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Establishing a value chain for human factors in nuclear power plant control room modernization

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Abstract

Commercial nuclear power plants in the United States (U.S.) have operated reliably and efficiently for decades. With a second 20-year life extension of operation beyond the plant's original operating licenses now being considered by many utilities, there are opportunities to achieve even greater efficiencies, while maintaining high operational reliabilities, through strategic, risk- and economically-informed, upgrades to plant systems and infrastructure. The U.S. Department of Energy's Light Water Reactor Sustainability (LWRS) program supports the commercial nuclear industry's modernization efforts through research and development (R&D) activities across many areas to help establish the technical and economic bases for modernization activities. The Advanced Instrumentation, Information, and Control Systems Technologies pathway is one R&D focus area for the LWRS program, and has researchers at Idaho National Laboratory working with select utility partners to use human factors and instrumentation and controls R&D to help modernize the plant's main control room. However, some in the nuclear industry have not been as enthusiastic about using human factors R&D to inform life extension decision-making. Part of the reason for this may stem from uncertainty decision-makers have regarding how human factors fits into the value chain for nuclear power plant control room modernization. This paper reviews past work that has attempted to demonstrate the value of human factors, and then describes the value chain concept, how it applies to control room modernization, and then makes a case for how and why human factors is an essential link in the modernization value chain.

Keywords: Human factors; Nuclear power plants; Control room modernization; Value chain

1. Introduction

Affordable electricity generation is an essential component to powering a nation's robust and globally competitive economy. In the United States (U.S.), nuclear power accounts for approximately 20% of current base load electricity generation, and does so without the release of carbon into the atmosphere (World Nuclear Association, 2014). Low carbon replacement technologies that provide base load electricity cost competitively at a national scale are still under development. Thus, without suitable replacements for nuclear power, the generating capability of nuclear power in the U.S. must be maintained through the continued safe and efficient operation of the current fleet of nuclear power plants (NPPs).

The Light Water Reactor Sustainability (LWRS) program is a research, development, demonstration, and deployment program sponsored by the U.S. Department of Energy (DOE). The LWRS program is operated in close collaboration with industry research and development (R&D) programs to provide the technical foundations for licensing and managing the long-term, safe, and economical operation of NPPs that are currently in operation. In short, the LWRS program focuses on research that contributes to the national policy objectives of energy security and economic sustainability.

One focus area in the LWRS program is the Advanced Instrumentation, Information, and Control Systems Technologies pathway, which includes human factors R&D on main control room modernization. However, some in the nuclear industry have not been enthusiastic about using human factors R&D to inform life extension decision-making. A survey of 11 U.S. utilities conducted by Idaho National Laboratory (INL) (Joe, Boring, & Persensky, 2012) revealed that there is a unique situation for control room upgrades: while there is desire to upgrade, practical constraints such as cost (primarily through lost revenue) are a formidable hurdle to the upgrade process. Thus, part of the reason for this lack of enthusiasm may stem from uncertainty decision-makers have regarding how human factors fits into the value chain for NPP control room modernization. That is, given the focus on costs and return on investment (ROI), and because it can be difficult to see how focusing on human factors helps address costs and ROI, it is understandable to see decision makers discount the importance of conducting R&D to address human factors issues. It is our assertion, however, that human factors is an essential link in the modernization value chain. This paper reviews past work that has attempted to demonstrate the value of human factors, and then describes the value chain concept, how it applies to control room modernization, and then makes a case for how and why human factors is an essential link in the modernization value chain.

2. The value of human factors

The need to demonstrate the important role human factors plays in the engineering of technological solutions is not new. Howell (Howell, 2008) provides an anecdote from when he was the chief scientist for research on human systems for the U.S. Air Force. He described his experience of receiving, at best, grudging acceptance and tolerance for human factors from some military decision makers, despite presenting to them what he considered very compelling technical and economic evidence. Thus, in many ways, this issue of how these technologies benefit the commercial nuclear industry is essentially the larger question of how human factors, as a professional discipline, adds value to the design, development, testing, and implementation of new complex technologies, and how technologies that have been “human factored” add value to the overall socio-technological system that has been engineered to solve a particular problem. This value proposition question has been studied extensively in the field of human factors, particularly for usability (Mayhew & Mantei, 1994), and cognitive modeling (Cooke & Durso, 2008). There also are a number of military case studies that are either 1) cautionary tales showing the undesired outcomes when human factors are not considered, or 2) provide confirmatory evidence that human factors improves important performance and safety outcomes while minimizing training needs, and costs to build, deploy, and maintain these technologies.

Among the cautionary tales, Cockshell and Hanna (Cockshell & Hanna, 2006) and Sutherland et al. (Sutherland, Hanna, & Cockshell, 2006) reported the command center aboard the Anzac class frigate used by the Australian and New Zealand Navies did not include human factors in its design. As a result, the frigate encountered a variety of problems as it was being put into service. Operationally, there were numerous space constraint issues in the command center, and the crew had additional issues with some controls being difficult to reach. Crews also had difficulty with the HSI in that critical information was often not properly displayed, which greatly affected their situation awareness during time-critical tasks. A number of workarounds were developed, but they were all reported as being less than optimal. Furthermore, the estimated cost to redesign the command center was so high that changes to the command center were delayed until a ship-wide retrofit was deemed necessary to maintain the ship's war fighting capability.

Another example is from Hawley (Hawley, 2007), which assessed the Patriot air and missile defense system. This system had been used reliably and safely for years, but was more recently involved in two fratricides during Operation Iraqi Freedom (OIF). Hawley's assessment noted that the Patriot system had been upgraded prior to OIF with more automation to defend against newer air threats (e.g., Tactical ballistic missiles and unmanned aerial vehicles), but that there were issues with the automation's ability to correctly identify whether the now wider range of targets were friendly or hostile. Hawley's report suggests that the automation designers did not effectively communicate these deficiencies to the operators. Furthermore, the HSI was not significantly improved when the automation was added, nor was the operator's training or role re-evaluated. The result was that the operator was often over-reliant on the automation, resulting in the operator losing situation awareness, and failing to have a questioning attitude towards the automation's decisions to engage incoming targets.

Some notable confirmatory examples include the U.S. Army's Fox M93A1 reconnaissance vehicle. The Fox vehicle is essentially a mobile laboratory that analyzes air, water, and ground samples for nuclear, biological, and chemical threats. When the Army decided to reduce the crew compliment from 4 to 3 soldiers, a human factors redesign was needed on both 1) the crew cabin and workstation controls, and 2) the conduct of operations, such that the roles and responsibilities could be reassigned. Booher and Minninger (Booher & Minninger, 2003) analyzed the effect the human factors involvement had in this redesign and found that the human factors subject matter expertise on how to reallocate tasks to address excessive workload and the use of human figure modeling tools were essential to the successful redesign of the Fox vehicle. In fact, Burgess-Limerick, Cotea, and Pietrzak (Burgess-Limerick, Cotea, & Pietrzak, 2010) report that the return on investment to cost ratio for the human factors involvement was around 30:1.

Booher and Minniger (Booher & Minninger, 2003) also analyzed how human factors involvement in the redesign of the Apache Longbow helicopter led to a 20:1 ROI to costs ratio. Specifically, the original design and location of some cockpit controls interfered with the proper functioning of a key safety system, and human factors experts were centrally involved in the redesign of those controls. Additionally, it was found that many aspects of the Apache's original design often complicated maintenance activities. For example, the design of some compartments made it difficult for maintenance personnel to access recessed components, and maintenance personnel would often inadvertently damage sensitive components by stepping or standing on the housing for those components while performing repairs on other parts because the original design of the helicopter's fuselage provided no footholds. Human factors reviews and analyses of these problems played an important role in coming up with cost effective solutions.

These studies, and many others (for a review, see (Burgess-Limerick, Cotea, & Pietrzak, 2010)), have led many in the armed services, National Aeronautics and Space Administration (NASA), Federal Aviation Administration (FAA), and academia (Bruseberg, 2008) to conclude that the cost of integrating human factors into the R&D of military and other technologies (Mayhew & Mantei, 1994) (Cooke & Durso, 2008) is a worthwhile investment in terms of cost savings, increased productivity, decreased training needs, and decreased errors when using the "human factored" system. According to the U.S. Air Force (U.S. Air Force: Directorate of Human Performance Integration, Human Performance Optimization Division, 2009) the human factors R&D costs are typically only 2-4.2% of the total R&D or system acquisition cost, and a frequently cited statistic in this literature is that the return on investment for human factors in military applications is typically 40-60 times the original investment.

These statistics are quite impressive, yet the methodology of the studies cited in this section provides only anecdotal evidence regarding the efficacy of human factors, which some researchers mentioned above recognize that others may dispute (Burgess-Limerick, Cotea, & Pietrzak, 2010). Be that as it may, it cannot be disputed that in warfare, end-users of military technologies need those technologies to work as expected when deployed in field, and especially when used during engagements. Both military leaders and designers of these technologies are keenly aware of this. It is safe to say that no military leader wants to put their subordinates, particularly those who are at the "point of the spear," into harm's way with military technologies that do not work. This in itself is an important reason why the armed services, and other high-risk industries, invest as much as they do in human factors. The possible negative consequences, from the loss of lives in the field, losing the battle, and the end of the leader's military career for failing to accomplish the mission objectives are significant. It is apparent, based on how much the military invests in human factors, that military leaders generally agree that these negative consequences should not hinge on poorly designed technologies.

This reason aside, it is nevertheless challenging to take the anecdotal evidence presented in these military human factors examples and apply them directly to modernization activities in the commercial nuclear industry. In light of this, we posit that LWRS human factors R&D needs to formulate more explicitly the value chain to demonstrate how these technologies benefit the commercial nuclear industry.

3. The value chain for human factors and advanced control room technologies

Rouse and Boff (Rouse & Boff, 2003) describe the value chain as a valuable construct to help understand how to tie initial costs to the expected return on investments. They write, “More specifically, it is quite helpful to consider the value chain from investments (or costs), to products, to benefits, to stakeholders, to utility of benefits, to willingness to pay, and finally to returns on investments” (pg. 641). In translating this generic value chain and applying it to this research problem, the value chain becomes the following questions:

1. What can operators do with this new technology that they could not do before? That is, by investing in these products, what are the expected technical benefits to operators and the plant?
2. What would that result in in terms of plant outcomes?
3. How would this show up in business or key performance indicators (KPIs)?

With respect to the first question, there is a range of technical benefits to the operators with the introduction of new control room technologies. Examples of new control room technologies includes digital control systems, new alarm systems, advanced digital displays for the plant process computer, and computer based procedures. The first obvious benefit to introducing and using these kinds of new technologies is the reduction in operator workload and mental burden. In NPP control rooms, the highest mental burden on the operators is typically during most critical situations, and these technologies have the ability to reduce workload during these critical situations. The inclusion of technologies that automate routine activities also benefits operators. Automating routine sequences of activities eliminates tedious, switch-by-switch control the operators currently perform, which then allows them to command the plant at a higher level rather than being weighed down in the tedium of getting systems aligned. Another technical benefit of these technologies is that they can help the operator integrate plant information when diagnosing plant conditions. This is particularly useful when the plant is experiencing abnormal and/or emergency conditions. These technologies can also provide trending information on key plant parameters that can provide advanced notification to the operator, prior to any alarm setpoint, thereby assisting operators with their task of diagnosing plant conditions. Similarly these trends can be used to forecast the future state of the plant (via extrapolation of past and current plant conditions), providing additional time for the operator to address issues. It is also possible to extrapolate past and current sensor data, based on system models and energy balances, to create additional “virtual” sensors that further enhance the operator’s understanding of plant conditions. In terms of improving the conduct of operations, the introduction of technologies that improve procedure implementation can provide numerous technical benefits, such as ensuring that operators correctly transition from different plant procedures based on plant conditions by validating the entry conditions, and automatically presenting the correct procedures to the operator. These technologies can also improve the communication interface between control room operators, plant support (i.e., field operators), and management systems. Finally, all of these technologies are designed with the philosophy of providing richer information in a more intuitive manner that improves the operator's comprehension of changing plant conditions.

With respect to the second question in our value chain (i.e., What would that result in in terms of plant outcomes?), the technical benefits described above would result in fewer safety challenges to the plant due to operators failing to detect and correctly diagnose off-normal conditions. That is, operators would be able to more quickly respond to plant transients, thereby minimizing the severity of the plant's deviations from normal operating parameters. The inclusion of these advanced monitoring and diagnosis technologies allows operators to focus on other ancillary duties with less concern that they are not maintaining adequate vigilance over the plant's state, and could lead to some reduction in the number of operations support staff (i.e., field operators). These control room technologies can also provide indications of the plant's state to field operators and other support staff outside of the control room, thereby facilitating the dissemination of information to key support personnel without burdening control room operators with the task of communicating this information. Overall, these technologies will result in fewer time-critical actions by both control and field operators.

The results mentioned previously would manifest themselves in business or KPIs. There are a number of industry standard KPIs that would be affected by the aforementioned technological enhancements, including a higher capacity factor, reduced forced loss rate, reduced organizational and management (O&M) costs, reduced radiation exposure to plant staff, and improved ratings from the U.S. Nuclear Regulatory Commission and Institute for Nuclear Power Operations. Figure 1 summarizes the value chain presented for advanced control room technologies.

Human Factors Technical Improvements

- Reduce operator workload and mental burden.
- Automate sequences of activities to reduce tedious manual control and associated human error.
- Assist the operator in integrating plant information to make diagnosis of plant upsets.
- Provide operators with early warnings of trends by validating them far below the alarm setpoint. This buys considerable time to deal with conditions.
- Provide accurate forecasts of where the plant will be at future times based on the extrapolation of plant conditions and the expected response of plant systems.
- Provide virtual sensors based on system models and energy balances. This will greatly augment the data set available to the operators.
- Ensure correct transition to plant procedures based on plant conditions. Automatically present the procedures to the operator, validating entry conditions.
- Provide a seamless interface to plant support work and management systems.
- Provide richer information in graphical forms that increases the operators' rate of acquiring an understanding of changing plant conditions.

Operations Performance Improvements

- Fewer safety challenges due to operators failure to detect off-normal conditions.
- Quicker responses to plant transients resulting in less severe plant deviations and better outcomes.
- Allow operators to perform ancillary duties without concern on ineffective plant monitoring. Could allow reduction of some Operations support staff.
- Greater throughput of support work when Operations can be more responsive and certain plant work activities can proceed without control room interaction.
- Fewer time-critical operator actions.

Improved Key Performance Indicators (KPIs)

- Higher Capacity Factor.
- Reduced Forced Loss Rate.
- Reduced O&M Cost.
- Reduced Dose.
- Improved Regulatory Ratings.

Fig. 1. The value chain for advanced control room technologies.

4. Signs of progress

Two examples within the commercial nuclear energy domain provide some preliminary indication that the nuclear industry and human factors professionals in nuclear energy are starting to integrate this value chain paradigm into their R&D activities. The first example is from research INL is conducting with a utility partner to improve the management of NPP refueling outages (St. Germain & Williams, 2014). The utility used new "human factored" technologies to improve organization and information sharing during one of their outages, and as a result, realized significant increases in productivity and reduced costs, primarily through avoiding the expenditure of additional weeks of time in outage.

The second example is from control room modernization research INL is performing in collaboration with a utility partner (Boring, Ulrich, Joe, & Lew, 2015). The utility partner is currently performing an upgrade to three of their NPP's turbine control systems (TCS). In reviewing and testing the design of the new digital TCS at INL for one of the NPPs, the utility's operators discovered through a knowledge elicitation process that repetitive manual control actions associated with increasing and decreasing turbine speed during startup were automated with the new TCS, thereby reducing the tedium of the activity and its associated human error potential. The expectation is that this human factors improvement in the design of the new TCS will lead to broader improvements in operations performance, and ultimately, improved KPIs for the plant.

5. Conclusion

These two examples aside, the field of human factors generally needs to demonstrate its value to complex, socio-technical applied engineering projects more effectively. Anecdotal evidence (Burgess-Limerick, Cotea, & Pietrzak, 2010) and accident investigation reports identifying human errors as root causes only go so far in convincing decision makers how much human factors adds value to these kinds of engineering problems. Even arguments that human factors R&D needs to be more scientifically rigorous and generate objective empirical evidence (i.e., be value neutral) may not be the silver bullet that it was once thought to be. Human factors needs to conduct empirically rigorous R&D, but within the context of the decision makers' value chain. Doing so provides a clearer roadmap for how human factors R&D can achieve greater success in its ultimate implementation in projects that are solving complex, socio-technical applied engineering problems.

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