrade program, and several INL research efforts document how early HFE in the systems engineering design phases helps support licensure requirements as well as a timely pathway to deployment (Ulrich et al., 2021). In other words, HFE must be present in the earliest stages of digitalization development and not simply as a tail end activity in mature iterations of the system's design (Boring et al., 2021) or during installation.

Figure 12 outlines the value chain of integrating human factors early on across key technical, operations, and performance indicators. Taken together, the felt benefits span everything from safety, reliability, efficiency, and importantly, the business case. Thus, conceiving of HFE as an afterthought will likely lead to suboptimal digitalized systems, regulatory uncertainty, and delayed deployment.

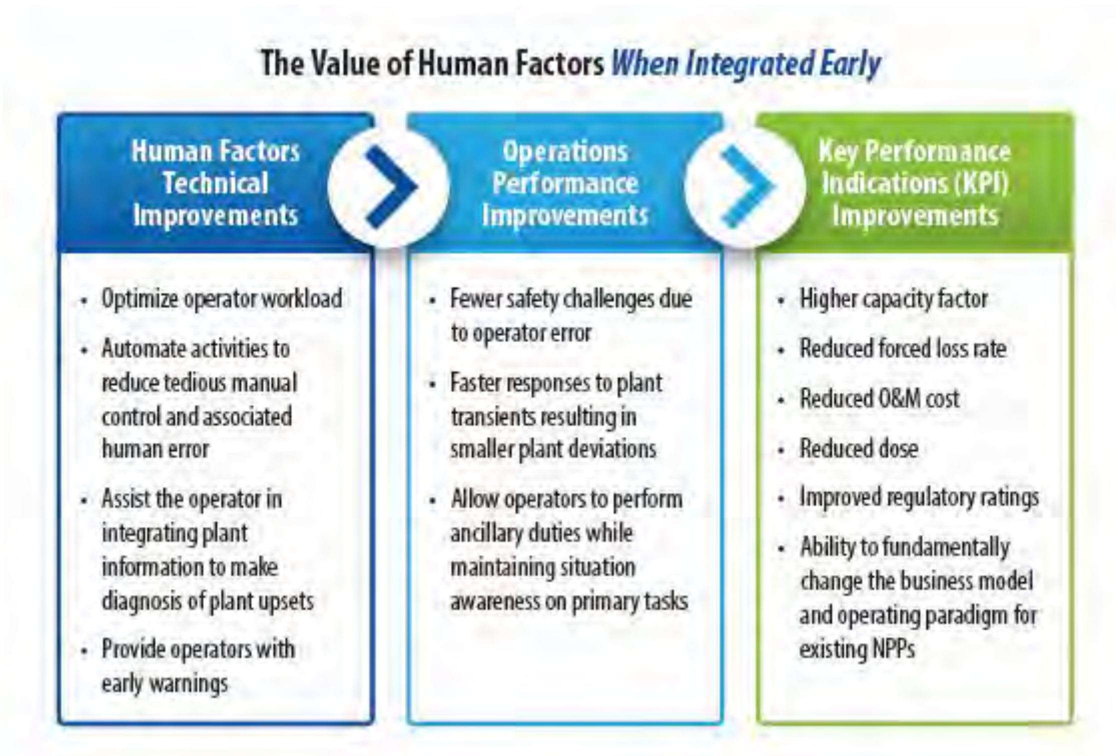


Figure 12. The importance of HFE in the digitalization strategy.

2.2.5 User Experience

Last, it cannot be overstated how important UX is in the successful adoption of digitalized technologies within the nuclear power community. UX goes beyond the interface (the point of human-machine interaction) and refers to everything that comprises the end-user's satisfaction with the technology. For example, UX encompasses not only whether user needs are met, but also simplicity, elegance, design, and functionality (Norman & Nielsen, nd). The importance of UX was made clear from the primary research conducted as part of this milestone (Section 4). Existing plant personnel must be able to observe immediate benefits, and likability and usability of the technology play a big role in approval and long-term adoption. HFE scientists can ensure that the HMI is designed with sound HFE principles that result in an effective product with which the users are apt to engage.

The HMI is the way that personnel interact with digitalized technologies. As a basic principle, the interface must use a presentation format that is consistent with the task functions the user is to perform (Braseth et al., 2009). Other design principles include being intuitive, holding the user's attention, minimizing errors, and affording nonexperts an understanding of how the system works. The interface undergoes early revision in parallel with the digitalized system design, and the new improved design is validated through an iterative process. Safety and usability are the chief priorities.

A rich HFE theoretical literature is devoted to interface design, with specific recommendations made for process control industries, such as nuclear power operations (Bennett & Flach, 2011). Ecological interface design uses cognitive psychology to inform ergonomic visual representations that best serve humans working with complex sociotechnical systems (Rasmussen, 1987; Vicente & Rasmussen, 1992). Two NRC documents offer guidance on HFE review criteria for interfaces, including style guide design features (O'Hara & Fleger, 2020) and interfaces to automatic systems (O'Hara et al., 2010). Together, the NRC makes clear that the display must both fulfill the needs of the system and users with safety as a priority.

A poor interface design, or one that is not user-centered (low usability), will likely be instantly rejected. Worse, HMIs that have been poorly designed and do not perform correctly have been contributing factors in major accidents (Hollifield, 2022). Given that digitalization will change the nature of the information presented to plant personnel, a key aspect of UX optimization will be soliciting user feedback in an iterative fashion to improve the design as well as understandability and interpretability.

Further, for the end users, it may not be a foregone conclusion that the new digitalized technologies will make life easier. Healthy skepticism is pervasive in nuclear power operations due to its rigorous safety culture (Agarwal et al., 2022), especially if there has been an instance in which the introduction of new technology in the past has failed or increased workload. Managing first impressions, and subsequently giving end users time (over weeks and months), and importantly, listening to feedback will pay dividends in overcoming any user-barriers to adoption in the long run. Personnel will need time to adapt, and their perceptions will likely change with each interaction.

Hall et al. (in press) tested preferences for four different HMI styles with industry professionals, including retired nuclear power operators. Clear preferences emerged for graphics with high contrast and bold coloring. However, High Performance HMI, a style with muted color tones, low contrast, and “dullscreen”, is widely praised for its effectiveness in assisting operators in fulfilling their duties (Hollifield et al., 2008). The design is simple and minimalist, and color is reserved for status changes (i.e., significant events) and not status conditions. It is also the case that operators will likely dislike this design when first introduced because of its perceived dull coloring. Over time however, as usage increases, appreciation grows (DeRubis, 2018).

2.2.6 Summary

Taken together, when applying HFE to digitalization, human-system interaction should be emphasized, along with a user-centric design that supports cooperation between the human user and digitalized technology. Altogether, this guiding principle in the digitalization initiative increases human control and trust in the system, a critical ingredient for success.

2.3 Principle #3: Establish Data Governance

The promise of digitalization is predicated on the production and accessibility of clean, accurate, relevant, reliable, unified, and contextualized plant systems data. Thus, our next guiding principle reflects important data considerations. Recent advancements in sensor hardware, cloud-computing, and bandwidth have lowered costs to put these data capture technologies in place (Al Rashdan & St Germain, 2018). However, while some utilities have made great strides updating their data information infrastructure, questions remain about the quantity and validity of the data available to generate new insights. Plants will have to invest in data management resources, including software engineering and architecture to address these questions.

A holistic approach to data use represents the strength of the digitalization method and is one of the key topic areas identified by the WDI in Section 3. Several challenges accompany this approach that can be summarized as data governance. Governance is the set of policies, programs, and procedures by which an NPP acts to collect, manage, and control its interconnected data resources. Figure 13 outlines five key aspects in a big data governance plan that a digitalization initiative must possess. To address them properly, the plant must contain the appropriate people and internal (work) processes and the application of the correct technology. Here we consider methods to support the key elements in digitalization for data governance.

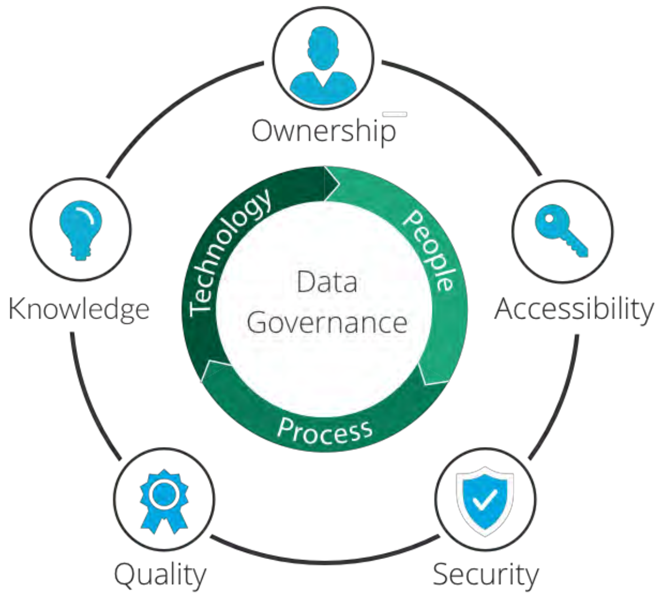


Figure 13. Data governance (image from Imperva, 2023)

2.3.1 Data Accessibility

Within the evolution of digitized information, the data must be stored in an accessible format. For example, information stored in PDFs is not readily obtainable for use by analysts compared to other digitized formats. Many plant tasks such as work orders, corrective action reports, and others, could be optimized by easy access to textual information stored in text-based documents. However, the vast majority of available textual information is currently stored as unstructured text, such that keyword searches still require the user to read the file once located. This process is labor intensive, error prone, and costly. AI/ML applications, such as natural language processing, can locate relevant textual information quickly from vast volumes of text-based documents and find patterns that are not readily apparent to users who perform a visual search. The transformation of free text into normalized, structured data is a requisite for optimizing digitalization processes that support decision-making during plant operations and maintenance.

2.3.2 Data Quality

Data must be recorded faithfully by devices, with errors detected and corrected before further data processing and analytics occur. Incorrect, mislabeled, or duplicate data values must be removed, and incomplete or corrupted data must be handled to produce valid information. Further, the data cleaning process must be performed in a consistent manner to ensure reliability. There must be checks and balances in place to verify that data cleaning was performed properly, with course-correct mechanisms in place via feedback loops. Last, the data may need to be transformed into a uniform and contextualized format, especially across multifield, multidimensional heterogenous datasets from disparate sources (Ma et al., 2022). Taken together, the data engineering and safe data storage that must occur before analytics can be performed is not a trivial issue and will require substantial backend and ongoing investments by the utilities to ensure suitability.

An NPP is one of the most complex engineered systems in the world, and systems that have already been digitized are producing vast amounts of data. Digitalization will mean that beyond data produced by digitized systems already in place, every human-system and system-system interaction will now generate data and may require analytics. Thus, a digitalization program will require dedicated data stewards (data engineers) that will take responsibility and ownership for data quality and accessibility and ensure its efficient delivery to the correct plant departments and systems. A CDO plays an integral role in digital transformation and should be engaged in ongoing research and development. A recent survey of CDOs showed that data governance is a top priority, while ownership and ultimate responsibility for the data is still unclear (Davenport, 2023).

2.3.3 Have a Plan for the Data to Generate Knowledge

As mentioned, NPPs produce vast amounts of data, and without a clear plan in place for how the data will be governed, they may not have been assigned meaning. The data complexities involved in digitalizing might produce a great deal of noise, which will cause confusion and undesirable additional tasking. In other words, make sure that data being processed is helpful and not cluttered with irrelevant metrics. This will allow personnel to focus on what's important. Plant engineers possessing the mentality that collecting all types of data all of the time is encouraging in helping create a data-driven culture. However, indiscriminate data collection and dissemination, without due diligence and possessing clear objectives for data analytics, is a limitation that must be overcome.

Some preliminary questions that might help determine data objectives are:

- What data do you have?
- What data are you collecting?
- How do you use that data?
- What do the data tell you about your work processes?
- What data are you missing?
- What do you not know?
- What data is not currently good enough?
- What data would provide assurance that the systems are working effectively?

Increasing the signal-to-noise ratio from digitalized-generated data will require a multidisciplinary approach, including plant engineers, business stakeholders, and data scientists. Deciding on actionable analytics derived from high quality and veridical data will be an evolving process.

2.3.4 Cybersecurity

The increase in readily available, hyperconnected electronic data streams brought about by digitalization will increase efficiency and lower costs. However, the shift to digitalized information also opens the door to increased risk in the form of unintended or intentional cyberbreaches (Pickering & Davies, 2021). This constitutes a serious safety concern and, by extension, a regulatory concern.

Cybersecurity within NPPs is at the forefront of discussions surrounding digitalization and should be considered during the formative, planning stages of the initiative. Keeping digitized nuclear power assets safe from cyberattacks is a matter of national security (Zetter, 2015). After a spate of cyber disturbances in the 2000s, the NRC mandated an ordinance that requires NPPs have a cybersecurity plan in place that meets the Commission's approval (Title 10 of the Code of Federal Regulations, as outlined in NRC Regulatory Guide 5.71; U.S. NRC, 2009).

Even without human decision-making, the increasing systems of systems complexity brought about by digitalization may generate unintended interruptions, such as system updates in one area or piece of equipment causing failures in another. The International Energy Agency (2017) has produced a comprehensive discussion on digital security including building resilience and cyber hygiene.

A recent plenary presentation at the American Nuclear Society's 13th Nuclear Plant Instrumentation, Control & Human-Machine Interface Technologies conference by Katya Le Blanc outlined the importance of having individuals with a deep understanding of the system when it comes to security. Moreso than any factor, such as new technological solutions or security tools, she emphasized the importance of the human element. Additionally, she encouraged organizations to view their cybersecurity programs as ongoing and requiring steady development and supervision. It is unlikely there will be a technological elixir; instead, digitalized systems should always be considered imperfect in their cyber defenses. Continuous vigilance should be applied. Outsourcing cybersecurity standards should likely be avoided.

When crafting cyber solutions, care should be taken not to decrease UX. For example, the need for password managers showcases cybersecurity's conflict with usability. There must be realistic assessments made of human capabilities to remember long, complex passwords that are not allowed to be written down. In reality, the theoretical benefits of this form of security are unrealized because users likely end up writing the passwords down anyway. Taken together, cyber experts should work closely with HFE experts in creating both user-centered and secure designs when developing digitalized tools.

Scientists and engineers at INL are at the forefront of cybersecurity research and development for energy operations, the grid, and nuclear power systems. These include technological solutions within cyber defense. Importantly, HFE scientists at INL can examine vulnerabilities in human-system interactions using the Human Systems Simulation Laboratory, such that digitalization initiatives can be developed via simulation experiments within the existing framework of a utilities' NRC-required cyber program. Importantly, the relationship between security and usability must be well understood so that systems can be engineered to find an appropriate balance. The cyber research works conducted at the Human Systems Simulation Laboratory thus far are documented in Hall et al., (2022).

2.3.5 Summary

The digitalization method must include a data strategy because one of its chiefs aims is to break down information silos to streamline work processes. Capturing quality data, solving data fragmentation, and effectively using new insights brought about by these data interactions will require a data governance infrastructure. The LWRS Plant Modernization Pathway recognizes this need—I&C architecture and digital infrastructure is one of its core research areas. Last, proper data governance paves the way for advanced AI/ML technologies, such as risk-informed predictive maintenance (Agarwal et al., 2022; Walker et al., 2023), to generate intelligent insights, predictions, and action recommendations.

2.4 Principle #4: Anticipate Unintended Consequences

Our last guiding principle concerns digitalization consequences that were not part of the original design. As mentioned, the significant business benefits to be gained from a new data-driven concept of operations are considerable, and integral to the industry's survival, but there will be trade-offs and potential unintended consequences. A poignant historical lesson here is to consider nuclear control room upgrades when the control systems went from analog to digital. The new digital systems created a great deal of additional information, especially with alarms, that the operators were not used to. They had to quickly figure out how to deal with the alarm flooding and work out alarm prioritization soon after the fact. Capturing precisely what the operators need to know, and balancing this with new system capabilities should be carefully considered beforehand.

In addition to anticipating unintended consequences, there are known ripple effects from similar implementations, such as automation and AI/ML applications, that should be considered. For example, time delays, glitches, and questions about reliability will all likely be introduced. An important aspect of the initiative will be to balance the digitalization benefits with the new vulnerabilities and liabilities that will occur.

2.4.1 Avoid Over-Digitalization

According to HFE principles, the digitalization strategy should strive to meet the essential functions of the system and avoid unnecessary functionality and overly sophisticated HMIs. Ideally, the system should be kept simple (avoid overcomplicating things), require as little as possible, and be resilient (i.e., be hard to botch). Over-digitalizing can result in over-reliance, complacency, and a drop in situation awareness.

Hall et al. (2023) recently published findings from an experiment that tested different types of computer-based procedures (CBPs) with varying levels of digitalization. Participants were randomly assigned to one of three levels of digitalization and assessed on a range of performance measures. Task load was measured as well as situation awareness. Participants were also asked to rate how helpful and likeable the procedures were. Hall et al. hypothesized that there would be less favorable impressions of the most basic procedures and that these would demonstrate lower usability than types with greater digitalization. The CBPs were classified according to the Institute of Electrical and Electronics Engineers (IEEE) Standard 1786, with three levels of digitalization integrated into the procedure (IEEE, 2022). These are:

- Type 1—closely resembles traditional paper-based procedures in that it displays the procedure on a computer screen
- Type 2—has more capabilities and can additionally display process data and step logic, display results, and provide access links to displays and soft controls that reside on a separate system
- Type 3—has Type 2's capabilities, can automatically carry out sequences in the procedure, and has embedded soft control features, though unlike Types 1 and 2, Type 3 procedures can manipulate the plant directly from within the procedure instructions.

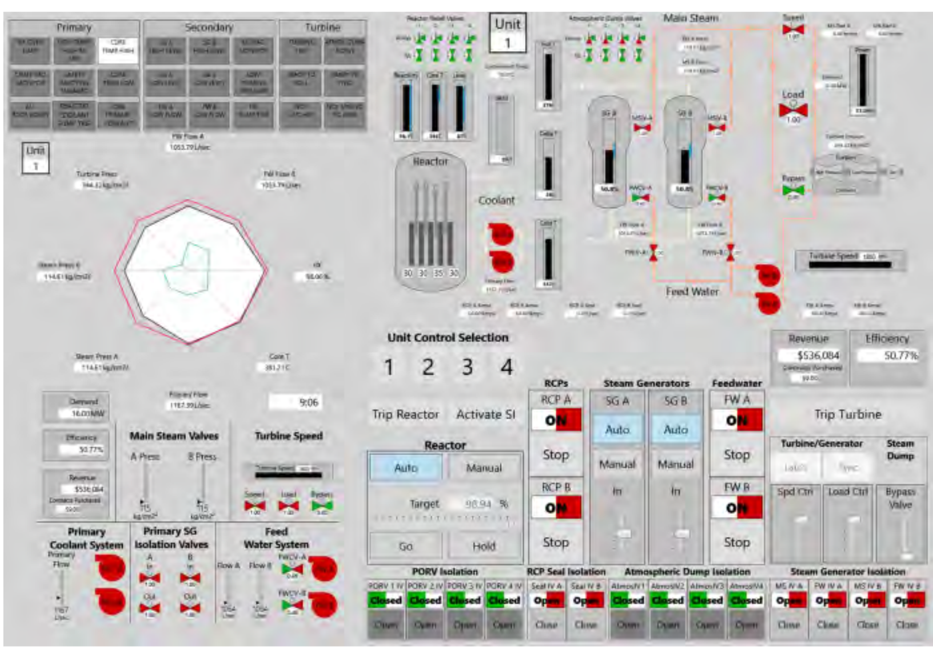
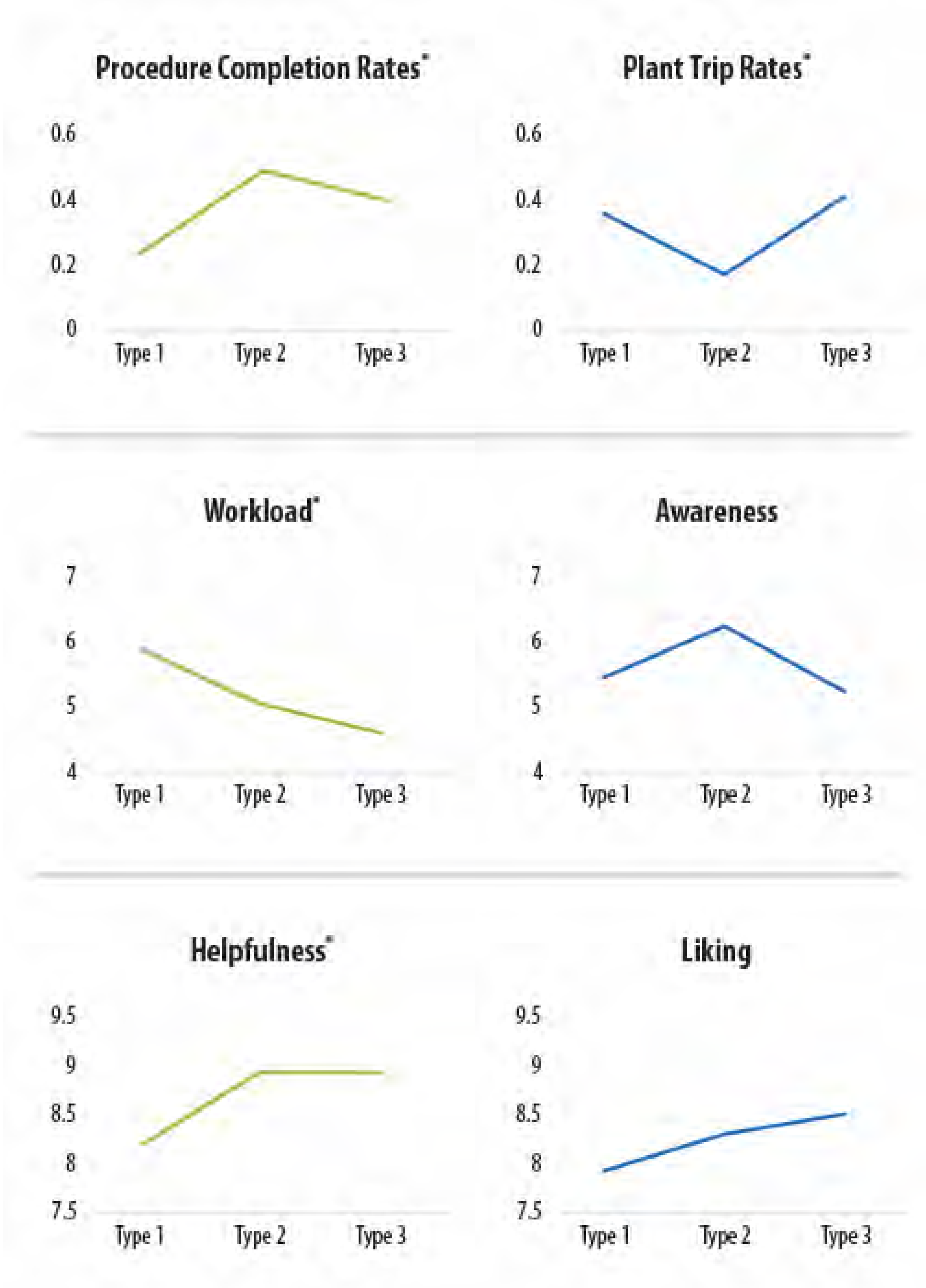


Figure 14. The Rancor Microworld Simulator.

The participants performed scenarios using the Rancor Microworld Simulator, a simplified simulator that mimics both everyday operations and emergency situations in an NPP. It was developed at INL and the University of Idaho (Ulrich et al., 2017) by human factors scientists and contains essential NPP components and systems. The interface consists of three areas (see Figure 14).



*Denotes statistically significant main effect of digitalization level

Figure 15. Assessment of computerized procedures with different levels of digitalization.

The results showed that procedure completion rates and plant trip rates varied significantly as a function of level of digitalization (see Figure 15)—Type 2, the middle level of digitalization, performed most favorably, producing the highest completion rates and lowest trip rates. Workload decreased as the level of digitalization increased, and Type 2 produced the highest situation awareness (note—although there was a trend, this finding did not reach statistical threshold for significance). Last, perceived helpfulness varied by level of digitalization. Taken together, these experimental data suggest that the procedures containing the mid-level of digitalization (Type 2), absent embedded soft controls as with Type 3 but with the addition of plant process indicators and step logic compared to Type 1, may represent the sweet spot of digitalized CBPs, at least for control room operations.

These results comport with the PPA, who assessed feedback from industry experts using the same IEEE Standard 1786 levels of digitalization integrated into the procedure. They similarly found Type 2 to perform the best. These findings also comport with known psychological and human factors phenomena. For example, it is well documented that exposure to some amounts of stress facilitates performance in domains such as organization (Anderson, 1976), work productivity (Wilke et al., 1985), and cognitive function (Sandi, 2013). This has also been demonstrated in animal research e.g., rats in a maze (Salehi et al., 2010). Too much or too little stress intensity results in a performance decline (see Figure 16). In terms of CBPs, optimal designs will likely embrace a manual / digital balance.

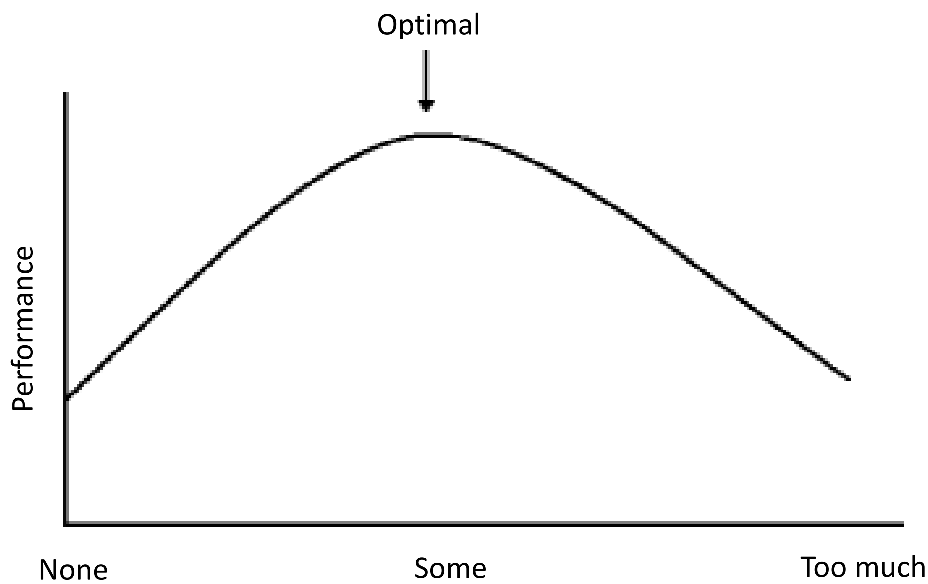


Figure 16. Inverted U-shape of level of digitalization in CBPs.

These findings converge with HFE recommendations that caution over-automation. In her seminal work *Ironies of Automation*, Bainbridge (1983) pointed out several decades ago the unintended consequences of automating industrial processes, including the observation that automation can at times expand rather than eliminate problems for the operator. Many of her documented ironies are relevant to the issue of over-digitalizing, including a potential drop, not increase, in awareness.

Another relevant topic for digitalization is that for functions deemed to remain within the purview of humans, it must be carefully considered how digitalization of surrounding processes will impact the original tasking. It is likely that the tasks left to humans are high level, arbitrary, and not easily defined. Thus, neglecting to consider how these tasks will be altered as a function of digitalizing accompanying processes, and by extension a lack of support for these tasks, will likely generate problems. The risk removed by digitalization will simply be shifted elsewhere in the system.

2.4.2 De-Skilling of the Workforce

Another issue Bainbridge identified was that, without thorough HFE application in system design, a habitual lack of awareness will lead to a decrease in skills and competence. In other words, highly skilled and experienced operators will become novices and may fail to intervene when necessary. This phenomenon, brought about by the introduction of technology that assumes many of the job roles and tasking of staff, is known as de-skilling.

With the progressive introduction of automation and autonomy, de-skilling has been identified as a major challenge in several safety-critical industries. such as aviation, rail, healthcare, and nuclear power operations (McLeod, 2022). Pilots have been complaining for several decades that they are no longer operators of the aircraft but instead monitors of a system. They no longer have direct interaction with the control surfaces of the airplane and instead interact with electrically mediated inputs. As a result, there are serious concerns about losing the skill of flying, and should an emergency arise, pilots may not be adequately prepared. The trade-off for the airlines is of course that the less the pilots physically fly the plane in a hands-on approach, the greater the fuel efficiency.

It is possible that the increased risk of workforce de-skilling brought about by digitalization may hamper deep-thinking in other areas. Daniel Kahneman, a Nobel laureate and known as the godfather of behavioral economics (decision-making), offers two modes of thought and decisions (Kahneman, 2011). System 1 is fast, instinctual, intuitive, and requires little effort. System 2 is slow, deliberate, and effortful, akin to critical thinking. It may be the case that the de-skilling evidenced in industry contributes to a lack of System 2 abilities, which will be further detrimental to operations.

2.5 Summary

In this section we have presented guiding principles and methods necessary to effectively digitalize nuclear industry work processes. Our first principle was to develop a coherent digitalization plan. This must involve both a vision and approach and should engage utility professionals, government, and industry stakeholders. Strategies to overcome organizational barriers were discussed. Our second principle was to apply HFE. The importance of HFE in regulatory approval was stressed and in maintaining situation awareness. UX should be one of the chief considerations in the digitalization design. Our third principle was to establish data governance. The vast quantities of data produced by digitalization must be accounted for, and access to clean, relevant, reliable, and secure data will be key for the initiative's success. Our last guiding principle was to anticipate unintended consequences. We presented primary research attesting to the dangers of over-digitalizing, and lessons learned from other safety-critical industries.

Digitalization is critical for nuclear power industry sustainability. However, no one principle contains all the answers, and there are challenges in applying this methodology. Digitalization is not an overnight process and given that it touches every aspect of the business, including people, processes, and tools, patience will need to be exercised to iron out kinks. Personnel will need time and support to adapt to the new work culture (Sharma, 2020).

3. THE WORK DIGITALIZATION INITIATIVE

3.1 Background

In 2016, the Nuclear Electronic Work Packages–Enterprise Requirements (NEWPER) initiative, an industrywide working group, was launched as a step toward a vision of implementing an EWP framework that included many types of electronic documents, from PDFs to CBPs. The goal was to enable immediate paper-related cost savings in work management and provide a path to future labor efficiency gains through enhanced integration and process improvement. The NEWPER initiative was organized by the Nuclear Information Technology Strategic Leadership (NITSL) group, which is an organization that brings together leaders from the nuclear utility industry and regulatory agencies to address issues involved with information technology used in nuclear power utilities. NEWPER was facilitated and led by LWRS researchers.

The main goal of the NEWPER initiative was to develop a set of utility-generic functional requirements for EWP systems. This set of requirements would support each utility in their process of identifying plant-specific functional and nonfunctional requirements. The overall goals of the initiative were:

- Define the core components of an EWP system
- Define functional requirements for these core components, covering the full spectrum of EWPs from basic PDF to dynamic smart documents
- Share operational experience that is related to ongoing EWP implementation activities in industry (e.g., benefits gained and identified issues)
- Communicate utilities needs and wants to solution providers
- Standardize terminology related to EWPs and smart documents.

In addition, the NEWPER initiative provided an opportunity for establishing new or reinforcing existing relationships between utilities and solution providers. NEWPER had 119 members across 33 organizations. Before the conclusion of the initiative in December 2016, the members composed one industry report and one standard document. The standard was published by the Procedure Professionals Association (PPA; AP-907-005.001 Functional Requirements for Advanced and Adaptive Smart Documents), an organization dedicated to developing and exchanging technical information about professional procedures. The PPA is the collective voice and leader in procedure and work instruction writing, processing, and associated training for member facilities. NITSL and INL published the Functional Requirements for an Electronic Work Package System (INL/EXT-16-40501).

Between 2019 and 2020, a follow-on initiative to NEWPER was created, again led by LWRS researchers. The DIRECTOR, or Dynamic Instructions Editing Tool Requirements initiative addressed the need for consistent and clear guidelines when transitioning from paper to DIs. DIRECTOR was unique because of the variety of organizations participating in its development and application. The DIRECTOR initiative included collaborating members from power-generating utilities, DI technology, procedure support, software development solution providers and research organizations. Additionally, the DIRECTOR partnered with the PPA from its inception. These collaborations ensured consistency between solution providers and utilities. DIRECTOR had 196 members across 67 organizations.

The DIRECTOR initiative provided a roadmap for the transition from paper to DIs, meaning that utilities would not have to start from scratch when they begin the process (PPA AP-907-005.002, Dynamic Instruction Set Editor Functional Requirements and Implementation Considerations). Key to the initiative was the development of the Common Dynamic Instruction Model (CDIM), which was published in December 2020 (in the PPA AP-907-005.003 CDIM). This vendor- and utility-generic model covers nearly all functionality types that a utility would want from a DI solution. This underlying structure provides a starting point for utilities, requiring only customization of the tool based off the CDIM functional requirements, saving time and effort. Even more importantly, when a utility's solution provider adheres to the CDIM, the utility reduces the risk of being tied to one solution provider in the long run.

Between the two initiatives, one industry report and three PPA standards were published. The initiatives created the opportunity for researchers to lead $6.6 million of additional research, development, and deployment projects.

Table 2 and Table 3 describe follow-on activities that resulted from both NEWPER and DIRECTOR, respectively.

Table 2. NEWPER follow-on projects.

	Funds In	External Match	Comment
Strategic partnership project with Solution Provider A	$40,000	—	Fiscal Year (FY) 2018
Technical commercialization funds project with Solution Provider A	$750,000	$750,000	FY18–FY19
Technical commercialization funds project with Solution Provider B	$1,500,000	$1,500,000	FY19–FY20
Total	$2,290,000	$2,250,000	

Table 3. DIRECTOR follow-on projects.

	Funds In	External Match	Comment
Technical commercialization funds project with Solution Provider C	$1,500,000	$1,500,000	FY20–FY21
Strategic partnership project with Solution Provider D	$75,000	—	FY20
Technical assistant program project with Solution Provider E	$6,000	—	FY21
Dynamic workflows at INL (indirect funding)	$300,000	—	FY20
Process architecture for continuous excellence—INL (indirect funding)	$550,000	—	FY18–FY22
Dynamic laboratory instructions at INL (indirect funding)	$200,000	—	FY23
Total	$2,631,000	$1,500,000	

NEWPER and DIRECTOR successfully brought the industry together to define a common language, identify industry needs and requirements and define a standardized path forward. The two initiatives were ground-breaking at the time. However, they stayed focused on procedures and instructions and were close to the traditional way of writing such documents. In other words, they did not have a data-centric approach to work management.

3.2 New Initiative for Digitalizing Work Processes

During the Dynamic Work Execution Symposium hosted by NextAxiom Technology, March 31–April 1, 2022, a new industry initiative was proposed. The initiative, created and facilitated by LWRS researchers brought stakeholders across the industry together to identify and address the current hot topics related to digitalization, specifically the digitalization of work. As with prior initiatives, the goal was for stakeholders to define a standardized path forward for industry digitalization by sharing concerns, potential barriers, insights, and lessons learned. The WDI was officially launched in May 2022. The initiative members represented the nuclear and nonnuclear industries, DOE research labs, other research organizations, regulators, solution providers, and standards organizations. This initiative was for all the power-generating industry, including advanced reactor designs, and comprised 155 individual members representing 63 different organizations (see Figure. 17). The members identified five main topics of interest, and working groups for each were established. Leaders for each working group were selected. The five critical areas identified within work digitalization were:

- **Information Automation**—Provide the process for an efficient integration of digital technologies with work processes through information automation, resulting in the SDE necessary for cost-competitive operation.
- **Holistic approach to data use**—Define the principles of asset data management governance and practices covering data acquisition, storage, maintenance, and use. Identify common operational, tactical, and strategic data on associated decisions and actions. Define quality data and identify methods to increase data quality through standard processes. Construct a process for mapping organizational asset data, including acquisition sources, processing flows, storage, and access points. Provide principles for developing a flexible technology architecture to enable the holistic data use approach.
- **Modern Workforce**—Develop a vision to convey the desired end state, compile architecture and application design best practiced that deliver the vision, develop a framework for creating a business unit data strategy to support the vision, compile best practices for on- and offsite remote worker support, develop a self-assessment tool, and develop a framework for determining costs and benefits.
- **Human-System Interaction**—Define a standard for data visualization to support the end users' decision-making process, including interfaces for executing and analyzing post-execution data. Provide a comprehensive technical basis for items, such as various step types and place-keeping approaches, that apply to DI. Identify potential human error traps related to DI human-system interaction and provide a strategy to ensure the user interaction is easy and efficient.
- **Digitalization Value Proposition**—Benchmark and evaluate benefits of digitalized work to identify the value proposition or business case for work digitalization. Part of the scope will be to identify opportunities for implementation strategy improvements and to identify highest value opportunities for digitalization.

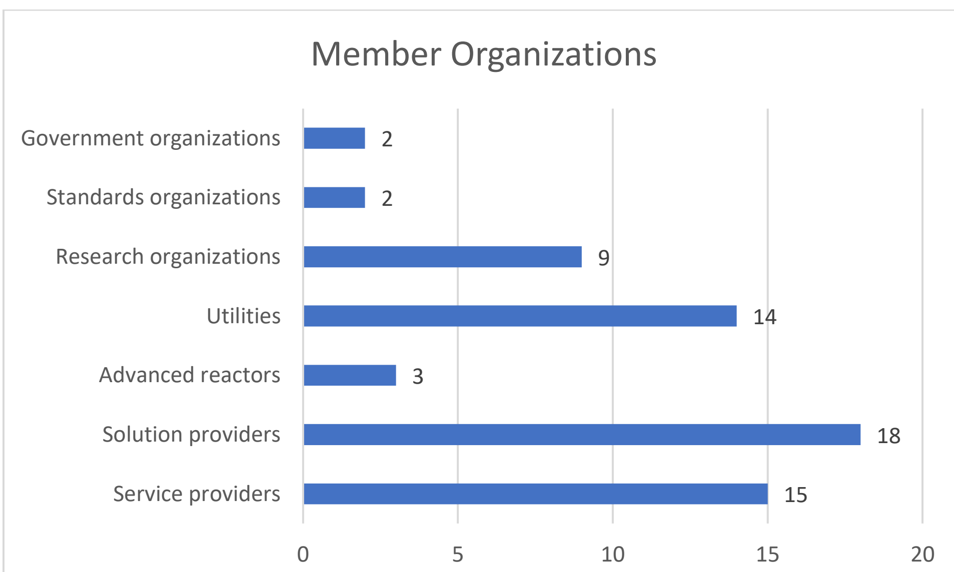


Figure. 17. Member organizations in the WDI.

The most significant outcome of the WDI has been the creation of a new writers' manual for DIs. The writers' manual was created by the human-system interactions working group and is an important step towards work digitalization in the nuclear industry as it will drive further standardization and adaptation of DIs. The manual has undergone extensive reviews by the PPA executive board and its members. The goal is for the PPA to publish the new writer's manual in early 2024. Specifically, they will include the specific guidance for DIs in the main writer's manual (historically only covering paper procedures) rather than creating a separate manual.

By including it in the main writer's manual, PPA is conveying to the nuclear industry that DIs are fully endorsed rather than a potential add on to provide guidance to workers. The importance of this is due to the critical role the PPA and its standards play in the commercial nuclear industry as well as in the DOE, the Department of Defense, and oil and gas. For example, DOE retired their own procedure writers' manual and adopted the PPA's in 2014. Taken together, this is a significant step forward for work digitalization since it signals that the PPA fully adopts and endorses DIs as one way of formatting step-by-step guidance.

3.3 Current Status

In May 2023, the core team was contacted and working group leaders were asked to produce an update of group activities since inception. Specifically, group leaders were asked to respond to the following questions:

1. What have you accomplished this year within your working group?
2. If you could have one wish, what would it be?
3. Do you believe that we should continue with this initiative?

Responses were captured for four of the five working groups. The leaders for the working group titled "Digitalization Value Proposition" did not respond. Table 4 outlines the current state of the art for the WDI. In terms of accomplishments throughout the year, most groups indicated that they had developed a charter. These were produced in a standardized format under the following subheadings: Business Problem and Opportunity, Proposed Objectives, Deliverables, and Hard and Soft Cost Savings. A brief description of some important aspects of each working group's charter will be presented here.

3.3.1 Charters

3.3.1.1 Information Automation

This working group identified the business opportunity of digitalization over traditional human-centric processes to be primarily the reduced probability of human error, interrelatedness of systems, and improved communications. Barriers included the departure from long-established technologies in which there is no information automation. Three tasks were defined within an overarching objective to develop a process for the information automation integration in the creation of an SDE. The tasks were:

1. Define the digitalization needs to support information automation
2. Develop the process, methods, and governance for information automation
3. Pilot an information automation use case.

Proposed deliverables included presenting the findings at the NITSL conference and drafting an information automation planning guide.

Table 4. WDI working groups status.

	Working Group			
	Information Automation	Modern Workforce	Human-System Interaction	Holistic Approach to Data Use
Q1	Defined the charter. Documented use cases.	Developed a charter, objectives, and deliverables.	Developed a charter. Developed a stakeholder management plan for a DI procedure upgrade project. Drafted DI procedure writer's guide submitted to PPA.	Finalized charter. Drafted a high-level view of technologies needed to implement a holistic approach to data use. Drafted a principles document with five principles and implementation roadmap.
Q2	Focus on integration and automation in the context of performing work. Draw the group together.	That more team members would step up.	More team participation.	Greater team participation, particularly by utility personnel.
Q3	Yes, as it is needed to innovate computer-guided work, expedite its adoption, determine highest return on investment from digital capabilities, and define new governance.	Possibly or no, as our team members lost interest, were unwilling to invest their time, or did not see the value.	Yes, but more team participation is required to meet deliverables.	Yes, but only if utility personnel contribute.

3.3.1.2 Holistic Approach to Data Use

This working group identified the digitalization business opportunity as a necessary means to address twenty-first century challenges, such as changing regulatory, economic, and social landscapes. A holistic approach to data includes processes that allow access to full lifecycle physical and transactional data in support of streamlined asset management. The identified challenges mostly surrounded the current issues in NPPs with data acquisition, storage, maintenance, and their lack of integration across systems (i.e., data governance). Group objectives and proposed deliverables involved developing principles and a roadmap to implement a holistic approach to data use and presenting this plan at NITSL.

3.3.1.3 Modern Workforce

The focus of this working group was developing digitalization solutions within nuclear power information technology systems that better reflect the expectations of the modern workforce. For example, younger generations such as millennials are tech-savvy, generation Z is tech-dependent (see Figure 18), and remote work options have become common in the workplace. This workforce status is largely incongruent with current analog or analog-digital hybrid nuclear plant operations. Broadly defined, the business opportunity is that digitalization will positively impact workforce recruitment and, just as importantly, workforce retention. As with most other working groups, one proposed deliverable was to present the findings at NITSL.

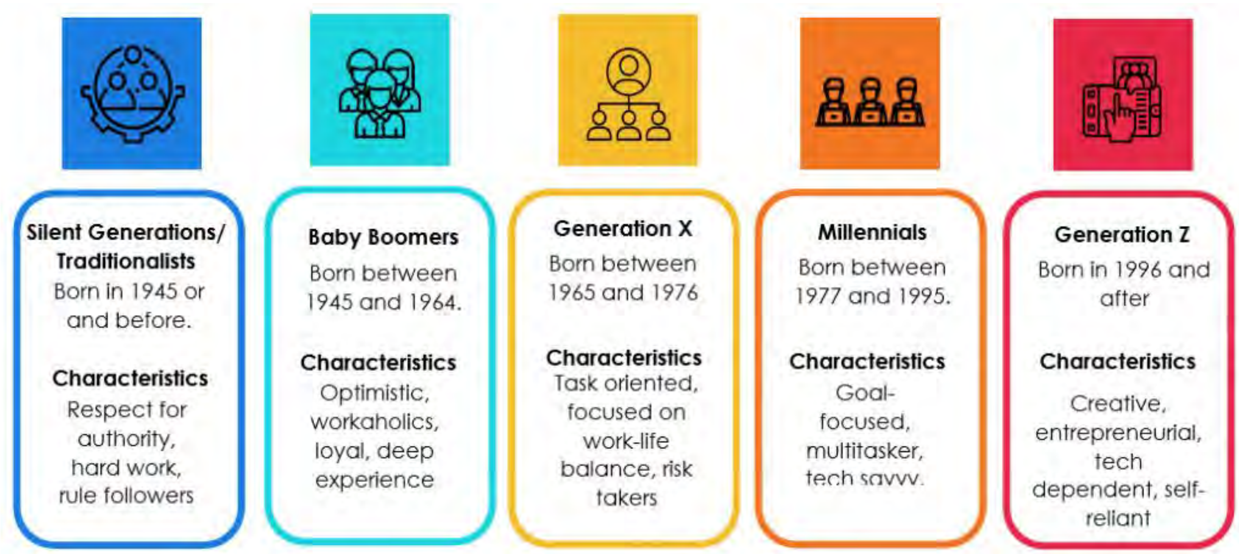


Figure 18. Understanding five generations in the workplace (image from National Human Resource Centre, 2023).

3.3.1.4 Human-System Interaction

This working group focused on human-system interaction within DI. The business opportunity identified surrounding this technology specifically was reductions in human error and reworks, access to integrated and interrelated data, systems, and processes, improved communications, and improved decision-making. Barriers include the introduction of digitalized instructions as a significant departure from the status quo and that the content and navigation of the new technology must intuitively align with established paper-based instruction methods. The group's proposed objectives included developing a framework for a stakeholder management plan, defining a standard for the visualization of data, and identifying potential human-system interaction error traps related to DIs. The main deliverable was the DI procedure writer's guide, submitted to the PPA.

3.3.2 Principles for Holistic Approach to Data Use

Beyond each active working group developing a charter, the Holistic Approach to Data Use group began a draft document sketching out principles and an implementation roadmap (Ives & Austin, 2023). This document is a work in progress and to date, the principles outlined comprise:

- Complete asset data record
- Data collection
- Data record maintenance and management
- Data record access and use
- Governance.

3.3.2.1 Complete Asset Data Record

The first principle dictates that an asset data record must be completed. This is based on market drivers and operational needs and will fluctuate over time as these forces change. Elements of a complete asset data record include but are not limited to the following attributes: financial, material, fabrication, specification, procurement, operational, and maintenance. Further, a complete asset data record must take into consideration the asset's lifecycle phases. Figure 19 demonstrates in detail, the nine phases an asset moves through from identifying a need for the asset through asset decommission.

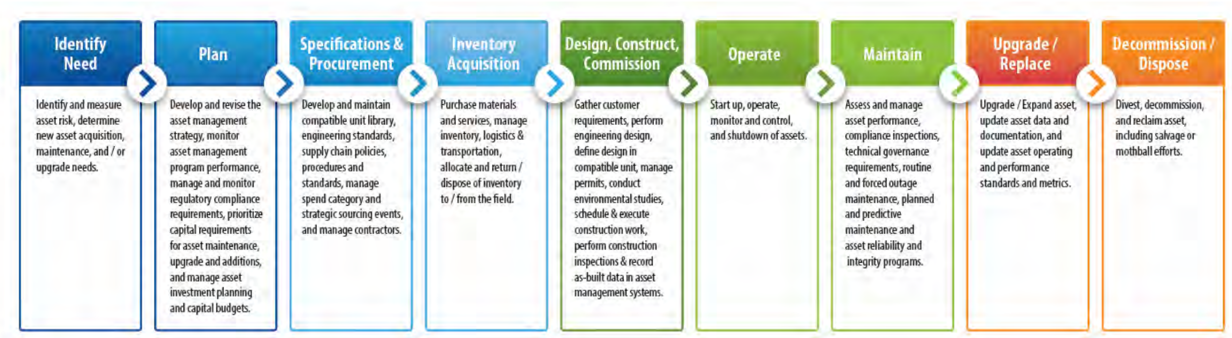


Figure 19. Asset lifecycle.

3.3.2.2 Data Collection (for the Asset Data Record)

Considerations outlined in this principle are to collect data as close as possible to the point of origin in space and time, use an interdisciplinary approach in which multiple individuals with access gather the data, minimize errors in data collection by using automated means aided by AI/ML techniques, and make sure that manually collected data be thoroughly validated.

3.3.2.3 Data Record Maintenance and Management

Given that data integrity is an ongoing process, this principle instructs that the asset data record be kept regularly updated throughout each phase of an asset's lifecycle. Further, the data needs to be periodically validated for completeness and an ongoing quality control check should occur, corrections should be made where needed, and obsolete data should be archived.

3.3.2.4 Data Record Access and Use

The principle outlined here stems from considerations of sensitive and confidential digital plant data. Data access should be restricted on a need-to-know basis. Data and records should be classified according to the utility's goals, objectives, and values. A holistic approach to data relies on highly interconnected digital data streams from disparate and varied sources, which poses an increased risk of cyberthreats.

3.3.2.5 Governance

The last principle outlined by this group is governance. Several important aspects to governance include: policies and procedures governing the collection, management, use, and security of data records are documented, made readily available, kept up-to-date and periodically reviewed; data management risk is clearly understood by relevant personnel; roles and responsibilities are established for overseeing and implementing a holistic approach to data program; management and leadership support and promote effective data management through sound decision-making and resourcing, including effective communications about the program's goals and objectives, as well as employee roles and responsibilities throughout the organization; continuous improvement of the data management program is embraced.

3.4 Aims and Future Directions

In response to Question 2 "If you could have one wish, what would it be?", Table 4 illustrates that universally, leaders of the each of the WDI initiatives reported that they wished for more member engagement. One group indicated that they particularly wished more utility personnel would take part. This was consistent with answers for Question 3 "Do you believe that we should continue with this initiative?" Responses were mixed, with the majority indicating that the status quo is not working, and that the initiative should only continue with greater team member participation. The reasons for scant WDI member engagement are unknown but may include a lack of time, lack of interest, difficulty perceiving the value or return on investment, or group dynamics.

In summary, the WDI was conceived as a means for nuclear organizations to help define and standardize the industry's approach to digitalizing work. Its first year saw the emergence of several working groups that identified important digitalization topic areas to develop. While charters were drawn, many groups were hampered by a lack of engagement, especially from utilities. LWRS researchers at INL have reached out to utilities to take the lead for the WDI moving forward and are awaiting a response.

4. INDUSTRY DIGITALIZATION RESEARCH

We now turn to primary research conducted by LWRS researchers to help understand the current state-of-the-art of digitalization in nuclear, as well as drivers and barriers to implementation. This section summarizes the results from two surveys and one poll on digitalization perspectives in industry. In 2022, two work digitalization surveys were conducted. The first, "Work Digitalization in Industry," targeted the current state and near-term plans of work digitalization in the industry. The second, "Dynamic Instructions—Vendors' Perspective," targeted specific solution providers in the market of DI solutions. This survey aimed to capture the solution providers' insights on the nuclear and oil and gas industries' current thoughts on DI solutions and where the solution providers believe the industries are heading in the next five years. In 2023, a poll was conducted at a nuclear digitalization conference to collect data on the significance of digitalization, chief advantages and drawbacks, and how INL can best support the industry in this space. The surveys and poll were developed via lessons learned from other energy industries, such as oil and gas, along with insights from service and solution providers.

4.1 Work Digitalization in Industry Survey

This survey was sent to 125 individuals representing utilities, advanced reactors, service providers, solution providers, research organizations, and regulatory agencies. There were 12 respondents representing three utilities (n=4), two advanced reactors (n=2), five solution providers (n=5), and one research organization (n=1). The sample comprised n=10 males, n=1 female (one nonresponse) with mean age M= 51 years (Standard Deviation = 12.66 years, Range = 30–69 years). The average time employed in the industry was 26.27 years (Standard Deviation = 14.01 years, Range = 3–48 years). One respondent did not provide answers to the age and industry experience questions.

The survey contained 22 questions about current levels of, and future plans for digitization and digitalization. A summary of the results is provided.

4.1.1 The Motivation and Focus of Digitization

Participants were asked to describe their motivations and perceived benefits for digitizing work management-related technologies, processes, and other items. All participants listed at least one reason to digitize (respondents could list more than one). The main reason to digitize concerned information and data (see Figure 20).

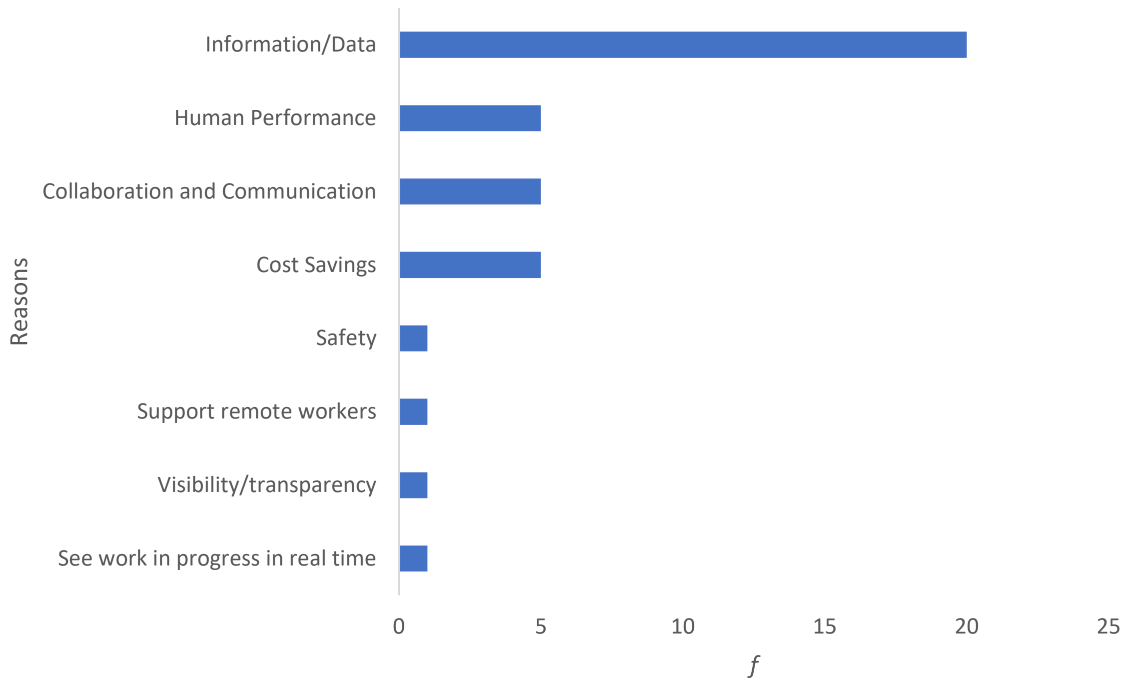


Figure 20. Motivation for digitizing.

Digitizing benefits included:

- Human error reduction
- Labor cost reduction
- Elimination of low-value work
- Reduced cost of paper and paper handling
- Collect data to be used in decision-making
- Documents are searchable, navigable, and auditable
- A single source of truth—no more chasing missing copies
- Provide a live view of work in progress
- Consistency of data across various stakeholders
- Performance consistency
- Support remote work and workers
- Easier storage and transferability.

There was a unanimous sentiment that the primary motivation for digitizing is that digital transformation is essential for nuclear utilities to be economically viable in the future.

According to the participants, nothing is entirely off the table regarding digitizing (see Figure 21). Many organizations have roadmaps to continue their digital transformation based on cost-benefit analyses and enablers in place to support. However, there are low-priority items (e.g., digitizing infrequently used documentation, enabling procedures to control the plant, and digitizing equipment in harsh environments) that may not be included in initial upgrades.

The mode response for not digitizing was the cost and time it takes to convert to electronic media. This is especially true for older nuclear plants. There is also a concern that organizations need a well-defined digital strategy and vision.

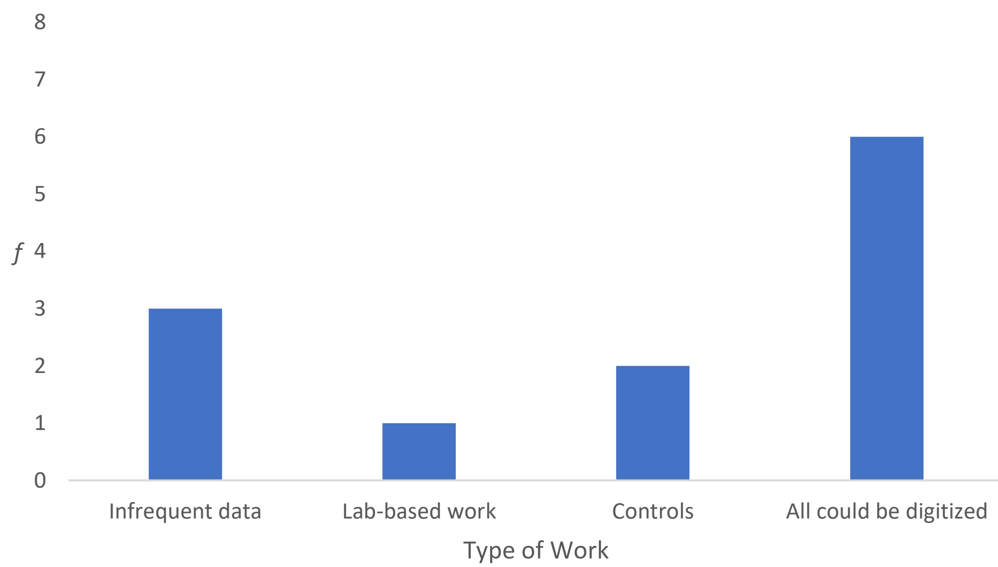


Figure 21. Types of work that will not be digitized.

4.1.2 Work Management and Electronic Work Packages

EWP solutions provide significant capabilities beyond paper-based procedures and work packages while reducing the overall day-to-day workload for most users. EWP solutions are instrumental in human error reduction opportunities, real-time feedback on work status, more realistic estimates of completion time, consistent application of work processes, and the historical tracking of work performance drive improvements across the existing fleet. Further, EWP solutions enable easier retrieval of past information, speed up the assembly process, and streamline the work package update and approval process. This technology can also automate the association to work permits, personnel training, qualifications, scheduling, and resource availability if proper interfaces exist for these information systems. EWP solutions also promote a standardized procedure format and a structured approach to multiple users executing the same procedures in multiple locations.

All three participating utilities use an EWP solution, indicating their work management processes are heavily digitized. One utility had also implemented a DI solution. One of the participating advanced reactor companies is currently piloting an EWP solution. The other participating advanced reactor is using EWPs. The first work management question on the survey aimed to discover the extent to which the work management process had been digitized. N=10 participants provided a wide range of answers:

- Personal information management system

- Office-based system (e.g., design, email, web calls, simulation)
- No work management process but processes for training, performance, and research are digitized
- Digital procedures for the units
- Work management, ideation, and scheduling systems
- Generation 1 EWP that is now complemented by dynamic procedures
- Every part of the procedure writing is digitized
- Document control and records management
- Scheduling
- Company planning, tracking, and piloting electronic procedures for operation and testing
- EWPs.

The solution providers focused on improving the efficiency of handling records and work packages. The acceptance and adoption of EWP solutions produced mixed results, depending on the stakeholder. Supervisors and records management tended to readily accept this new technology. In the past, the craft was not readily open to digital procedures. The takeaway is that the response to EWP adoption has not been consistently positive. Future research should parse out why this is the case. One solution might be to adopt DIs instead of EWPs.

4.1.3 Smart Planning and Scheduling Technologies

Two utility participants and one advanced reactor participant indicated plans to use smart planning and scheduling technologies. Regarding acceptance, each of the three participants planning to implement these technologies has support from leadership and the affected work groups.

Smart planning and scheduling technologies may improve process automation and error reduction, reducing labor costs. One example is the ability to shorten an outage duration by ensuring scaffolding is in place when needed. Smart planning and scheduling technologies are also essential when moving toward condition-based maintenance instead of periodic maintenance.

Only the solution providers addressed the cost of digitalization of the planning and scheduling processes and the expected hard or soft savings. The cost was estimated to be somewhere between $10,000 and $500,000. The expected savings were estimated to be over $700,000. Most cost savings were believed to come from improved safety, compliance, and labor reduction.

There was difficulty estimating the timeline to deploy smart planning and scheduling technologies due to the need for more readily available technology and management support. Nonetheless, the top key expected returns on investment for smart planning and scheduling technologies were:

- Achieving condition-based maintenance
- Reduced scheduling costs during construction
- Reduced future operations and maintenance costs
- Reduced rework
- Improved cycle times.

4.1.4 Dynamic Instructions

One of the participating utilities currently uses DIs; the others have plans to deploy DIs in the future. Both advanced reactor participants have plans to use DIs.

DI solutions provide the ability to capture metadata related to the task execution, such as a step's start and stop time. This data is used to improve resource scheduling and schedule accuracy. The captured data can also be trended and made accessible for other users and applications. As with EWPs, work progress can be tracked in real time. However, DI solutions provide much greater granularity and detail due to the ability to capture metadata for each step. This level of detail allows coordinators and issue resolvers to mobilize work crews more efficiently. DI solutions also provide a better UX for the craft compared to EWP solutions. This improved UX, ease of use, and the ability to embed relevant training material engage the newer workforce and speed up the onboarding of new staff. The DI solution currently used by one of the participants was mostly well received, especially by the younger generation of workers.

The participating utilities estimated the cost of implementing a DI solution to be $10–20 million, including solution development, deployment, change management, and conversion of existing procedures to the DI format. The expected savings were more than $10 million annually. This saving will come from reduced labor, reduced operations and maintenance costs, and optimized plant performance. The timeline to complete the DI implementation was estimated to take 2–4 years, depending on scope. It is still being determined if this estimate includes a year to pilot the solution. The top key expected returns on investment for DI solutions were:

- Reduction in rework and work delays through human error reduction capabilities
- Improved oversight of work activities through real-time access to procedure progress, particularly during outages and critical path system outage windows
- Access to data captured digitally, which eliminates manual transcription and enables numerous use cases for manipulating the data for better trending and decision-making
- Improved interconnectivity between applications that use data.

4.1.5 Data Analytics for Work Management-Related Activities

The participating utilities use data analytics for work-management-related activities to varying degrees. The utility using DIs collects data from the DI solution to optimize work schedules and improve handoffs between work groups. Across the three utilities, multiple ongoing projects use AI/ML to automate various work management processes, including work screening and procedure reviews.

Additional (future) use of data analytics would enable process performance monitoring and optimization. For example, the use of historical work performance data to identify which equipment consumes the most human labor hours or has the most human performance issues. This would inform decision-making when prioritizing capital projects. Another example is to tie real-time dose information to work orders to provide more accurate safety and risk information. Data analytics can also identify more accurate timelines, automate testing, improve hiring, and can bridge the various applications used for work management to allow for seamless process flows (e.g., between engineering, document and records, work management, analytics, and real-time plant monitoring).

4.1.6 Digitalization Perspectives

The main benefits of digitalization were a reduction in cost and improvement in performance, safety, and reliability (see Figure 22). The participants ranked performance improvements as most important followed by reliability and then safety of plant operations. Digitalization is believed to reduce costs through process improvements and enhancement of the application’s functionality to get work done. Digitalization could improve the employee experience by eliminating low-value work, providing easy access to required information, supporting faster and better decision-making, enabling remote workers, and accelerating the transition from old fashioned processes to more streamlined operations.

Figure 22. Main benefits of digitalization.

The participants agreed that there needs to be more understanding of how to attain the end-state vision for digitalization (see Figure 23), including knowledge of the tremendous work and cost it will take to achieve. The biggest challenges include financial resources and change management, educating those impacted on the benefits of digitalization, what the immediate and long-term benefits are, and providing them with the resources needed. Across industry, there needs to be a better understanding of the costs and benefits of digitalization. Another identified challenge is regulatory approval, contributing to unknown costs.

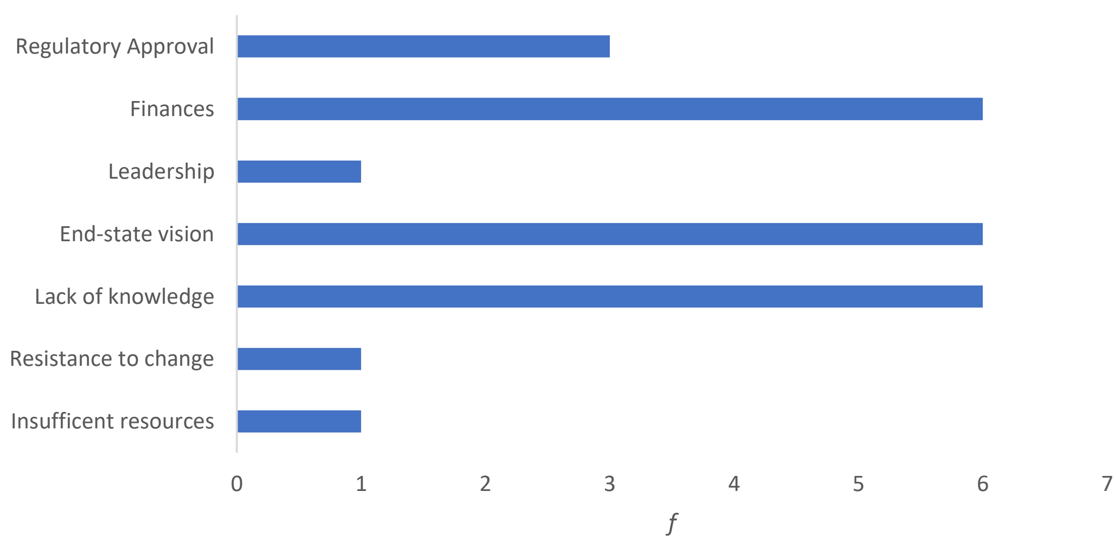


Figure 23. Main challenges to incorporating digitalization.

When asked about whether digitalization can help industries reach net zero, participants responded that the nuclear industry is already net zero. Digitalization will help the industry continue to be net zero and remain competitive. In other words, digitalization is an essential enabler for utilities to be economically viable and maintain competitiveness with alternative non-green energy sources. In addition, the benefits of digitalization and cross-application in power generation, transmission, and distribution can significantly enhance remote services, worker collaboration, and expertise sharing.

Most participants agree that, with the focus on carbon-free energy, the nuclear industry is heading for a renaissance that will include new plants, such as small modular reactors, and an extension of licenses to run existing plants longer. These plants must embrace and leverage digital transformation to be competitive with alternative energy options. The electricity generation, transmission, and distribution industries are moving toward digitalization, but different parts of the business are moving at different speeds. Renewables appear to be much further along than nuclear.

Digitalization seems promising, but the end-state vision and implementation strategy seem primarily unknown. Once the value of digitalization is clearly stated and communicated, digitalization will become standard for NPP designers, owners, and operators. Some participants even noted that digitalization is inevitable for industry survival. This dovetails with survey findings from Hall et al., (2023) in which half industry respondents indicated that control room modernization was necessary for industry survival. Digitalization will also be a requirement to attract and retain the next-generation workforce.

The participants suggested that INL develop best practices and a process to develop an implementation plan and strategy for the industry. It is believed that this would help educate senior leaders and decision makers about the value of digitalization and the steps needed to get to the desired end state. Part of the implementation plan should describe what the end state should or could be. In addition, INL should keep supporting industry efforts to share lessons learned and develop guidance while maintaining a neutral and unbiased position regarding supporting and promoting specific solutions or vendors.

Limitations of this survey include a very low response rate (9.6%), and thus caution should be exercised when considering the generalizability of industrywide acceptance and plans for digitalization according to these findings.

4.2 Digitalization Conference Poll Data

Polling data was collected at the NextAxiom Nuclear User Group Conference: Digitalization Through Computer Guided Work hosted by Southern Nuclear in June 2023. Forty-two audience members participated, depending on the question, and results were produced in real time. The first question asked audience members to describe in one word the significance of digitalization to the nuclear industry. Consistent with the Work Digitalization in Industry survey, Figure 24 displays a word cloud indicating that the top responses were efficiency, survival, and critical. This suggests a degree of digitalization necessity for industry survival.

Figure 24. One-word responses regarding the significance of digitalization. Bigger sizing indicates greater endorsement.

The second question was a forced-choice question regarding the main benefit to digitalization, which was enhanced functionality (see Figure 25). Reduction of costs also ranked high.

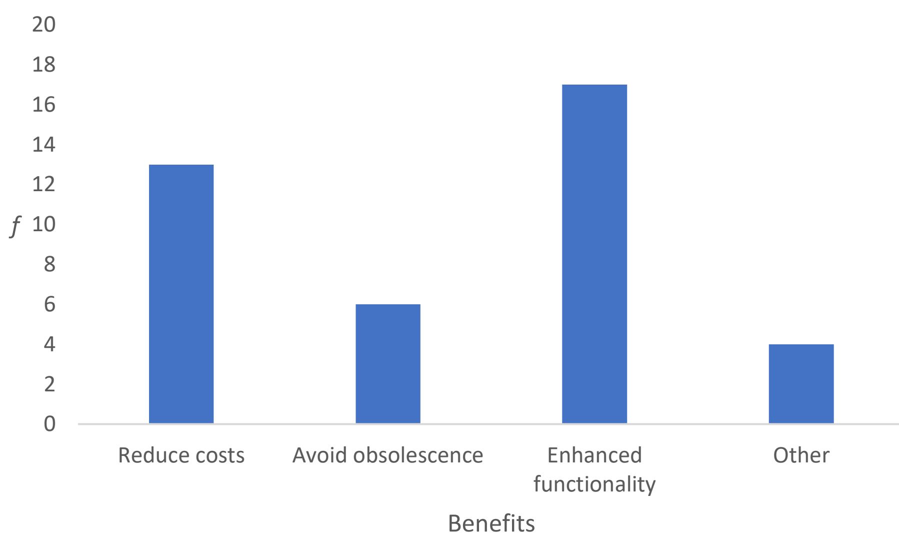


Figure 25. Main benefits to digitalization.

Cost was clearly the main challenge to incorporating digitalization (see Figure 26).

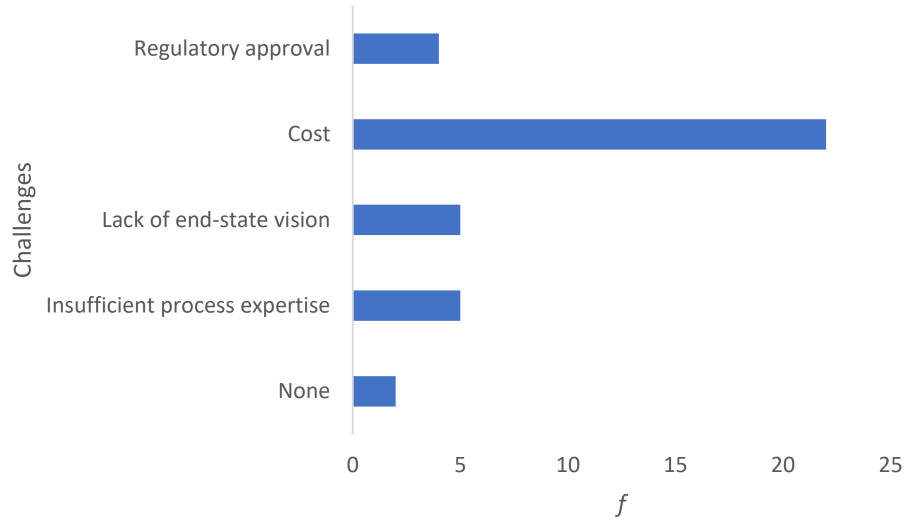


Figure 26. Main challenges to digitalization.

When asked what INL should focus on in terms of digitalization, 36 participants generated a wide range of topics. Two participants responded twice. The top answers were cost-benefit analysis (n=6), performance improvement (n=5), return on investment (n=5), UX (n=4), AI/ML (n=3), and hands free (n=3).

Regarding what INL should be asking stakeholders about digitalization, 33 participants responded. Lessons learned and obstacles as well as user acceptance were the mode responses (see Figure 27).

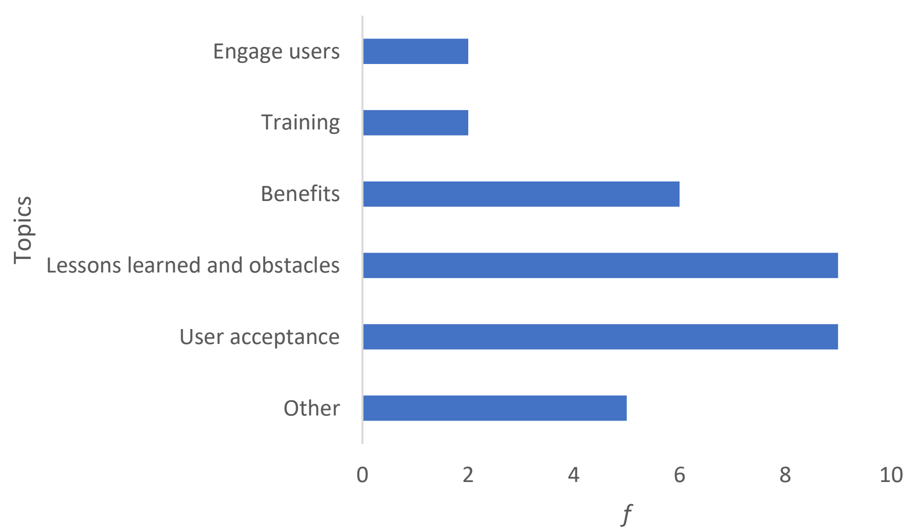


Figure 27. What INL should be asking about digitalization.

4.3 Digitalization Survey and Poll Conclusions

In terms of work management, the process might already be heavily digitized as illustrated in the sample from the 2022 survey. However, acceptance of EWPs was mixed on the part of end users. Thus, greater incorporation of more advanced digital technologies supporting end users could facilitate acceptance. One clear message from the poll data is that the needs of the end users should be paramount.

This request by participants is consistent when considering that the main benefit of digitalization is the enhanced functionality of new technologies. If end users do not receive enhanced functionality from digitalization, the goal of incorporating new technologies will not have been realized. Thus, achieving enhanced functionality must be balanced with the main challenge to digitalization, which was cost. The first step at any NPP should be to talk to the operators.

4.4 Dynamic Instructions—Vendors' Perspective

Data was collected from DI vendors to better understand perceptions towards technology changes within the nuclear industry. Three questions were posed:

- Compared to 5 years ago, what are the major shifts in customers' wants and needs?
- What are the most asked-for functionalities and capabilities for DI solutions?
- What are the main barriers to DI deployment?

4.4.1 Summary of Results

Compared to 5 years ago, the industry is faced with an even more significant challenge of employee and knowledge retention. Therefore, there is a substantial push for fully digital solutions that empower workforces, and solutions that provide automated processes governed by workflows. There is also a strong desire for well-designed user interfaces that support improved human performance and reduced human errors.

It has also become clear that there is no "one-size-fits-all" solution. Instead, the offerings must be tailored to the customer's approach to digital transformation, risk tolerance, and end vision.

As the availability and use of software and enterprise platforms such as CMMS (e.g., Maximo) increases, so does the need for integration within these platforms. Customers require integration, as well as expanded functionality, to further enhance productivity and eliminate administrative work. In addition, there is a need for the increased use of technology to make work scheduling and execution more efficient, including the use of CBPs and DIs integrated within an EWP.

To drive data-informed decision-making, improve work efficiency, and eliminate waste within processes, customers are seeking increased access to work execution and equipment data and the ability to learn from the activities and captured data.

To enable a more mobile workforce, the availability of more dynamic and interactive instructions with multimedia support is a growing customer need.

4.4.1.1 Most Requested DI Capabilities

In general, there are many functionalities and capabilities to consider for a DI solution; however, there are some commonalities. Vendor research and experience indicate the most requested functionalities and capabilities are:

- A tightly integrated procedure lifecycle system
- The ability to view a dashboard for live-tracking procedure executions
- Increased labor efficiencies
- Reduced administrative tasks related to analog procedures and processes
- The ability to have data and business processes contextualized for each execution
- A solution that is device agnostic, browser deployable, and functions in a range of connected states

Regarding reducing administrative work, DIs lessen the need to assemble paper procedures. There is no need for copying or rekeying data captured on paper by administrators. Filing and archiving are done automatically, removing the need for this to be done manually. In addition, DIs are kept in a database. This allows instructions or snippets of instructions to be used across many procedures. When steps or a series of steps are updated, it need only be done once, and all the procedures that use those instructions are updated automatically. This dramatically reduces administrative work around procedure updating. This also ensures that all procedures that use that snippet of steps get updated and no procedure is missed.

Regarding labor efficiencies, DIs will not enable workers to “turn the wrench faster”; however, DIs have features that allow schedules to be compressed. Automated notifications can be inserted at the step level, automatically alerting coworkers or management of messages pertaining to job status. For instance, if Worker A is on Step 5 and Worker B is going to be needed at Step 10, a text message or email notification can be sent to Worker B when Step 5 is completed. Worker B can then go to the job site or log into the job on their tablet at the appropriate time. This type of workflow reduces waiting times for both workers. In addition, workers can collaborate on the same procedures in real time in connected environments. Approved procedures can be sent to field workers or accessed by field workers immediately when in connected environments, which reduces wait times for work package assembly and pickup.

The most requested functionality or capability regarding data is access to fully mobile, interactive non-PDF procedures, with the ability to collect and trend execution data accurately.

Table 5 provides the most requested functionalities and capabilities related directly to executing the DIs. For a DI solution to be viable to the customers, it must provide the tools needed to create new DIs and edit existing ones. The most requested functionalities and capabilities related to editing include are also listed.

Table 5. Requested DI functionality for execution and editor tools.

Category	**Requested Functionality**
Execution tool	Automated place-keeping that ensures steps cannot be skipped or done out of sequence
	Independent and concurrent verifications
	Conditional statements
	Parallel activities
	Repetitive sections
	Continuous actions
	Timed steps
	Built-in cautions and warnings
	Smart data widgets that are reusable, integrated, and configurable
	Advanced features for offline support with concurrent or parallel work
	Immediate access to training materials and manuals
	Ability to attach a how-to video to a process step
	Automated calculations to prevent math errors
Editor tool	Ease of editing and formatting procedures or autoformatting
	Global automated changes to large volumes of procedures
	Automatic conversion of existing procedures and forms
	A no-code or scripting integration solution embedded within the platform
	Ability to set parameters in data fields that can flag inaccurate information

An additional benefit from DIs that customers are interested in is the ability to monitor work in real time from the global view of work progress and track it down to the step-by-step execution. This would allow supervisors to identify deviations from expected performance and to support activities that prevent challenges from becoming problems.

4.4.1.2 Main Barriers to DI Deployment

The vendors identified three main categories of barriers to deployment:

Institutional resistance to change. Even when deploying new technology, the urge to perform work exactly like it has been done in the past is very strong. However, it is essential to realize that the only way to gain benefits from new technology is by optimizing one's processes to fully utilize and leverage the new technology's capabilities. This requires rethinking business practices and identifying the drivers that matter. These practices and drivers should then be applied to the new paradigm to meet underlying requirements while leveraging the latest technologies and opportunities. The nuclear industry is averse to change, which introduces risk and potential errors. The industry needs to understand and internalize that change, specifically digitalization, can increase safety, reduce human error, and improve human performance while increasing productivity, reliability, and efficiency across the enterprise.

Users need to realize the flexibility provided by the technology. An intelligent work platform can be standalone or integrated with existing enterprise asset software. Smart work platforms should have application programming interfaces that are accessible to enable easy connection and data flow with existing systems where needed. If the company does not have the internal resources to make this integration effort, it is recommended to utilize an experienced partner to enable those integrations.

Dedication of resources. Due to many paper-based procedures, the most significant hurdle relates to conversion costs and resources required for review and approval. Obtaining the full benefit of dynamic work instructions and integrated capabilities with data systems requires additional work, such as replacing hard-coded equipment references, creating feedback mechanisms for data excursions, and providing appropriate branching mechanisms based on user selections. As most facilities are running lean and already have significant procedure change request backlogs, companies struggle with dedicating resources.

4.5 Summary

Work digitalization is considered promising and needed for the survival of the nuclear industry. Most industries are currently moving towards fully digital solutions and digitalization to empower the workforce while adding much-needed efficiencies to business and work processes. Automation and data analytics are needed and desired to support improved human performance and reduction of human errors. Specifically, the industry would like to use additional data analytics to improve data-informed decision-making, improve work efficiency, and eliminate waste within processes; customers are seeking increased access to work execution and equipment data, as well as the ability to learn from the activities and data being captured. In other words, data analytics should bridge the various applications used for work management to allow for seamless process flows.

However, to reach the benefits of digitalization, the industry needs to better understand the steps necessary to get there. While some facilities already possess an end-state vision, others need guidance, and there are calls for a digitalization roadmap and implementation strategy. Findings converged from the survey and poll research revealing the two main barriers to achieving the digitalization vision to be dedication of resources and change management. It is also essential to recognize that there is no "one-size-fits-all" solution. The implementation strategy must be tailored to each organization's approach to digital transformation, end-state vision and risk tolerance.

Based on the outcome of the surveys and poll data, INL should continue to support the industry's digital transformation by:

- Developing a transition strategy or roadmap that utilities can tailor to their needs
- Educating stakeholders, such as senior leadership and government entities, on the value and benefits of digitalization
- Supporting industry efforts to share lessons learned and develop guidance.

A major challenge for the U.S. nuclear industry to achieve its sustainability objectives is successfully integrating digital technologies as it modernizes its business model. The guiding principles and method to digitalization outlined in this report (Section 2) speak to this need. LWRS researchers are developing and demonstrating nuclear-specific solutions, and ensuring proven methods are available for the industry as it moves to a sustainable and cost-competitive digital business. The goal is to provide the process for an efficient integration of digital technologies with work process automation and workforce modernization, resulting in the SDE necessary for cost-competitive operation.

5. DIGITALIZATION USE CASE

In this section, we document highlights from a digitalization use case, which was a collaborative initiative between INL, NextAxiom Technology Inc., and Xcel Energy. NextAxiom produced a full report of these activities, which can be found in Appendix B. INL has long-standing partnerships with both NextAxiom and Xcel, and through these collaborations has provided research-based technical and business solutions to the industry. For this digitalization demonstration, these industry partners were selected because NextAxiom is a leading solutions provider of the work process objectives, and specific use case functional requirements presented by the utility.

The use case for the demonstration was to generate a specific type of digitalized condition report (CR) which is currently paper based. A CR is the way in which plant conditions that do not meet required industry standards are documented, managed, and rectified. The CR process starts with field documentation and then progresses to review, assessment of impact and priority and then a decision on a course of action. The CRs are categorized to keep track of common issues in the plant. For substantial issues, several ongoing meetings and evaluations are undertaken, altogether at a cost of hundreds of millions of dollars to the industry each year (Al Rashdan et al., 2022). Generation of a digitalized CR offers several improvements such as reduced time consumption, greater standardization, reduced error, and ultimately better decision-making.

5.1 Current Condition Report Generation Process

Currently, the field operator starts the CR process by taking notes on paper that are later entered at a workstation to electronically document and report the condition. Several areas for improvement to the current CR generation process were identified:

- The online form application at the workstation provides no guidance or prompting and has no capability to retrieve information that may be helpful to the operator based on the data provided. For new users especially, this could mean sending CRs lacking important information or containing errors, requiring reviewers to follow up with the user and complete the missing information after the fact
- There is no prompting from the application as to what information is needed in the form besides an asterisk (*) on required fields. These fields are dropdown lists or text entry fields
- Users have no knowledge of prior CRs, or the actions taken. They cannot know if anything is currently scheduled to address the condition. This results in CR duplications
- Field operators can take photographs with company-issued cellphones to be included with the CR. However, they must email the images to themselves and then upload them to the CR. These additional steps create a burden for operators who want to include images

- For urgent or critical conditions, field operators contact the control room or designated personnel immediately. In these cases, electronic documentation is completed later after returning from the field, carrying the risk of an incomplete CR or one lacking detail.

Additionally, it was identified that the digitalized workflow for CRs should possess the following characteristics:

- can be created with or without internet connectivity
- hierarchically organized dashboard
- autopopulating capability when connected to archive directories
- automatic generation of the CR upon task completion
- automatic archiving.

5.2 Software Method Development

Part of the challenge of realizing the potential of digitalization is the disparate middleware technologies, operating systems, and applications that could be running at an NPP. Operating systems carry out the basic functions of a computer while applications are designed to carry out a specific task not related to the basic functions of a computer. Middleware functions as a translation layer between the operating system and applications and provides communication and data management between systems. Often, different plant departments use different software within their siloed workflow. This type of departmental organization and digital development poses a challenge when digitalizing the current fleet of NPPs. NextAxiom has created a platform that takes different middleware and brings it together to function as one to support an SDE that will break down the existing silos in the workplace. By using the current digital functions at an NPP, software development costs can be kept to a minimum.

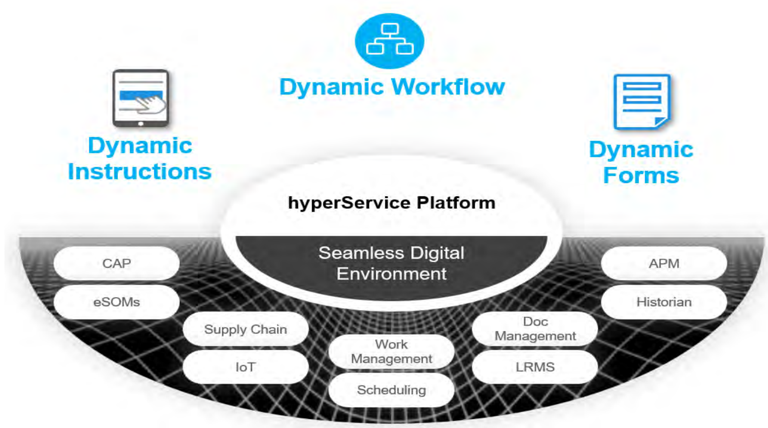


Figure 28. Computer-guided work.

The Dynamic Work Execution Platform (DWEP) is a hyperservice platform (Figure 28). DWEP provides software that simplifies the review and approval processes and quickly adapts to workflows based on key data points. The digital environment contains all existing technology being used at the plant. The operating systems and applications could have different middleware technologies acting as plumbing facilitating information transfer. Much like the iPhone brought various applications together, DWEP brings various middleware technologies together to function as a single pipe for information transfer.

The design of the application prototype was completed following the Rapid-Application-Development methodology (see Figure 29). Using this methodology, the initial prototype was created by firstly gathering requirements.

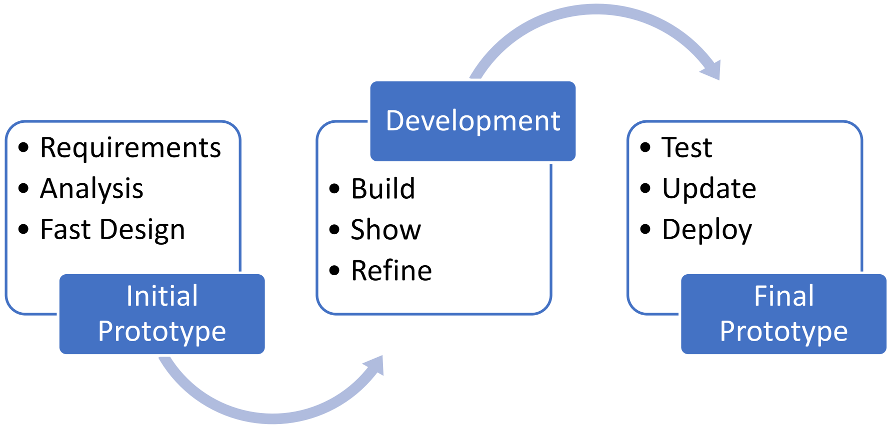


Figure 29. Rapid-Application-Development process applied to the prototype development.

5.3 Technical Requirements

For the technical requirements, the functional design had to work on the user's mobile phone and the application had to communicate seamlessly with the backend system (Zylka, 2015).

For the technical design, two components were addressed:

- Authoring of the prototype using the DWEP Authoring Tool
- Integrating with backend system using hyperservices.

The authoring of the DIs did not require any coding or specialized technical knowledge since the DWEP application allowed the author to use the tools in the DI interface to build the application by dragging and dropping data and control widgets into the DI steps. Conditional behavior was easily built in the new version of DWEP. The authors could see all the conditions added on a data or control widget with the click of a button, and they could add, edit, or remove conditions from that list.

For the integration, the NextAxiom team used existing hyperservices integrated with Asset Suite 9 by importing them into the DWEP DI during authoring and mapping the fields for the inputs and outputs of the services. This was also done via drag and drop from the service fields to the data widgets in the DI. Xcel was already using DWEP applications that were integrated with SAP and DRMS (Document Management). The prototype was not developed in the Xcel environment because the required utility programs were only available in the new version of DWEP in NextAxiom's development environment.

The DWEP application ran on a browser-based thin client user interface. The application could run on Chrome, Edge, Safari, and Firefox. Edge was used at Xcel Energy. The prototype was tested on both iPhone and Android devices. Relevant data was retrieved from backend systems into the CR via Wi-Fi during the demonstration, but it could also operate offline had the data been downloaded to the device and no communication was needed with the backend during that time.

One challenge was the necessary blocking of the NextAxiom web domain on the company cell phones because it is outside their firewall. Consequently, participants at the demonstration used their personal cell phones and logged into Xcel's guest Wi-Fi.

The CR application used speech to text (STT) recognition and optical character recognition (OCR) technologies, increasing the ease with which information can be entered and minimizing entry (and potential errors) by hand. The prototype used a free, open-source SST application programming interface called Web Speech (Mozilla, 2023). An open-source OCR called Tesseract was used (Tesseract, 2023) to read the text in equipment tags in the Xcel Flow-Loop Training Facility using the mobile phone camera. Tesseract is free software, released under the Apache License.

The initial prototype provided a browser-based interface in which any person on site could initiate a CR from their mobile phone in the field (Murray, 2023). This application was done as a DI to guide the user through the successful initiation of a CR and a work request or notification for equipment-related conditions. The application collected data directly from the user for the CR via button selection prompts, typed text entries, or spoken information, and used the device camera to scan the equipment tag. The initial functional design was created by the project's subject matter expert as mobile phone screen wireframes for the application (Murray, 2023). The wireframes contained minimum basic questions designed for any user at Xcel Energy to create a CR. Figure 30 displays the wireframe for the home screen, which displayed questions to initialize the CR. See Appendix B for the full suite of wireframes contained in the application.

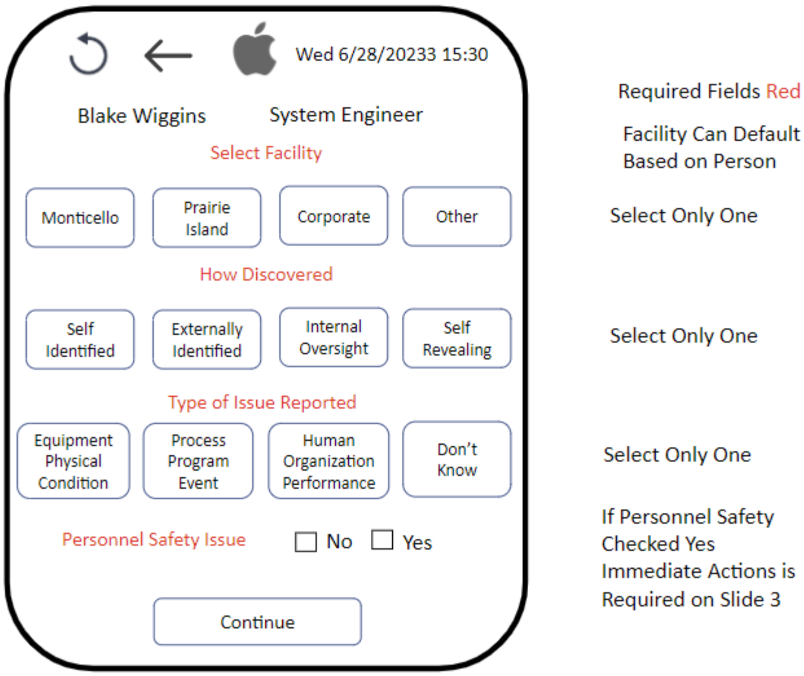


Figure 30. Wireframe screen displaying initial questions for the user.

5.4 Digitalization Development "De-Design" Principles

Information technology design researchers have been caught between formal principles in design and the real-world problems that design science is intended to address. In terms of the best approach, some researchers have noted that there are problems concerning specific designs. Thus, a movement criticizing both the design and design research principles has emerged, which has led to the rejection or de-emphasis of the role of design in technology development. The de-design perspective does not emphasize formalized a priori models of the information technology. For example, the zensign approach argues that should the designer have two equally feasible choices, the best choice is to not incorporate a feature. Instead, a decision could be made in situ when the opportunity to develop something innovative arises. This perspective prevents the designer from being constrained by what is decided at the design board. Applying this to digitalization, features could be incorporated later in an iterative design process as the problem becomes better understood. Furthermore, the potential for learning within the system might exist.

5.5 Functional Requirements

In the development of the CR software, NextAxiom generated a high-level description of the solution to the use case. The requirements for the solution were not constrained by a particular design at a functional level. The goal of the functional requirements was to provide the application designer with a set of requirements to design the application from an end-user perspective without constraining the designer with a rigid design.

Functional implies that there is no discussion of technical aspects, such as where the data is stored, or IT-level concerns, such as performance or where the app resides on the network. It also means that the requirements are designed at a level of detail that is more granular than business requirements.

The functional requirements were collected from the Xcel Energy business team via online meeting interviews and reviews of current process limitations:

- Enable the user to verbally indicate applicable equipment information, such as the equipment name or tag number. The application should then automatically identify and locate the equipment or component information.
- Identify and present to the user other equipment in that system (from the functional location in the main equipment identified) and enable the user to select other involved systems, structures, or components.
- Indicate if the equipment or involved systems, structures, or components are tech spec related, or represent a single point vulnerability.
- Identify and present current and prior related corrective action program issues to the user to enable an informed decision to proceed or cancel the CR.
- Enable the user to create a new CR at any point during a procedure, work notification, or work order operation.
- Prompt the user based on the CR content and enable the user to create a work notification with the CR submission.
- Enable the user to provide generic data if equipment tag information is missing, damaged, or unreachable. In such cases, the application should find equipment with similar characteristics and enable the user to select which to use for the CR. Additionally, the application should flag these instances and automatically notify applicable plant facilities personnel so that the equipment tag is repaired, replaced, relocated, or added to the applicable database.
- Enable users to enter anonymous CRs only from company-issued computers or mobile devices.
- Clearly identify required information.
- Fit as much as possible on one screen to provide an effective UX.
- Enable users to scroll forward and backward across the CR entry fields.
- Automatically capture user information based on the login data.
- Prompt the logged-in user with questions based on their proficiency, training, and qualifications.
- Prompt the user to indicate the urgency of the CR and other applicable attributes, such as industrial safety, and automatically use these data to drive notifications based on business rules.
- Automatically record the date and time of CR creation.
- Enable the user to save the CR as a draft but not submit should they wish to complete it later.

5.6 Summary of Results

5.6.1 Functionality Demonstrated

After the application development and testing was complete, the prototype application was demonstrated as part of a two-day meeting at the Xcel Energy Flow-Loop Simulator—Monticello

Training Center. The scenarios for the prototype were based on two different equipment components: a pump motor (P01) and an air pressure valve.

The scenarios included:

- Motor pump leaking oil
- Air pressure valve making noise
- Non-equipment conditions

On all scenarios the user was prompted for basic information:

- Site for the report (could be different from the logged-in user's site)
- Selection of how the condition was found
- Selection of type of issue—which prompted additional information for equipment identification were the issue was equipment related
- For safety-related issues, the user was prompted to contact the control room or senior reaction operator (SRO) immediately
- Remedial actions taken by the user
- Initiated CR and work request (equipment scenarios only) or initiated CR (non-equipment scenarios). Users were shown related CRs and work requests for the equipment-related scenarios.

5.6.2 Utility Reception of Prototype

The following feedback was collected during the prototype demonstration as the users were going through the application to enter various CRs.

5.6.2.1 What the Team Liked

Quick Navigation and Efficient Guidance: The ease with which needed information could be provided for the CR. A minimum amount of information was requested to create the CR in the backend system. The user did not need to login and access the backend application, which is not easily accessible in the field.

Speak to fill required information: The idea behind STT technology is to free the user from having to type. Cell phones and tablet keyboards are cumbersome when users are exposed to bad weather conditions, extreme temperatures, when wearing heavy gloves, or when the information on the screen is covered by the online keyboard.

Equipment information from the backend: The equipment characteristics and attributes information that was retrieved from the backend system when the user provided the equipment tag ID was accurate. This reduces human error and saves the user time when entering equipment issues. Not all users will check the equipment history information, which includes other CRs or maintenance notifications (work requests). For users and reviewers that use this information, having it available will save a lot of time in online searches and pulling the information manually into the CR.

Non-equipment Conditions: Entering the information was simpler and faster. The team easily demonstrated that a CR could be created in a few minutes.

The ability to take photos while completing the CR: This functionality made it easier for the user to take and attach images to specific steps for the CR reviewers.

CR involving personnel safety: Direct access to the control room via Teams call or chat, which allows users to do a screen or camera share while they are talking, was functionality that promoted the urgency and facilitated action by the user to contact the right people immediately. The other option they had was a direct call to the SRO from that same step.

Notify other personnel that the CR was on the way: Users could select an individual or a group to receive an email with basic information on the CR. This eliminated the delay from users to manually log in to check in the backend application whether there were any pending reports that needed their attention.

Confirmation and Creation of CR: Users had the option to create the CR by tapping one button, edit it before creating it, or cancel out by closing the browser screen on their cell phones.

5.6.2.2 What the Team Did Not Like:

STT recognition function: In the application, some questions prompted the user to type or speak their answer using their device's microphone. The STT tool did not recognize pauses in speech and would overwrite anything that was said prior. A note was added to alert users on the steps with the speech option to press the microphone icon when pausing to prevent this problem. Users were not used to this glitch when voice commands are used on other mobile interfaces. The NextAxiom team recognizes that more investigation is needed for better STT utility options. Consideration will also be given to another possible challenge when the user speaks into the device in a noisy environment, and speech may not be properly converted to text due to interference.

OCR function: Using the OCR proved more challenging than expected and adjustments were made to improve Tesseract prior to the demonstration. However, users could not control which text was included. It read all the text in the image, and anything that showed outside the tag was interpreted as text content and converted as bad characters or symbols in the text field. Zooming too much into the equipment tag to keep the whole tag in the image frame made it hard for the camera to focus. It is challenging to use the cell phone camera to take a clear picture of the equipment tag. Low light in the area can also affect the result. Users in the prototype had to revise the equipment tag ID field to correct the text string using the cell phone keyboard. The NextAxiom team recognizes that more investigation is needed for better OCR options.

5.7 Future Iterations

This prototype application effort demonstrated that a potential next step for nuclear facilities is to present equipment risk and historical data that has meaning for operators when submitting or reviewing a CR. Analysis of this data can suggest preventive measures to mitigate or eliminate a corrective condition in the future. Using this information on a pilot with limited scope will allow an operations team to understand how risk and historical information can be best used by the facility, and the operations team can provide valuable feedback.

Some nuclear facilities have this historical data but need an assessment of the risk. Risk can be estimated when the data are normalized and proper statistical models are applied to equipment based on maintenance, probability of failure, environment, age, plant conditions, and safety limits. The LWRS Program at INL has condition-based maintenance initiatives, such as Technology-Enabled Risk-informed Maintenance Strategy, which uses data reconciliation and normalization efforts (Agarwal et al., 2022). The work is being developed to integrate the results of predictive analytics with enterprise resource planning (e.g., work orders and work packages).

Future directions for this digitalization use case include harnessing the power of a Virtual Resource Manager Framework (VRMF), an open framework to systematically plug-in AI/ML and enable process automation around resources for the nuclear industry (Figure 31). Central to the VRMF lies the concept of a Virtual Resource, which can represent information, actions, and physical objects such as a pump motor or valve, as well as intangible resources such as AI or an operational risk assessor. The VRMF provides management of these resources to create an SDE for particular plant domains, continually monitoring and even taking relevant actions according to the plant's business model. For a digitalized CR as with the current use case, the VRMF would act like a ChatGPT assistant, helping perform and capture work processes, and well as share them directly to relevant work groups as they occur.

Figure 31. Virtual Resource Manager Framework (image from Primer & Massoudi, 2023)

The nuclear facility for this use case demonstration has historical data stored in their enterprise resource planning system or data warehouses that has not been used by AI/ML. This facility can become the next case study whereby their data can be analyzed for risk and embedded into the CR initiation for a specific situation. This application should be able to provide guidance to the end user and pass on relevant information to the remediation team. After the application is accepted by users and they see the value in this guidance, the facility could be ready for the next phase in which the application has an equipment risk assessor. This is a virtual resource that can be trusted to provide preventative actions that minimize remediation and operations costs. For digitalized CR to be adopted by plant personnel, it is imperative that demonstrable benefits to operations and work processes are carried out.

6. CONCLUSIONS AND PATH FORWARD

The LWRS Pathway projects have been conceptualized as ushering utilities towards an economically sustainable future (Joe et al., 2021). The INL Digitalization project seeks to take advantage of digital technologies to synthesize and transform work processes. The increased functionality brought about by data-driven insights affords new day-to-day operational possibilities and optimized decision-making. Thus, the Digitalization project serves as the necessary scaffolding to help transition utilities to a new digitalized future, incorporating technological advancements into the current fleet.

The purpose of this milestone is to provide guiding principles and methods necessary to effectively digitalize nuclear industry work processes. We developed these principles from industry engagement, as well as scientific methods, including primary data collection that we documented throughout the report. Our four guiding principles for digitalization are to develop a coherent digitalization plan, apply HFE, establish data governance, and anticipate unintended consequences. Together, these principles form a method that plants can use to effectively digitalize nuclear industry work processes.

The LWRS Pathway researchers have been invaluable in proposing solutions to technological gaps. From the 2022 survey concerning future digitalization plans, it was apparent that data information (i.e., collection, analysis, visualization, and management) was a critical concern. Technological advancements focused on data translate into cost reductions. For example, LWRS researchers have observed that 80% of plant work tasks revolve around surveillance and preventative maintenance and recommend that unnecessary tasks be eliminated and the frequency of necessary tasks be reduced (Al Rashdan and St.

Germain, 2018). Digitalization will be essential in accomplishing this goal. Thus, the digitalization guiding principles outlined here represent core considerations for all other LWRS Pathway projects and will be used to inform research activities for all forms of plant modernization.

Paths forward for this project include enhancing work automation by expanding the digitalization method to other plant work processes. This will include developing and performing an assessment to determine the current state of a utility's digitalization effort and then, based on the findings, develop a digitalization plan that supports ION strategic transformation priorities. The goal is to establish a standardized digitalization method. Working with industry collaborators, future objectives include:

- Determining digitalization needs and mapping the current digitalization status
- Applying digitalization guiding principles developed in this research effort to create a specific digitalization plan and supporting success metrics
- Documenting the digitalization methods and refined guiding principles.

Together, these future research activities will leverage the principles and method developed in this research effort to create digitalization optimization, allowing utilities to operate safely and cost-competitively with all other electrical generation sources.

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APPENDICES

Appendix A
LWRS Briefing Paper

Briefing Paper
Author: Anna Hall and Jeffrey Joe
September 30, 2023

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Digitalization Guiding Principles and Method for Nuclear Industry Work Processes

Introduction

Commercial nuclear power plants (NPPs) generate gigawatts of electricity in a highly efficient, safe, and non-carbon emitting fashion. However, two primary factors challenge the continued operation of U.S. NPPs:

- The business model of current plants is not as viable as it was when nuclear power was developed.
- The cost to maintain current analog systems continues to increase as the supply for such equipment becomes costlier due to the outdated nature of such systems.

The digital-age and associated technologies are where the future lies in process control, and yet, the nuclear industry has yet to take full advantage of the capabilities offered therein. As such, Light Water Reactor Sustainability (LWRS) Program researchers have developed digitalization methods and design principles for the industry that will enable them to effectively digitalize their work processes.

Digital Transformation of the Nuclear Industry

In the past couple of years, the amount of plant data accessible to NPPs has increased drastically. The industry now has potential access to highly valuable insights to support planning and work management as well as high-level business decisions. A core aspect of the digital transformation of the nuclear industry is identifying what data to access, how to access it, what to do with the data, and most importantly how to utilize the insights for decision-making across all levels within the business. Thus, through the LWRS Plant Modernization Pathway, researchers at Idaho National Laboratory (INL) and the nuclear industry are working together to enable a digital transformation via digitization and digitalization. Specifically, the digitalization methods and design principles described below provide the guidance needed to effectively digitalize nuclear industry work processes.

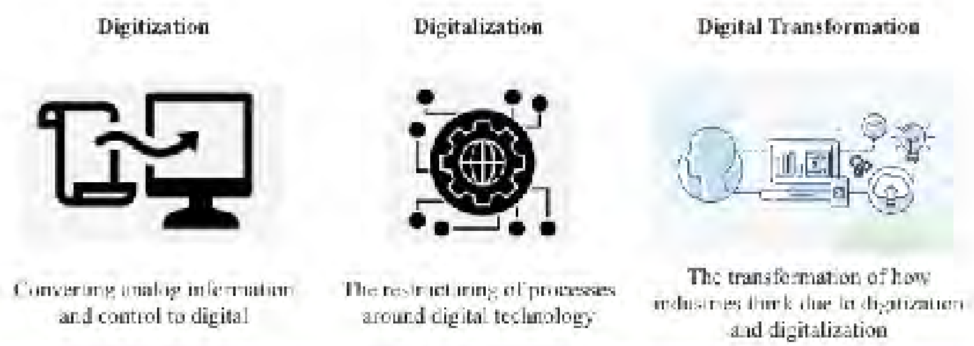

Figure 1. Digital Transformation Process for the U.S. Nuclear Industry.

U.S. DEPARTMENT OF ENERGY

Guiding Principles and Method for Digitalization

Principle #1: Develop a Coherent Digitalization Plan

Having a clear new end state for digital transformation is required for successful digitalization. Additionally, the new end state must strike the right balance between its forward-thinking vision, the practicalities of its approach (i.e., what is feasible in the near term), and have a clear understanding of the organizational and cultural barriers to implementation.

Principle #2: Apply Human Factors Engineering

A multi-disciplinary team is needed to successfully digitalize NPPs, and people who can expertly apply human factors engineering are essential. Digitalization without recognition of how to make digital technologies usable to the humans using those technologies will not achieve the new end state vision and will not transform the business model for operating and maintaining NPPs.

Principle #3: Establish Data Governance

The promise of digitalization is predicated on the production and accessibility of clean, accurate, relevant, reliable, unified and contextualized plant systems data. NPPs must invest in data management resources, including software engineering, and sophisticated software architecture to address data governance challenges (e.g., data accessibility, data quality, and cybersecurity).

Principle #4: Anticipate Unintended Consequences

Digitalization brings about both changes that are planned and changes that are unexpected, in part because traditional approaches often do not consider unexpected interactions that can emerge in dynamic systems. For example, over-digitalization (i.e., automating every aspect of a process that can be practically done without regard for the role of the human) often does not result in improved overall human-system performance. The unintended consequences of digitalization need to be anticipated and mitigated.

Contact

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More on the LWRS Program: https://lwrs.inl.gov/

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Appendix B
NextAxiom App Development

8/21/2023

Integration Operations for Nuclear (ION): CAP Use Case

Xcel Energy

Esther Karoleski & Mitchell Burke
NEXTAXIOM TECHNOLOGY

Introduction

Idaho National Laboratory (INL) and NextAxiom Partnership

NextAxiom Technology Inc. has served the United States Department of Energy (DOE) and commercial nuclear utilities for over eighteen years with proven, diverse, and customer-focused software solutions. Our engagement with INL dates back to 2008 and includes implementing and maintaining a comprehensive Mobile Work Package and Primavera P6 scheduling solutions.

In 2011 NextAxiom pioneered the Electronic Work Package in partnership with DOE/NNSA (National Nuclear Security Administration) with procedure annotation and real-time integrations to multiple backend systems. We have also been a long-time INL R&D partner. In 2017, NextAxiom was selected by the DOE to commercialize over seven years of Human Factors research around the Computer-Based Procedure (CBP) initiative at INL through Cooperative Research and Development Agreement (CRADA), No. 17-TCF-8. The computer-guidance technology resulting from this collaboration was the initial proof of concept for computer guided work. We are currently engaged with the ION program and CRADA No. 23CRA8, titled Resource Virtualization and Management Framework (VRMF), for an open framework to systematically plug-in AI and enable process automation around resources for the nuclear industry.

NextAxiom's Dynamic Instructions (DI), part of our Dynamic Work Execution Platform (DWEP) provides INL with proven software to simplify the review and approval processes and quickly adapt workflows based on key data points. The DWEP software suite is part of a patented technology developed by NextAxiom that combines the results of a CRADA with the US Department of Energy (DOE) with over ten years of field experience in the nuclear industry around automating work processes such as Mobile/Electronic Work Packages.

The NextAxiom DWEP suite of products is used to "digitalize work" through computer-guided workflows, instructions and forms. Outside the initial CRADA with INL, NextAxiom has invested over seven years of extensive R&D to create the DWEP product-lines, in collaboration with our customers, perfecting the DWEP software suite to enable the "digital worker" and to incrementally bring about the digital transformation of large organizations such as INL.

With the NextAxiom DWEP, almost every aspect of work within a process-centric organization can be digitalized – from laboratory and maintenance work to back-end support functions. From a work performance perspective, the organization can be defined as a collection of processes, often governed by regulatory requirements or business policies. These processes have historically been implemented using paper-centric procedures, work instructions, forms and checklists, frequently touching many hands during preparation, performance, review, approval, and ultimately, record management and storage.

Because of the need for cost reduction without compromising safety, NextAxiom, in cooperation with our customer partners, are committed to the digital transformation - replacing paper-centric processes with computer-guided and integrated operations across the entire enterprise.

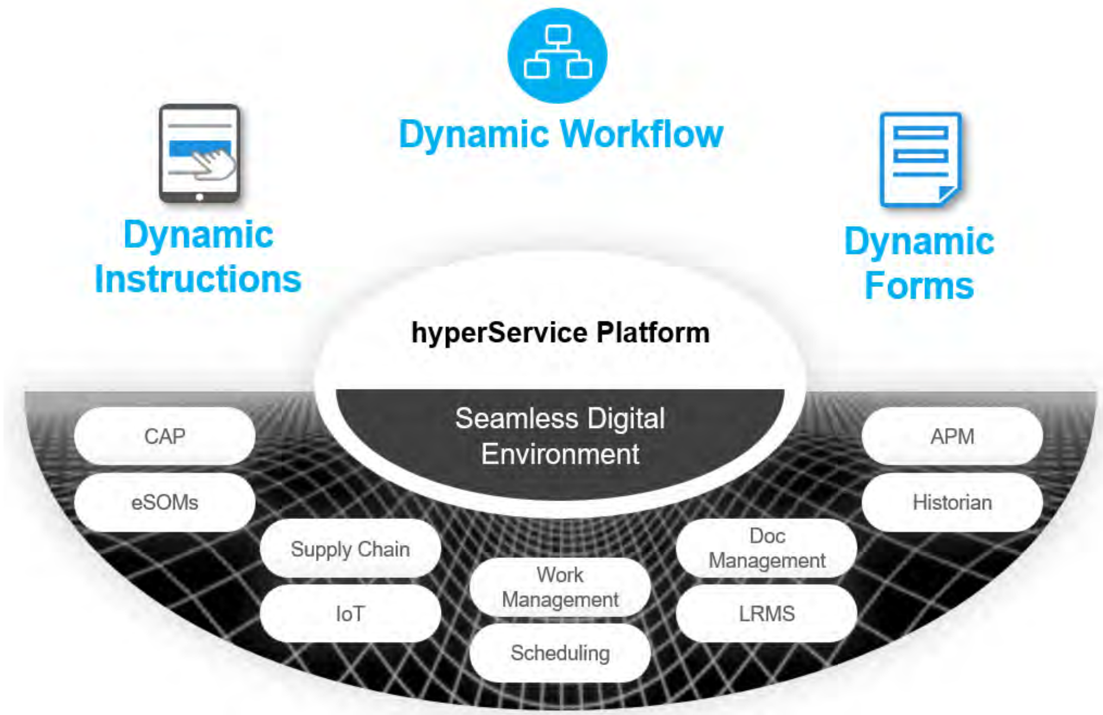


Figure B1. From *2023 NNUG NxA Vision and Roadmap* - Nuclear NextAxiom Users Group presentation on Computer Guided Work. (Sandy Zylka, 2023)

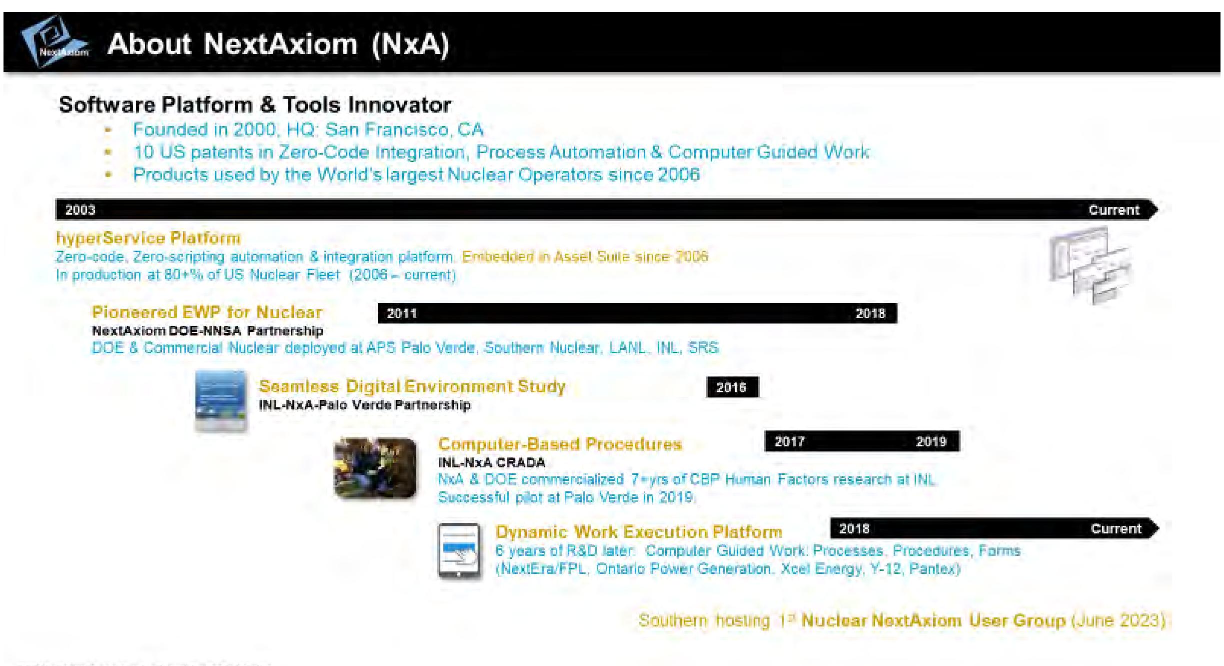


Figure B2. From 2023 NextAxiom Nuclear Users Group (NNUG) DWEP Presentation by Blake Wiggins. (Sandra Zylka, 2023)

In 2023, INL partnered with NextAxiom and Xcel Energy for the ION Use Case project to evaluate the effectiveness of how ION work reduction domains could use the VRMF as a seamless digital environment accommodating systematic information flow and automated actions. (Jeffrey, INL LWRS Information Support Demo for Xcel MRM Gap Review, 2023) To address the concern, Xcel Energy presented to the team for missed opportunities to create a condition report (CR) or to easily and effectively revise, or progressively elaborate existing CRs, a prototype application was developed to facilitate the initiation of a CR in a nuclear facility quickly and easily.

Use Case: **Xcel Energy Problem** (Wojchouski, 2023)

Routine Verify Corrective Actions have been identified:

- Missed Condition Reports (CRs)
- Rectified CRs

Xcel background/history that led to this change:

- Condition Reports (CRs) are entered in MOC/SAP via a desktop/laptop screen which are not present on the field unless the user carries a laptop. They will have to take notes on paper and enter the condition report later.
- There is no prompting from the application as to what information is needed in the form besides and asterisk * on required fields. These fields are dropdown lists or text entry fields.
- New users or users with no prior experience in the application could send condition reports lacking important information or containing errors. These reports require the reviewers to follow up with the user and complete the missing information later.
- Users have no knowledge of prior condition reports, or the actions taken. They cannot see if there is work or activities currently scheduled to address the condition. This will result in condition reports that are duplicates of existing ones and creates additional work for the reviewer to validate manually.
- For conditions requiring immediate attention, users call the control room or the shift supervisor. A condition report will be entered after actions have been taken. This carries the risk of a report that is never entered or entered later and lacking detail.

Analysis for Effective Digitalization

The work process objectives, business requirements summary, and business functional requirements presented below result from a concurrent engineering process between INL, NextAxiom and Xcel Energy. The purpose of this collaborative effort is to streamline the design effort, and to deploy a solution that safely, reliably, and cost-effectively meets industry objectives. This effort includes:

- Identification of Critical to Quality attributes most important to the end user
- Enhanced process capabilities - determining what the process can deliver.
- Reduction in variation to ensure consistent quality.

Work Process Objectives (Jeffrey, INL LWRS Information Support Demo for Xcel MRM Gap Review, 2023)

- **Self-contained** - application that enables users to create a condition report (CR) with or without network connectivity using a computer, laptop, or mobile device equipped with a flat liquid-crystal display or an organic light-emitting diode screen, a mobile operating system, a touchscreen interface, and digital or physical buttons. Users can create a condition report from their cell phone, tablet, or laptop. This application has to work without any network connectivity since some areas in the plant do not have wifi or cellular coverage.
- **Display capability (Dashboard) - available 24/7 with hierarchical drill down structure** - application is always available and can be accessed by authorized employees and contractors via their company default browser. Users are logged in via SSO protocol and can access the dashboard as soon as the application is opened. The application knows which level of data access, training and job qualifications the user has based on their profile information. To create a CR, the user taps or clicks on the button or verbally tells the application to create a new CR.
- **Auto-Populating ability interacting with other data repositories** - when the application is connected to the network via Wi-Fi or cellular access, it accesses information from Active Directory access, SAP, and other backend systems. These systems will auto-populate relevant equipment and facility information based on the user's location, or a specific equipment id provided by the user. This equipment id can be spoken by the user, captured by the Object Character Recognition (OCR) feature in the application with the device's camera, or via typed entry.
    - The application will retrieve and populate relevant equipment information for the condition report. This information can include but is not limited to work history, open or pending work orders, operational data, equipment and system health scores. The instruction will contain intelligent prompts for the user to answer, record observations, readings, or any necessary information based on equipment criticality, technical specifications, and performance history.
    - The application will suggest the appropriate personnel to be notified based on identified accountability, responsibility, past maintenance, work, and acquisitions made for the equipment.
- **Automatic notification capabilities** - when the user confirms and indicates completion, the application will automatically generate the CR, make all notifications to applicable supervision (e.g., Shift Manager), and notify users that are needed to address the condition via phone, text, or e-mail. Any resulting work or action requests will be auto generated when applicable without any user intervention and the appropriate personnel will be notified, including inventory or procurement personnel of potential requests based on needed actions.
- **Automatic archive capabilities** - application will push the information to the backend systems.

Business Requirement Summary

These are extremely high-level requirements that define the main goals of a given solution. They are not detailed enough to start designing the details of an application, but they give the entire project direction and objectives that must be met. (Zylka, 2015)

Xcel Energy management wants to encourage users to report conditions found in the field by simplifying and minimizing the time it takes to initiate a report. The prototype should create a condition report in 2 minutes or less from the user's mobile device. The application will also use the latest and most relevant data in their backend systems to populate the report for the end user and for the review staff to expedite a resolution. (Wojchouski, 2023)

Business Functional Requirements (Zylka, 2015)

These define the pure requirements, at a functional level, without an implied design. The perfect requirement will be devoid of any implied design. This is the hardest part to master.

The goal of the Functional Requirements is to give the application designer the requirements because they need to design the application from an end-user perspective. If there's a user interface involved, then that means that the requirements are detailed enough to allow a designer to design the front-end of the application.

'Functional' implies that there's absolutely no discussion of technical aspects, such as where the data is stored, or IT-level concerns such as performance or where the app resides on the network. It also means that the requirements are designed at a level of detail that is more granular than 'business requirements'.

The functional requirements were collected from the Xcel Energy business team via online meeting interviews and reviews of current process limitations. (Wojchouski, 2023)

The application should:

- Enable the user to verbally indicate applicable equipment information such as the equipment name or tag number. The application should then automatically identify and locate the equipment or component information.
- Identify and present to the user other equipment in that system (from the FLOC - functional location in the main equipment identified) and enable the user to select other involved Systems, Structures, or Components (SSCs).
- Indicate if the equipment or involved SSCs are Tech Spec related including identification of potential for LCOs or represent a Single Point Vulnerability.
- Identify and present to the user current and prior related CAP issues to enable an informed decision to proceed or cancel this CR.
- Enable the user to create a new CR at any point during performance of a procedure, work notification, or work order operation.
- Prompt the user based on the CR content and enable the user to create a work notification with the CR submission.
- Enable the user to provide generic data if equipment tag information is missing, damaged, or unreachable. In such cases, the application should find equipment with similar characteristics and enable the user to select which to use for the condition report.

Additionally, the application should flag these instances and automatically notify applicable plant facilities personnel so that the equipment tag is repaired, replaced, relocated, or added to the applicable database.

- Enable users to enter anonymous CRs only from company issued computers or mobile devices.
- Clearly identify required information
- Fit as much as possible on one screen to provide an effective user experience.
- Enable users to scroll forward and backward across the CR entry fields.
- Automatically capture user information based on the login data.
- Prompt the logged in user with questions based on their proficiency, training, and qualifications.
- Prompt the user to indicate the urgency of the CR. and other applicable attributes such as industrial safety and automatically use these data to drive notifications based on business rules.
- Automatically records the date and time of CR creation.
- Enable the user to save the CR as a draft but not submit should they wish to complete it later.

Data Requirements

The requirements for data are part of the business and functional requirements. It is getting addressed separately in this section because for this prototype, the backend systems data for equipment, condition reports and work notifications will come from Asset Suite 9 Work Management module in the NextAxiom development environment. The data will be auto populated for the user in the application based on the equipment id provided. The condition report (CAP) and work request (work notifications) will be created in Asset Suite, and notification emails from the application will be generated via hyperservices.

Xcel Energy uses SAP as their backend system and the application will be integrated with SAP when it is moved to their development environment. NextAxiom has hyperservices in place at Xcel which retrieve user access, equipment functional location, and work management data for the currently implemented DWEP dynamic instructions (procedures) and work package workflows. Notification emails from DWEP are also implemented at Xcel.

In the next section we cover potential improvements to the current process and enhancements to encourage users to report conditions from the field, improve efficiency, reduce time and costs.

Explored value-added capabilities/Capability enhancement and streamlining. What could be done to enhance the work process.

The current work process at Xcel Energy requires the user to collect information while in the field via notes on paper before they can reach a workstation to electronically document and report the condition. For urgent or critical conditions, users contact the control room or designated personnel immediately via telephone or page system and complete the electronic documentation later when they return to their office.

Users have company cell phones to take photographs that can then be added to the report, but only after they email the images to themselves so they can upload them to the report. This adds an additional burden for users that want to include images.

Users can access an online form where they can enter information for their report and attach additional files. This form provides no guidance or prompting for the user. The form does not retrieve additional information for the user based on the data provided.

Identified Key Work Enhancement Opportunities (Wojchouski, 2023)

- Problem Statement 1: Users do not like being asked organizational or human performance questions. These questions can be perceived as sensitive information and the user can perceive the application is evaluating them. This can result in users not reporting conditions on the field.
- Enhancement Opportunity 1: The application should be able to pull organizational and human performance information from the user's human resource file and from the Learning Management System including but not limited to position, experience, training, and qualifications.

- Problem Statement 2: Users do not like being asked process and program questions. Some users do not know the answer to these questions. This can result in users not reporting conditions on the field.
- Enhancement Opportunity 2: The application can deduct some of this data from the identified equipment or facility, such as the equipment characteristics and work activities that have been performed or are scheduled to be performed.

- Problem Statement 3: Users do not want to spend more than a few minutes creating a new condition report in the field.
- Enhancement Opportunity 3: Users need the ability to easily identify equipment that does not have a functional location and the ability to create a simple condition report that is not equipment related.

- Problem Statement 4: Technical limitation - CR titles are truncated at 40 characters due to SAP limitations.
- Enhancement Opportunity 4: The application should:
    - Clearly indicate the number of allowed characters remaining so that they can manage within the constraint.
    - Enable an additional field so that an expanded description can be entered.

- Problem Statement 5: CRs cannot be generated without an identified functional location.
- Enhancement Opportunity 5: The application should:
    - Enable creation of situational or non-equipment related CRs. This will necessitate a modification to the backend system to include special qualifiers for situational condition reports. Where facility CRs, a room, closet, etc., could be identified.

- Enable the user to provide images of the issue when environmental conditions allow it (e.g., sufficient lighting), and attach it on the specific step.

The following section will cover:

- The functional design for the prototype
- What is in scope and out of scope on the design.
- Protype Design using Rapid Application Design.
  - Final wireframes of the mobile application.
- Technical Requirements

Digitalization Development and Design Principles

Prototype Development

Digitalization of work at Nuclear Facilities is pushing their capabilities by using all the information collected in their backend systems to better respond to facility demands. (Massoudi, 2022) The application prototype was designed to allow workers in the Xcel Energy facilities to initiate a condition report in real-time, to immediately notify and pass all the information needed to the personnel that will review and take the appropriate actions.

The elements of digitalization development addressed in this project satisfied the business and functional requirements (covered in Section 5.2) within the confines of the information available in Xcel Energy systems. Prototype Design was done to provide an application that encourage users to report any condition found on the field in the simplest and fastest way possible, while providing relevant and accurate information to the people that would take actions to address the issue.

Functional Design (Zylka, 2015)

This is a design, at a functional level, that meets all the requirements stated in the Functional Requirements.

If the Functional Requirements are pure, there will be different ways to meet the same Functional Requirements. In this part, designing for the end user makes all the difference.

For applications that have a user interface, the design is composed of complete mock-ups of the intended application that describe all possible interactions. We find that the most effective way to review Functional Design is via screen storyboards or wireframes.

Prototype Scope:

The initial prototype provided a browser-based interface where any person on the site could initiate a condition report from their mobile phone on the field (Murray, 2023). This application was done as a digital Dynamic Instruction (DI) to guide the user through the successful initiation of a condition report and a work request/notification, for equipment-related conditions.

The application collected data directly from the user for the condition report via button selection prompts, typed text entries, or spoken information, and used the device camera to scan the equipment tag.

The application used technologies like:

- Speech To Text (STT) recognition and
- Object Character Recognition (OCR)

to make it easier for the user to enter the condition report information, while pulling relevant data from backend systems and minimize the need for keying any data on a cell phone.

The scenarios for the prototype were based on two different equipment components from the Xcel Energy Monticello Flow-Loop Training facility. A motor pump (P01), and an air pressure valve (AOV). (Primer D. C., 2023)

Not included in the Prototype Scope:

- Prompting the logged in user with questions based on their proficiency, training, and qualifications. Use of organizational and human performance information from the user's human resource file and from the Learning Management System including but not limited to position, experience, and training and qualifications. These applications need to have the data structure to facilitate integration with other systems and they are not ready for this at Xcel.
- Integration to Xcel Energy SAP system - this could be done as part of project application development. For the prototype, the application interfaced with Asset Suite in NextAxiom's development environment backend system. NextAxiom's version of the application was not available to Xcel, and it could not establish network communication between Xcel's SAP and the NextAxiom development environment due to firewall access and security considerations.
- Could not use the application in Xcel company-issued mobile phones. The Xcel network currently blocks external application addresses. This could be addressed with more time by their IT department.
- Use of other virtual resources like learning models or artificial intelligence - Xcel Energy did not have learning models or artificial intelligence integrated with their backend systems. This is something that could become a separate project. Another option is to have another nuclear facility that has these elements integrated become the use case for the project.

Prototype Design

The design of the application prototype was done following the Rapid-Application-Development methodology.

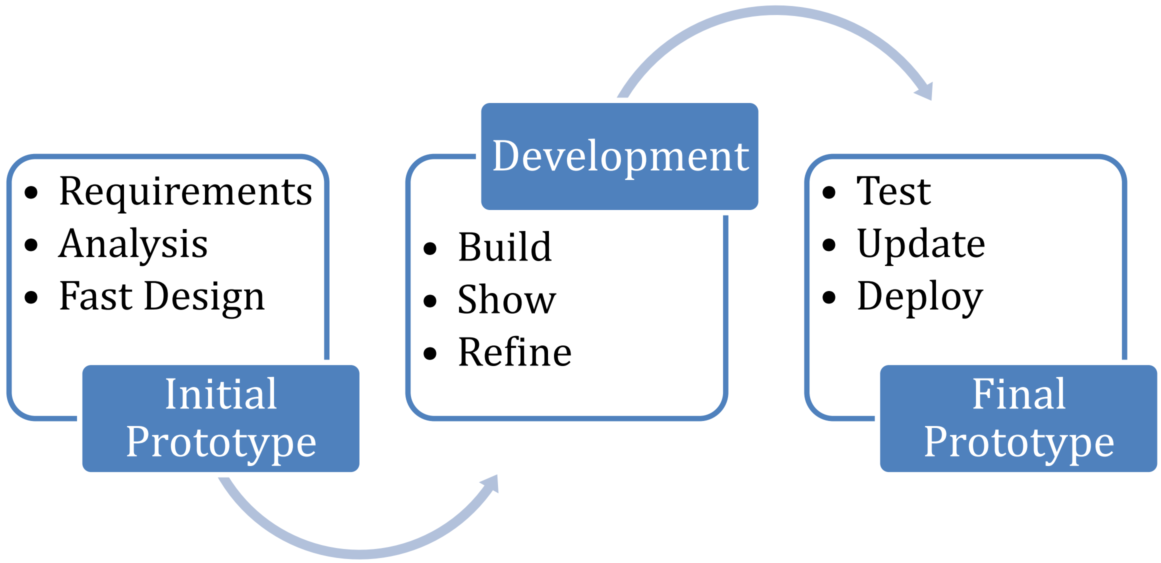


Figure B3. Rapid Application Process applied to Use Case Prototype Development.

After conducting user interviews at Xcel Energy and collecting the business and functional requirements, the initial functional design was created by Project SME, Pat Murray, as mobile phone screen wireframes for the application (Murray, 2023). These wireframes contained minimum basic questions designed for any user at Xcel Energy to create a condition report (CAP).

Revision 3 - Final Version of the Wireframes (Murray, 2023)

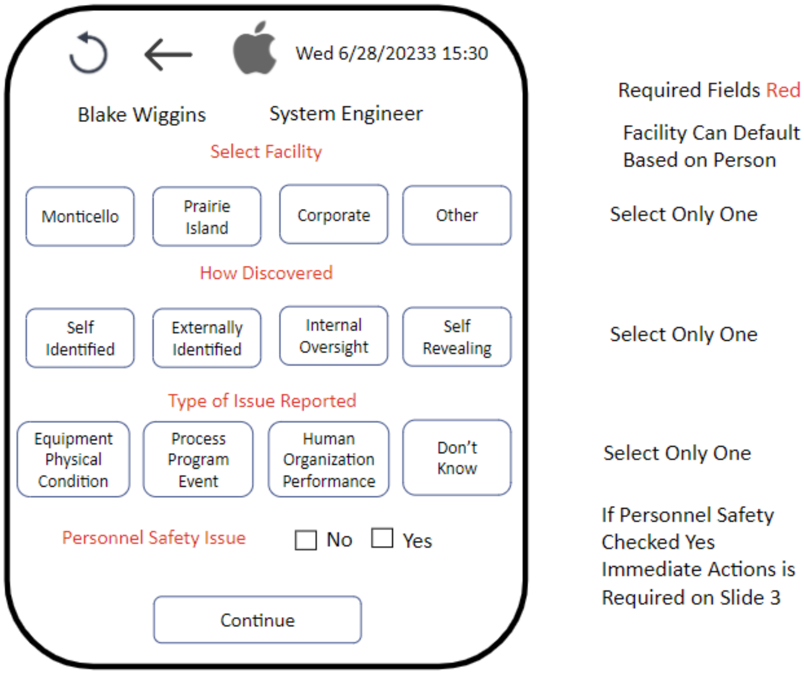


Figure B4. Wireframe screen 1 - Displayed the initial questions for the user.

'Facility' could be auto populated based on the logged in user active directory record, but Xcel indicated that some users will be entering condition reports for different sites than their own. Showed all the possibilities so they could select the facility for the condition report.

'How Discovered' and 'Type of Issue Reported' provided a simple selection of adequate answers for the user.

In the 'Personnel Safety Issue' options, the user needed to select 'Yes' or 'No', and if they answered 'Yes', they would be prompted to notify specific personnel.

Figure B5. Wireframe screen 2 - Equipment's tag id could be scanned using the mobile device's camera.

If there was no tag id, the user could take a picture with the device's camera that was included with the condition report. Equipment characteristics were to be auto populated from the backend system based on the equipment tag id provided.

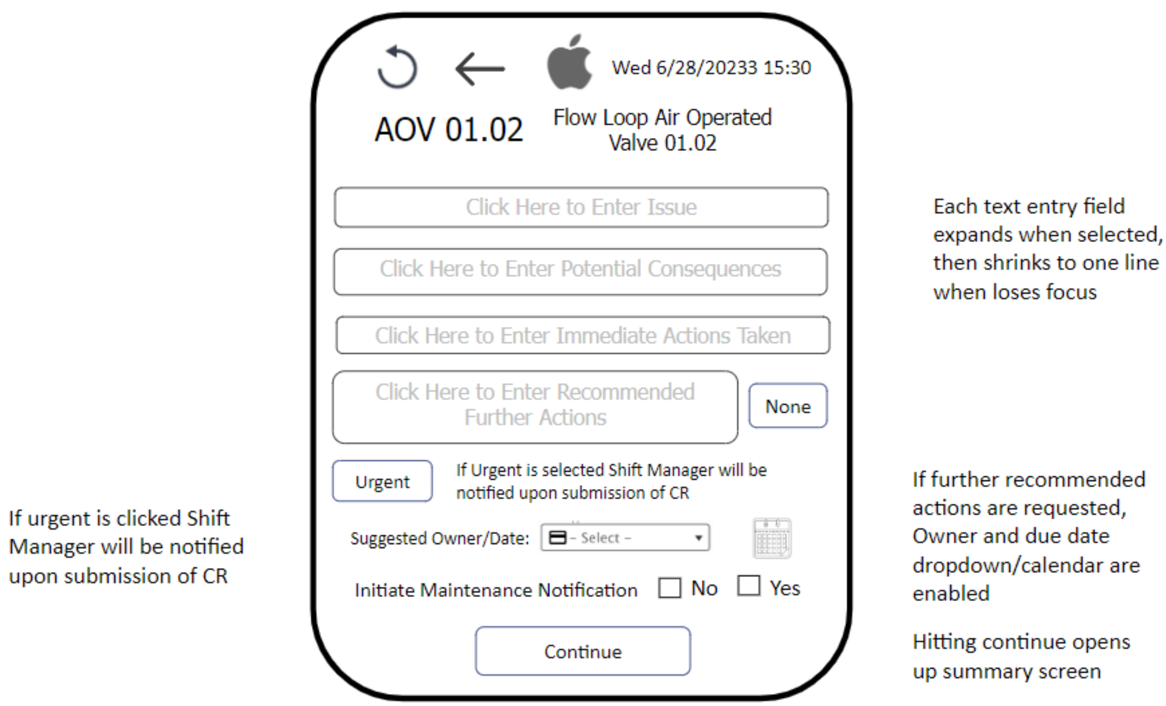


Figure B6. Wireframe screen 3 - User entered condition report information with actions

taken. Options presented to select if 'Urgent' and the owner to be notified when condition report was submitted.

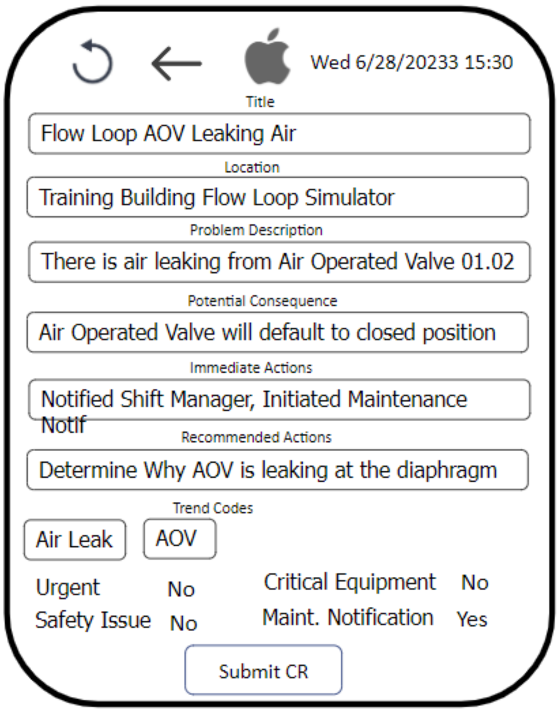


Figure B7. Wireframe 4 - User confirmed information to initiate condition report and submit

The business team at Xcel Energy, Dylan Wojchouski and Jesse Rain, reviewed the wireframes and provided feedback to the SME, Pat Murray, and NextAxiom. There were several meetings and iterations between Pat Murray and the Xcel Business Team to review the wireframes. Their feedback improved the functional design.

Technical Requirements (Zylka, 2015)

For the technical requirements, the functional design had to work in the user's mobile phone and the application had to communicate seamlessly with the backend system.

After the wireframes were finalized between Pat Murray and the Xcel Energy Team, the NextAxiom Team started working on the technical design for the prototype.

For the technical design two components had to get addressed:

- Authoring of the prototype using the DWEP Authoring Tool
- Integration with backend system using hyperservices.

Note: The NextAxiom team considered building the application as a 'Dynamic Form' instead of a 'Dynamic Instruction'. The challenges faced were related to the lack of guidance in navigation. How to implement conditional responses based on user answers when they could be entered in random order. Future development on NextAxiom's DWEP application will address some of the issues found during the technical design.

The authoring of the dynamic instructions did not require any coding or specialized technical knowledge since the DWEP application allowed the author to use the tools in the DI interface to build the application by drag and drop of data and control widgets into the DI steps. Conditional behavior was easily built in the new version of DWEP. Authors could see all the conditions added on a data or control widget with the click of a button and they could add, edit or remove conditions from that list.

For the integration, the NextAxiom team was able to use existing hyperservices integrated with Asset Suite 9 by importing them into the DWEP dynamic instruction during authoring and mapping the fields for the inputs and outputs of the services. This was also done via drag and drop from the service fields to the data widgets in the dynamic instruction.

The DWEP application ran on a browser-based thin client user interface. The application could run on the following browsers: Chrome, Edge, Safari and Firefox. Edge browser was used at Xcel Energy.

The prototype was tested on both iPhone and Android devices.

One challenge faced was due to The Xcel Energy network blocking the NextAxiom web domain on the company cell phones since it is outside their firewall. Participants at the demo used their personal cell phones and logged into Xcel's guest Wi-Fi.

The application communicated with the back-end system via Wi-Fi during the demonstration, but it could also operate offline if the data had been downloaded to the device and no communication was needed with the backend during that time.

As we previously mentioned, the prototype was integrated with Asset Suite 9 in the NextAxiom development environment. Xcel was already using DWEP applications that were integrated with SAP and DRMS (Document Management). The prototype was not developed in the Xcel environment because we needed the new utilities, which are only available in the newer version of DWEP in NextAxiom's development environment.

One of the utilities used for the prototype was an open-source Object Character Recognition (OCR) called Tesseract (Tesseract, 2023). The application used this utility to read the equipment tags in the Xcel Flow-Loop Training Facility using the mobile phone camera. Tesseract is an optical character recognition engine for various operating systems. It is free software, released under the Apache License. During the development and testing we realized that using this utility proved more challenging than expected and could make it difficult for the user of the application. NextAxiom's engineer, Aaron Bly, made adjustments to improve the utility prior to the demonstration. The NextAxiom team recognized that more investigation is needed for better OCR utility options.

In the application, some questions prompted the user to type or speak their answer using their device's microphone. The prototype used an open-source speech recognition API called Web Speech (Mozilla, 2023). It is also free open-source software. We noticed during development and testing that this utility did not recognize pauses in speech and would overwrite anything that was said prior to pausing with the spoken words after the pause. The team added a note to alert users on the steps with the speech option to press the microphone icon when pausing and resuming to prevent the information from getting overwritten. The NextAxiom team recognized that more investigation is needed for better speech-to-text utility options.

Prototype Demonstration and Evaluation

Functionality Demonstrated

After the application development and testing was completed, the prototype application was demonstrated as part of two-day meetings at the Xcel Energy Flow Loop Simulator – Monticello Training Center (MTC) - 2100 W River St. Monticello, MN 55362 (Spielman, 2023)

July 25 & 26, 2023.

The scenarios included:

- Motor pump leaking oil
- Air pressure valve making noise.
- Non-equipment conditions.

On all scenarios the user was prompted for basic information:

- Site for the report (could be different from the logged-in user's site)
- Selection of how the condition was found.
- Selection of type of issue - which prompted additional information for equipment identification if the issue was equipment related.
- If the issue was a safety-related one, the user was prompted to contact the control room or SRO immediately.
- Remedial actions taken by the user.
- Initiated condition report and work request (equipment scenarios only) or initiated condition report (non-equipment scenarios).

Users were shown related condition reports and work requests for the equipment-related scenarios.

Participants on the demonstration:

- Xcel Energy: Todd Hurrle
- Xcel Energy: Jesse Rain and Dylan Wojchouski - demonstrated the application.
- Idaho National Laboratory: Patrick Murray, Jason Remer, Zach Spielman, Anna Hall
- NextAxiom Technology: Sandy Zylka, Ronald Williams, Blake Wiggins (Remote)

Prototype Application Steps to Initiate Condition Report (CAP) for Equipment

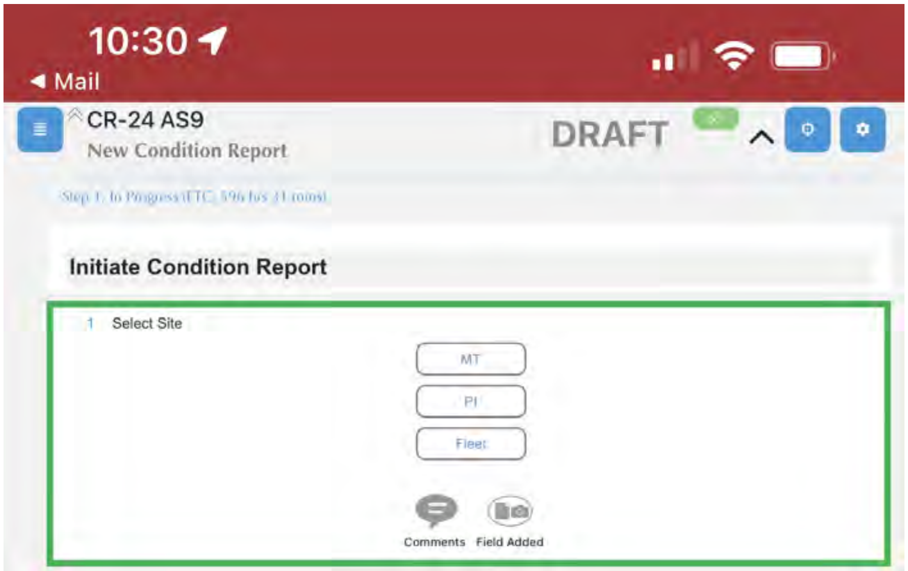


Figure B8. User selected the site for the condition report.

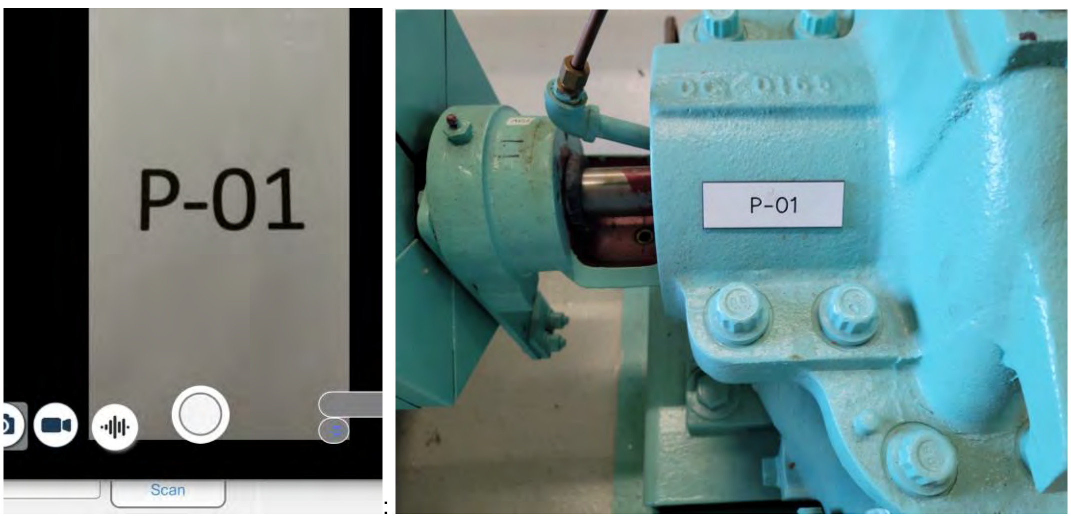


Figure B9. On the left: Depiction of the mobile phone's camera reading text (not an equipment label). On the right: Equipment tag at Xcel Energy for motor pump.

During the demonstration, users observed the challenges with the object recognition (OCR) utility in the application. The scan would not render the correct string of characters due to:

- Low light where the tag is placed.
- Having other items besides the tag (part of the motor casing) in the image corrupts the string of characters with additional characters and symbols.
- Putting the device camera close enough to the equipment tag to exclude the motor casing from the scan blurs the image and the utility cannot recognize the characters.

Users corrected the characters scanned in the text field by editing them with the device's keyboard.

Figure B10. See how additional characters could be introduced by the OCR utility.

As previously noted,: The NextAxiom team is researching better OCR utilities in the market to be used with DWEP applications.

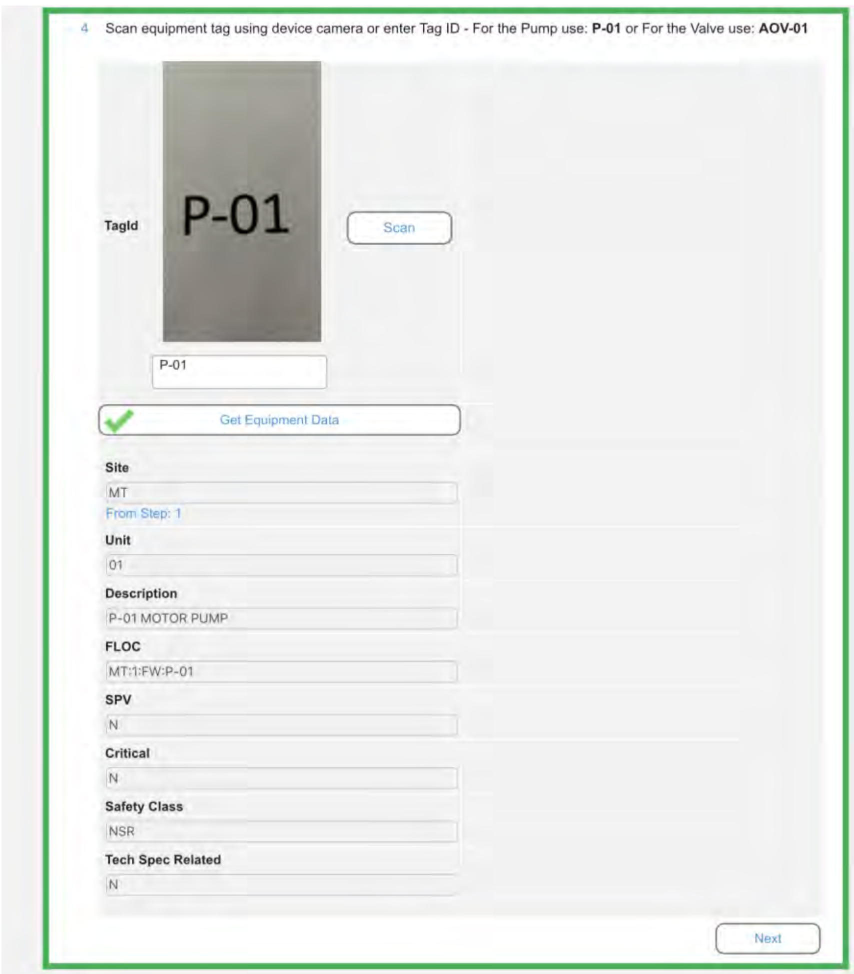


Figure B11. When the equipment tag id was correct, the user tapped the 'Get Equipment Data' button to retrieve equipment information from the backend system.

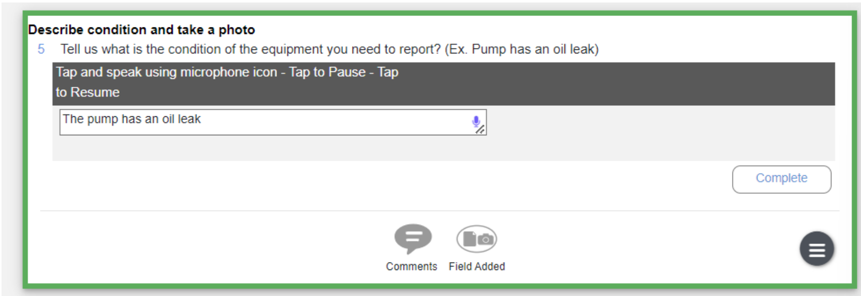


Figure B12. User spoke and described the condition they were reporting.

Users could also add a photo taken using the cell phone camera by tapping the 'Field Added' icon.

Observations were made during development and the day of the demo related to the microphone behavior in the 'speech to text' (STT) utility. It overwrites anything said if the user naturally pauses and resumes speech. As previously stated, we noticed this during development and testing. Users followed the notes added for the use of the microphone icon to prevent the utilities default behavior. As previously noted, The NextAxiom team is researching better STT utilities in the market to be used with DWEP applications.

Figure B13. User spoke about the additional preventive maintenance (PM) information.

This PM question only appeared if the condition was being reported for equipment.

Figure B14. User selected button with answer (No or Yes) if condition was a personnel safety issue.

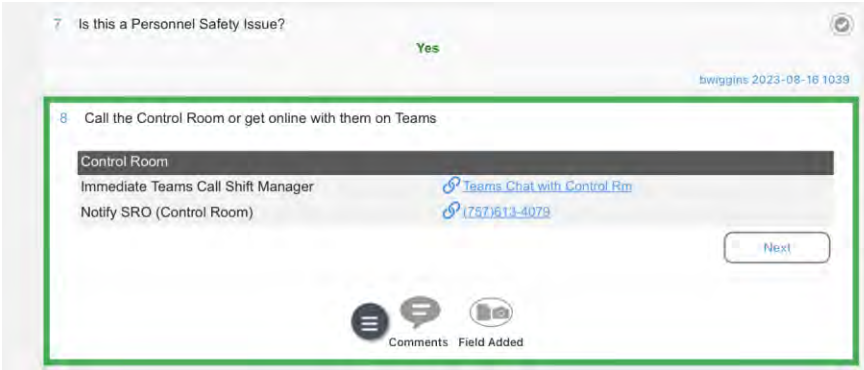


Figure B15. If the answer selected was 'Yes', the user was offered links to open a live Teams chat with the Control room, or a phone number link to call the SRO from the cellphone (clicking the phone number link opened the phone app and dialed the number).

Figure B16. Users spoke the details of actions they took.

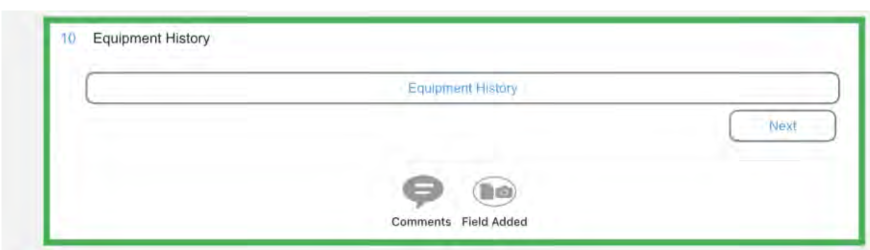
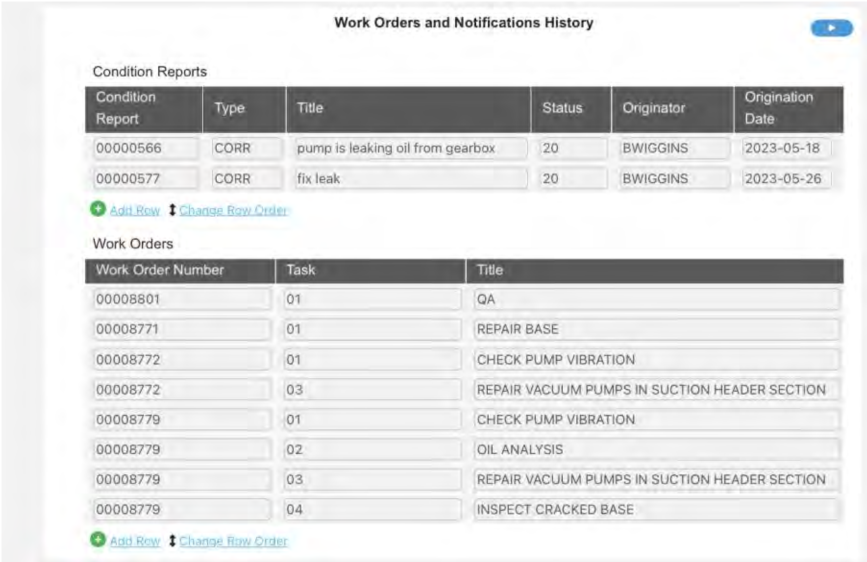


Figure B17. Users had the option to look at equipment history for the specified equipment by tapping the 'Equipment History' button.



Work Orders and Notifications History

Condition Reports

Condition Report	Type	Title	Status	Originator	Origination Date
00000566	CORR	pump is leaking oil from gearbox	20	BWIGGINS	2023-05-18
00000577	CORR	fix leak	20	BWIGGINS	2023-05-26

Add Row Change Row Order

Work Orders

Work Order Number	Task	Title
00008801	01	QA
00008771	01	REPAIR BASE
00008772	01	CHECK PUMP VIBRATION
00008772	03	REPAIR VACUUM PUMPS IN SUCTION HEADER SECTION
00008779	01	CHECK PUMP VIBRATION
00008779	02	OIL ANALYSIS
00008779	03	REPAIR VACUUM PUMPS IN SUCTION HEADER SECTION
00008779	04	INSPECT CRACKED BASE

Add Row Change Row Order

Figure B18. If the user tapped the ‘Equipment History’ button (Figure 17), the application opened a separate tab for the user to see other CRs and WOs for the specified equipment.

When the user clicked on the blue play icon, the screen closed and went back to the condition report initiation screen.

If the user needed to return to this information, they could open the tab again from the main initiation screen.

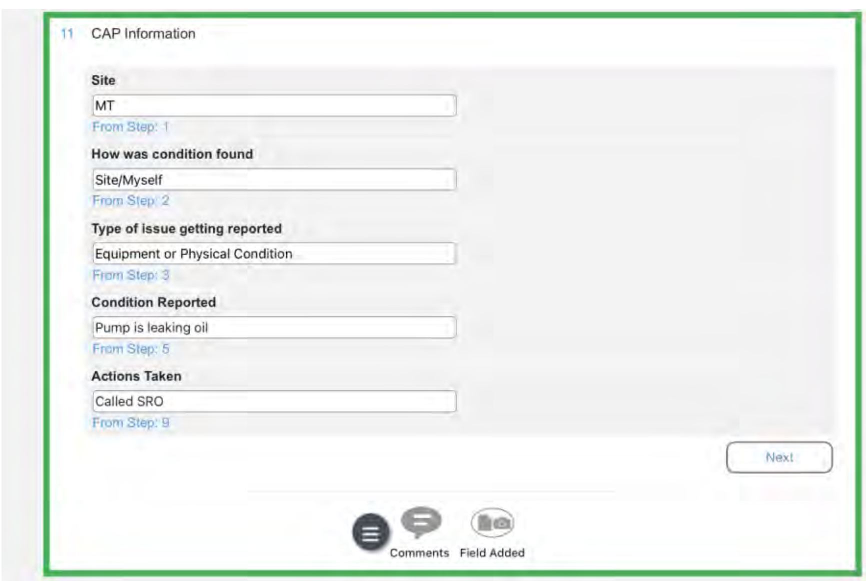


Figure B19. User confirmed CAP information and tapped the ‘Next’ button to proceed. Note that the user has the option to go back to previously entered information and redo a step.

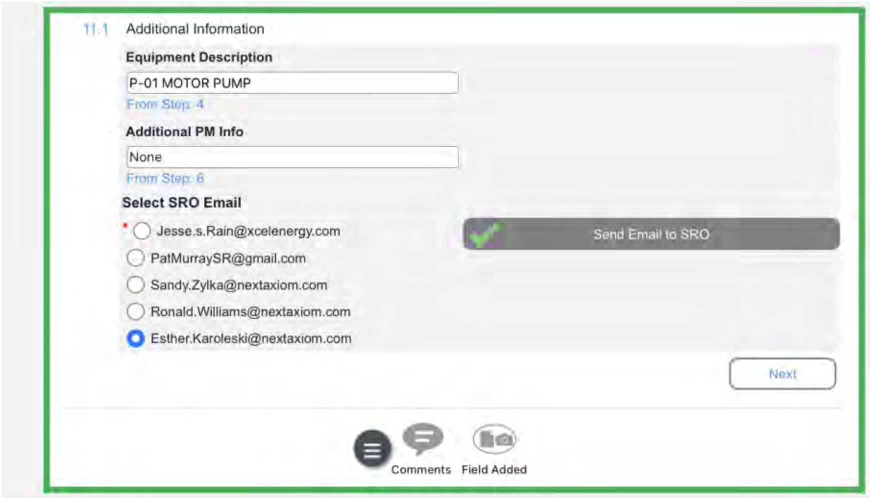


Figure B20. In the equipment scenario, the user confirmed the equipment description supplied by the backend system, and additional information provided by the user related to preventive maintenance. The user had the option to send a notification email to the SRO alerting them of the condition report by tapping the 'Send Email to SRO' button.

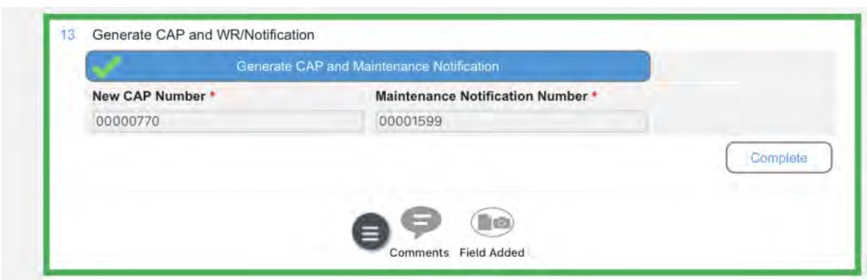


Figure B21. User tapped the 'Generate CAP and Maintenance Notification' button which created the condition report and the work maintenance notification in the backend system.

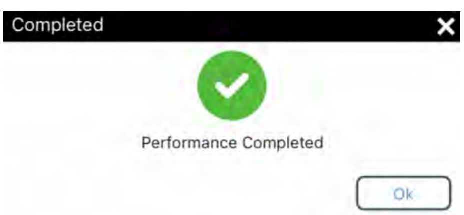


Figure B22. After the user taps the 'Complete' button (Figure 21), they get a pop-up letting them know they are done and can close the browser.

Application Steps to Initiate Condition Report (CAP) for Non-Equipment

During the demonstration, the team generated condition reports for non-equipment scenarios. These scenarios were streamlined by the application since the equipment information was not required. No need to use the OCR utility, entry for preventive maintenance, or lookup of equipment history. If the condition did not endanger personnel safety, it did not present the user with the options to contact the control room or the SRO.

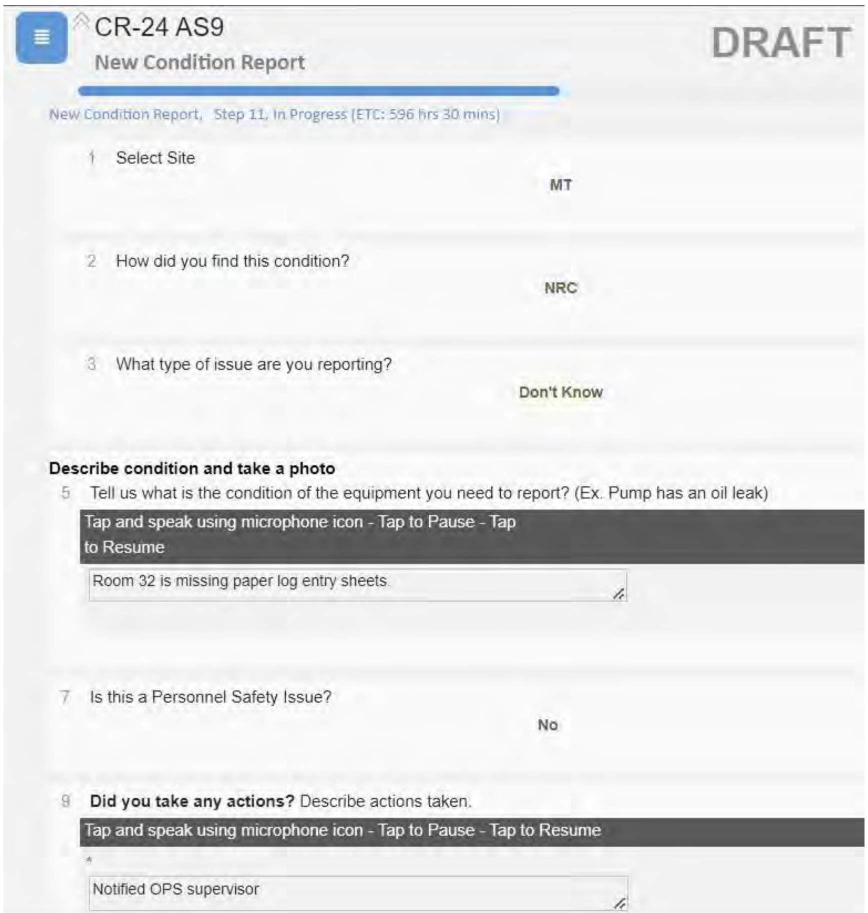


Figure B23. Information entered for a condition where the user was not sure which type, and it was not a personnel safety issue.

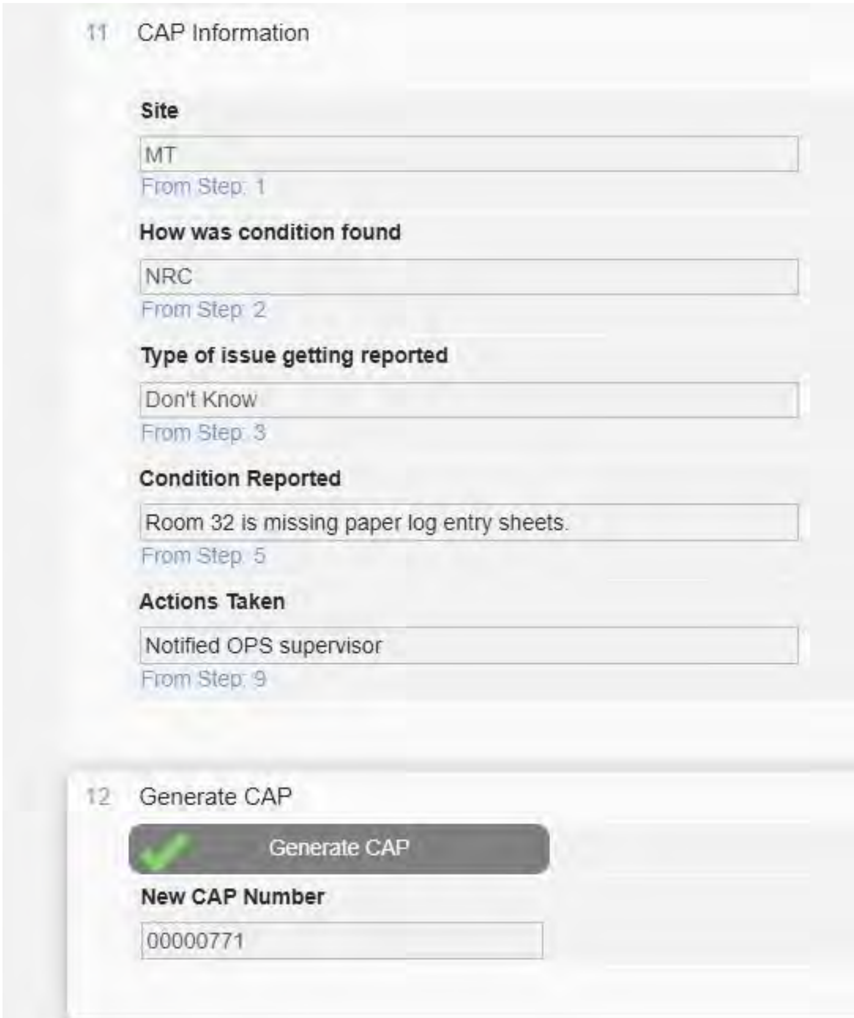


Figure B24. **CAP confirmation and button for user to tap and 'Generate CAP'. It took about 2 seconds for the backend system to issue the new CAP.**

Utility Reception of Prototype

The following feedback was collected during the prototype demonstration as the users were going through the application to enter various CAPs (condition reports).

What the Team liked

Quick Navigation and Efficient Guidance: How easy it was to provide the needed information for the condition report. A minimum amount of information was requested to get the report created in the backend system and the user did not need to login and access the backend application, which is not easily accessible in the field.

Speak to fill required information: the idea behind speech to text technology (STT) was to free the user from having to type anything on the field. Cell phone and tablet keyboards are cumbersome when users are exposed to bad weather conditions, extreme temperatures, wearing heavy gloves, or when the information on the screen is covered by the online keyboard.

Equipment information from the backend: The equipment characteristics and attributes information that was retrieved from the backend system when the user provides the equipment tag ID was accurate. This reduces human error and saves the user time on the entry of equipment issues. Not all users will check the equipment history information which includes other CAPs (condition reports) or maintenance notifications (work requests). For users and reviewers that use this information, having it available will save a lot of time in online searches and pulling the information manually into the CAP.

Non-equipment Conditions: Entering the information was simpler and faster. The team easily demonstrated that a CAP could be created in a few minutes.

Having the ability to take photos of the problem on the field as they are filling the report: The application allows the user to take images and attach them on specific steps for the reviewers of the report. This functionality made it easier for the users to attach relevant images in their CAP and it could be easier for reviewers to assess the situation.

If the issue affected **personnel safety**: Giving the user direct access to the control room via Teams call or chat- which allows them to do a screen/camera share while they are talking to them was functionality that promoted the urgency and facilitated action by the user to contact the right people immediately. The other option they had was a direct call to the SRO from that same step.

Notify other personnel that the report was on the way. Users could select an individual or a group to receive an email with basic information on the condition reported. This eliminated the delay from users to manually login to check in the backend application to see if there was any pending reports that need their attention.

Confirmation and Creation of CAP: Users had the option to create the CAP by tapping one button, edit it before creating it, or canceling out by closing the browser screen on their cell phones.

What the Team did not like:

OCR (Object Character Recognition) utility: Is challenging to use the cell phone camera to take a clear picture of the equipment tag. Users could not control which text is included. It read all the text in the image, and anything that showed outside the tag was interpreted as text content and converted as bad characters or symbols in the text field. Zooming too much into the equipment tag to keep the whole tag in the image frame made it hard for the camera to focus. Low light in the area can also affect the result. Users in the prototype had to revise the Equipment tag id field to correct the text string using the cell phone keyboard.

STT (Speech to Text) recognition utility for users to speak on data entry fields posed a challenge due to the utility replacing any prior text converted if the user paused while they were speaking, and if users did not follow the short instruction to use the microphone icon to pause and resume. Users were not used to this glitch when voice commands are used on other mobile interfaces.

Another possible challenge is a noisy environment where the user speaking to the device could not be properly converted to text due to noise interference.

As previously discussed in the development and testing section, more research is needed to find better OCR and STT utilities.

Follow-on

A Gateway to Artificial Intelligence for the Nuclear Industry (Primer & Massoudi, 2023)

The Virtual Assistant user experience is an example of Artificial Domain Intelligence and domain-augmented Natural Language Processing in action. The Light Water Reactor Sustainability (LWRS) Program, sponsored by the Department of Energy, in collaboration with leading nuclear utilities has been pioneering domain-specific Artificial Intelligence (AI) which can form the Artificial Domain Intelligence building blocks required to bring these ChatGPT-like assistants to life. (Primer & Massoudi, 2023)

The question is how do we integrate Virtual Assistants and domain-specific AI automations with plant data, business processes, procedures, and other plant resources? The challenge is that business processes and procedures typically rely on a mixture of resources to accomplish the desired activities and there is no universal software framework to virtualize these drivers' resources for the purpose of process digitalization and AI infusion.

At the heart of VRMF lies the concept of a Virtual Resource. A Virtual Resource represents information, actions, and AI focused on a particular concept or domain. A Virtual Resource can represent physical objects such as circulating water pump 1-01, a class of objects such as motor operated valves, or an intangible resource such as an operational risk assessor.

Figure B26. Virtual Resource Manager Framework (Primer & Massoudi, 2023)

ION Use Case

This prototype application effort taught us that a potential next step is for nuclear facilities to present equipment risk and historical data that has meaning for their users when submitting or reviewing a condition report. Analysis of this data can take the condition report beyond initiation by suggesting preventive measures to mitigate or eliminate a corrective condition in the future. Using this information on a pilot with limited scope will allow an operations team to see how the risk and historical information can be best used by the facility and they can provide valuable feedback. The intelligence part of a future Virtual Management Resource Framework (VRMF) could be learned from the people that have experience working on that equipment or system.

Some nuclear facilities have this historical information and only need to get an assessment of the risk. Risk can be estimated when the data is normalized and proper statistical models are applied to equipment based on maintenance, probability of failure, environment, age, plant conditions, and safety limits. The Light Water Reactor Sustainability (LWRS) Program at Idaho National Laboratory has Data Architecture & Analytics initiatives like the Condition-based maintenance via a Technology-Enabled Risk-informed Maintenance Strategy (TERMS), which is part of data reconciliation and normalization efforts. (Jeffrey, INL LWRS Information Support Demo for Xcel MRM Gap Review, 2023). TERMS platform is being developed to integrate the results of predictive analytics with enterprise resource planning (e.g., work orders and work packages). (Jeffrey, Miyake, & Hall, Guidance on Transforming Existing Light Water Reactors into Fully Modernized Nuclear Power Plants: The Role of Plant Modernization R&D, 2021)

The nuclear facility for this potential pilot has historical data stored in their enterprise resource planning system or data warehouses but they have not implemented any machine learning (ML) or artificial intelligence (AI). This facility can become the next case study where their data can be analyzed for risk and embedded into the condition report (CR) initiation for a specific situation. This application should be able to provide guidance to the end user and pass on relevant information to the team in charge of remediation. After the application is accepted by users and they see the value in this guidance, the facility could be ready for the next phase where the application has an equipment risk assessor. This is a virtual resource that can be trusted to provide preventative actions which minimize remediation and operations costs. For ION to be adopted by facilities personnel, they need to see how it benefits their operations and support their work.

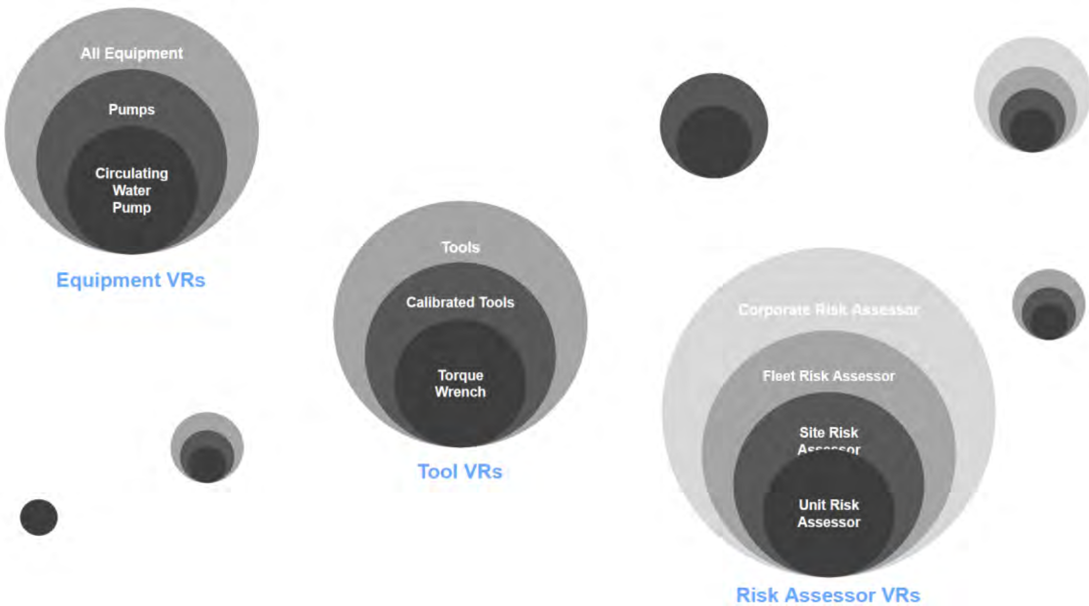


Figure B25. From *2023 NNUG NxA Vision and Roadmap* - Nuclear NextAxiom Users Group presentation on Computer Guided Work (Sandy Zylka, 2023)

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