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LEVELS OF DIGITIZATION, DIGITALIZATION, AND AUTOMATION FOR ADVANCED REACTORS

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Much has been written about levels of automation (LOA), but comparatively little has been written about levels of digitization (LODi) and levels of digitalization (LODa). Digitization is a digital representation of analog information and is typical of migration from analog to digital control systems, digitalization involves enhancing the functionality of digital information, and automation changes control from humans to machines. Each of these technology implementations has its own scales, and each forms a viable type of functionality that should be considered not as a continuum toward automation but rather as separate categories of solutions that meet the needs of advanced reactors. In this paper we develop separate LODi, LODa, and LOA scales and demonstrate how conflation of these technologies, using the example of computer-based procedures, can lead to confusion in the design process. With the race to develop advanced reactors, the surest metric of success and safety is proper consideration of the right technology requirements for different control systems.

INTRODUCTION TO ADVANCED REACTORS

After a relative standstill in nuclear reactor deployment in the U.S., a promised nuclear renaissance (Boring et al., 2008) did not materialize as envisioned. New safety concerns following the Fukushima Daiichi accident coupled with the low cost of natural gas electricity generation dampened the demand for new nuclear power plants. However, renewed interest in zero carbon electricity generation and the prospect of smaller, more cost effective reactors has reenergized interest in nuclear power (Boring, 2023). There are currently dozens of vendors developing advanced reactors. Much of the focus of development to date has been on engineering aspects of this new generation of plants.

DIGITIZATION, DIGITALIZATION, AND AUTOMATION

As advanced reactors are developed, there is a need to resolve the fundamental technologies that are enlisted, especially for control systems that interface with human operators. There remains some confusion of the degree to which digital or even automation technologies are the essential roadmap toward advanced reactor deployment. In this paper, we explore *digitization*, *digitalization*, and *automation* for reactor control room design. Brief definitions of each are provided in Table 1. Note that these definitions refer to specific control system technologies, not organizational or societal attitudes toward technology (Schumacher & Sihn, 2020; Muro et al., 2017). Each of these definitions falls within a continuum of use that we will map out as levels of digitization, digitalization, and automation. These levels should not be confused with digital maturity levels, which tend to map organizational stages of transformation to digital systems and processes. Levels of digitization, digitalization, and automation are measures of the implementation state of technological systems used by personnel, with no assumptions tied to successive maturity. The point of this paper is to demonstrate that digitization, digitalization, and automation are distinct technologies that should be considered independently of each other in designing plant systems.

We acknowledge that analog or manual systems will continue to exist for plant operations, and it is not a goal of this paper to urge toward more digitization, digitalization, or automation, especially where existing solutions have demonstrated successful operability and safety records.

Table 1. Simple definitions of digitization, digitalization, and automation for advanced reactors.

Digitization	Digitalization	Automation
Turning analog information into digital	Enhancing analog information with digital processes	Augmenting human monitoring and control with machines

Digitization

Digitization is simply turning an analog artifact into a digital state, akin to scanning a paper page to turn it into a digital form. A control room can be digitized, such as when taking a three-dimensional laser imaging, detection, and ranging (LIDAR) scan of the control room, which provides a digital record of dimensions within the control room. Another form of digitization is converting analog signals to digital equivalents. Such digitization is the hallmark of control room modernization (Boring, 2014). A traditional or legacy control room in a nuclear power plant consolidates analog gauges and controls that are directly linked to the sensors or actuators in the plant. In a digital control room, this analog information is translated into digital signals that are conveyed through a digital human-machine interface, typically in the form of computer screens and controls.

Table 2 presents levels of digitization (LODi), ranging from analog control rooms (LODi 0), to hybrid control rooms (LODi 3), to fully digital control rooms (LODi 4). Sandwiched between are different levels of digitization not directly manifest in the control room. For example, LODi 1 covers the process of mapping of the plant or control room (e.g., a LIDAR scan as described above). This is a static capture of a physical or analog system. LODi 2 represents turning the analog information into a model, such as in the form of a simulation of a plant system or the simulator of the overall plant. It is understood that Table 2 is imperfect in that it force-fits multiple dimensions at the intersection of physical systems and their controls.

Table 2. Levels of digitization (LODi) for reactors.

LODi	Level	Description
0	No digitization	Entirely analog instrumentation and controls
1	Static digital representation	Computer mapping of analog/physical world (e.g., schematic or LIDAR)
2	Dynamic digital representation	Computer model of analog/physical world (i.e., simulation or simulator)
3	Hybrid digitization	A mix of analog or digital systems (e.g., a legacy control room with upgraded digital islands)
4	Full digitization	A full digital system with a lack of analogy instrumentation and controls (e.g., an end-state control room without any analog instrumentation and controls)

Digitalization

A digitized control room does not expand the functionality of the plant or control room. In contrast, a digitalized control room is one where the instrumentation and controls (I&C) have been migrated to a computerized control system, with functionality added as a consequence of digital capabilities. Digitalization occurs when functionality is transferred from a real-world physical or analog system to a computerized system and goes beyond like-for-like replacement.

Digitalized enhancements to basic digitized functionality are easy to conceptualize for control room upgrades, where there is a legacy system like an existing analog control room that provides a baseline. Analog instrumentation, for example, provides a very simple single measure such as a level or rate. Digitized instrumentation maintains that basic mapping. In comparison, digitalized instrumentation goes beyond these simple one-for-one mappings of physical phenomena and expands on them. It may provide historic information like trends. It may provide contextual information like ranges for specific operating modes (e.g., startup vs. full power) of the plant. It may provide integrated measures like enthalpy, the sum of internal energy and the product of pressure and volume. It may color-code information like alarms to represent the severity of an alarm. It may translate physical information into a form more readily understandable by an operator such as through ecological interface displays. Such information enhances operator performance and represents human factors engineering efforts to arrive at something considerably better than the simplest indicator.

Digitalization is also not an all-or-nothing construct, and there are levels of digitalization (LODa) as depicted in Table 3. LODa 0 encompasses the absence of digitalization, which could overlap with any LODi. The LODa progresses from partially digitalized systems (LODa 1), which coexist with LODi, to fully digitalized systems (LODa 2). A final level (LODa 3) represents the interconnections between different systems, e.g., reactor systems and hydrogen production at a nearby facility.

Table 3. Levels of digitalization (LODa) for reactors.

LODa	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

Automation

Automation involves a machine performing a task on behalf of, complementary to, or instead of a human. *On behalf of* implies that the automation is requested by the human as supervisor; *complementary to* suggests a degree of assistance through human-automation teaming; *instead of* implies that the machine performs tasks without human supervision.

The machine can perform tasks mechanically, which falls within the realm of robotics. The machine can also perform mental tasks like monitoring or making decisions, which is usually the purview of some form of artificial intelligence, such as a trained machine learning algorithm or a programmed production system. While most automation is centered on control, there also exists an equally important consideration of information automation—assisting with gathering information (Parasuraman, Sheridan, & Wickens, 2000; Boring, Ulrich, & Mortenson, 2019).

Fitts crafted an early taxonomy of what machines vs. humans were better at (1951), which helped anticipate what types of processes could be automated. Working within telerobotics, Sheridan and Verplank (1978) famously developed ten of levels of automation (LOA) to describe the different types of interactions between humans and computers, ranging from the human performing all decision making, to varying degrees of shared decision making, to the computer having full autonomy. Note that Sheridan and Verplank were primarily concerned with decision making for control, not the mechanical task of carrying out actions.

LOA has been revisited extensively, including the distilled six-level scale used by the Society of Automotive Engineers (SAE; 2021) to describe driver autonomy: (0) no automation, (1) driver assistance, (2) partial automation, (3) conditional automation, (4) high automation, and (5) full automation, with a primary demarcation between automation supporting human drivers (SAE Levels 0 – 2) vs. automated driving (SAE Levels 3-5).

Albertini et al. (2023) proposed a nuclear specific LOA similar to SAE (see Table 4). We have color-coded the levels to denote supported operations (orange) for LOA 0-2 and automated operations (green) for LOA 3-5. Note that LOA 0 in Table 4 can overlap with LODi or LODa.

Table 4. Levels of automation (LOA) for reactors (after Alberti et al., 2023).

LOA	Level	Description
0	No automation	Manual control by operator
1	Operator Assistance	Operator prescribes the state of a component and automation maintains that state
2	Automation by Consent	Operator prescribes the optimal condition of system and automation maintains that condition under operator supervision
3	Automation by Exception	Automated system performs tactical and operational tasks in limited domains under operator approval with fallback to operator
4	High Automation	Automated system performs tactical and operational tasks in broader domains with some operator fallback
5	Full Automation	Automated system performs tactical and operational tasks in all operational domains with remote supervisory monitoring by operator

Note: In the present paper, we suggest LOA 0–2 are supported activities, while LOA 3–5 are automated.

INTERRELATIONSHIPS

Figure 1 shows the notional relationship between LODi, LODa, and LOA, with the caveat that there is some overlap between each phase of technological implementation as noted previously. Because of either this overlap or definitional ambiguity, there remains some confusion over the relationship between technological implementation categories, especially between digitalization and automation. In many industries, digitalization is viewed as a stepping stone on the continuum toward automation (Muro et al., 2017). We maintain that each technological implementation is a distinct category, not a continuum.

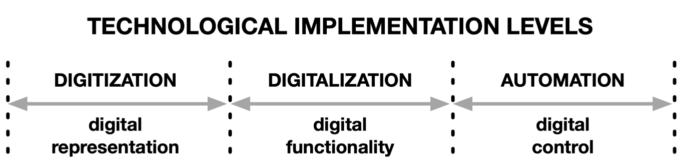

Figure 1. Relationship between different ways of grading digital implementations.

In an attempt to clarify the relationship between LODi, LODa, and LOA and not espouse the inevitability of automation, here we present a new amalgam of concepts. Table 5 presents a crosswalk between types of tasks and performers. The types of tasks consist of macrocognitive functions, following four-stage information processing models proposed by Parasuraman, Sheridan, and Wickens (2000) and Whaley et al. (2016). In a nuclear operations context, human tasks include (1) *detecting* plant status and changes, (2) *understanding* the implications of those plant states, (3) *deciding* on a course of action, and (4) *acting* on that decision. Note that some models of macrocognition delineate further tasks, and most do not culminate in taking action, which can be seen outside the realm of cognition. For the present purposes, the performers are divided into three categories: (1) *human*, meaning the task is primarily performed manually by the human; (2) *shared*, meaning the activities are split in some manner by the human and the machine; and (3) *automation*, meaning the task is primarily performed by the machine. The shared task performer is analogous to "driver supported" in the SAE LOA classification (2021). The taxonomy in Table 5 is called the Advanced Reactor User Guideline Underlying Levels of Automation (ARUGULA), a word play on a nuclear power plant being a "green plant." Similar taxonomies have been used to help understand adaptive automation (e.g., Kaber & Endsley, 2004) and computer-based procedures (O'Hara et al., 2000). A chief advantage of ARUGULA is its simplified categorization relative to reactor operations.

Table 5. Example applications of Advanced Reactor User Guideline Underlying Levels of Automation (ARUGULA).

		Task Performer		
		Human	**Shared**	**Automation**
Task Type	***Detection***	Manual Monitoring	Automated Information Gathering and Alarming	Information Automation
	Understanding	Manual Diagnosis	Operator Support Systems	Anomaly Detection System
	Deciding	Manual or Procedure-Driven Decision Making	Computer-Based Procedures	Control Automation
	Acting	Manual Actions	Soft Controls and Scripted Actions	Control Activation

As noted, digitization such as upgrading an analog control room to digital I&C primarily maintains the same functionality and largely keeps human tasks centered on the human continuing to perform those tasks, just with an upgraded interface. Digitalization shifts functionality to the control system. The operator is supported in their activities while still being primarily in charge of monitoring and controlling the plant. Much current human factors research in nuclear power is based in this area through various operator aids afforded by digital technology. Digitalization goes beyond like-for-like upgrades and adds new functions that aim to increase operator situation awareness and decrease workload.

Finally, there is the shift beyond operator support to actual autonomy. There remains some overlap in technology, e.g., a monitoring system that feeds information to the operator in a shared performer role may instead feed that information directly into an autonomous control system without a human intermediary. Automation is characterized by the absence of a human performer.

LOA is typically considered without the task type. ARUGULA demonstrates the value of considering task type separately from the task performer, because it demonstrates it is possible to have a mixed LOA such as when a human shares monitoring roles (i.e., detection and understanding) yet defers control actions to the automated system. As the next section demonstrates, computer-based procedures (CBPs) present a good example of how not considering separate task types can cause confusion in how to classify CBPs in terms of autonomy.

Example: LODi, LODa, and LOA in CBPs

CBPs—also commonly referred to as computerized operating procedure systems (COPS), digital instructions, and smart procedures, among other terms—take the paper-based procedures that are the mainstay of nuclear operations and turn them into a digital form. There are many types of operating procedures at NPPs, with the simplest delineation being between those procedures for actions carried out in the main control room and those carried out in the field. Field procedures tend to be less detailed and rely more on skill of the craft than control room procedures. Generally, anything that has the opportunity to affect the reactivity of the plant—such as the centralized operation of the plant from the control room—will feature more detailed step-by-step procedures.

Table 6. Capability matrix for computer-based procedures (after IEEE-1786).

	Capability	Computer-Based Procedure Type 1	Computer-Based Procedure Type 2	Computer-Based Procedure Type 3
A	Select and display procedure on computer screen	✓	✓	✓
B*	Provide navigation links within or between procedures	✓	✓	✓
C	Display process data in the body of procedure steps	×	✓	✓
D	Process step logic and display results	×	✓	✓
E*	Provide access links to process displays and soft controls that reside on a separate system	×	✓	✓
F	Provide embedded soft controls	×	×	✓
G*	On operator command, initiate procedure-based automation	×	×	✓

*Features from IEEE-1786 that should be optional

The Institute of Electrical and Electronics Engineers (IEEE) publishes IEEE Standard 1786 (2022), which outlines three types of CBPs, as depicted in Table 6. Put briefly, the three types are defined as follows:

- *Type 1 CBP:* Procedure text appears in digital instead of paper form
- *Type 2 CBP:* Plant indicators are embedded in the procedures instead of requiring the operator to seek the values on indicators outside the procedures
- *Type 3 CBP:* Soft controls are added to the procedure, allowing the operator to control directly from within the procedure, instead of operating separate controls

In the IEEE-1786 classification, each type of CBP adds features to the previous type, i.e., Type 3 includes all capabilities of Types 1 and 2.

Here we expand on the formal explanation in IEEE-1786 by suggesting not all capabilities listed for each type are obligatory to qualify for that type. For example, a Type 2 CBP might include Capabilities C and D but not Capability E. The absence of all capabilities does not disqualify membership in that type. For the present purposes, Capabilities B (Type 1), E (Type 2), and G (Type 3), although included in IEEE-1786, may be considered extended or optional capabilities beyond the basic requirements for that CBP type.

Some research suggests that CBPs provide an optimal testbed for LOA (Jamieson & Skraaning, 2020; Le Blanc, Oxstrand, & Joe, 2015). We fully agree with this suggestion, but we caution that there is the opportunity for conflation between types of CBPs and LOAs. IEEE-1786 is not about automation, and types of CBPs must not be considered synonymous with LOA. Instead, the discussion in this paper provides a better way to understand the CBP types. The obligatory capabilities of Type 1, 2, and 3 CBPs are largely about digitization. Type 1 CBPs represent digital counterparts of paper-based (i.e., analog) procedures. Type 2 CBPs embed indicators into the procedures, and Type 3 CBPs embed soft controls, which are a digital implementation of I&C found elsewhere in the plant. The optional capabilities for Type 1 and 2 (i.e., Capabilities B and E) add new features beyond mere digital representations and can be considered digitalization. In Capability B, we see computerized navigation systems that enhance the functionality of the CBP vs. the paper-based procedure. In Capability E, we see links to additional systems and indications, which similarly add functions beyond the paper form. Capability G, the optional part of Type 3 CBPs, clearly bespeaks control automation.

Table 7. Technological implementation levels by type of computer-based procedure according to obligatory and optional capabilities.

Capabilities	Type 1	Type 2	Type 3	Type 4*
Obligatory	LODi	LODi	LODi	LOA
Optional	LODa	LODa	LODa	LOA

*Suggested new type of CBP beyond IEEE-1786

Jamieson and Skraaning (2020) defined four types of procedures used for their study on degree of automation: paper-based, computerized, semi-automated, and fully automated procedures. The semi-automated procedure is squarely in the optional realm (Capability G) of a Type 3 procedure, while the fully automated procedure encompasses capabilities beyond those described in IEEE-1786. It may be expedient to redefine Type 3 so that it more fully includes LOA capabilities. However, a more far-reaching change would be to add a Type 4 CBP that centers on automation. Such an approach would concur with the four types of CBPs suggested in NUREG/CR-6634 (O'Hara et al., 2000), an important forerunner guidance document to IEEE-1786. Automation could be defined obligatorily in terms of batch step execution capabilities vs. optionally in terms of capabilities that span the remaining possibilities of automation described in Table 4. Like the bifurcation between supported and automated in the SAE LOA standard, obligatory would encompass features of "operator support," while optional would be "automated operations." Further delineation of operator and automation roles may be aided by the use of task types in ARUGULA. Table 7 provides a crosswalk that frames CBPs in terms of LODi, LODa, and LOA. We believe such a framing provides a systematic way to account for CBPs when technological implementation decisions are made for advanced reactors. There is a strong case to be made for Type 4 CBPs that systematically consider LOA.

DISCUSSION

The distinction between LODi, LODa, and LOA matters for a number of reasons:

- Each scale denotes a distinct type of technological implementation that should be considered independently—not as a necessary continuum—for new reactors. The technology and human readiness (Human Factors and Ergonomics Society, 2021) for each technology may vary, and it is important for advanced reactor timelines and licensing to be able to design for the needed—not the desired—technology. Automation is not inevitable nor necessary for all aspects of new reactors.
- Conflation of technological implementation levels (e.g., confusing digitalization and automation) may defeat true advances, as leapfrogging technologies may prove more failure-prone than advancing a level within a technology.
- There are different usability challenges and human error traps for each technological implementation, and it is important to understand the technology scope to properly risk-inform it. This is essential in safety critical domains like advanced reactors.

Ensuring a proper consideration of digitization, digitalization, vs. automation is essential to the success of advanced reactors. In this paper, we have provided several novel scales (i.e., LODi and LODa) and a taxonomy (i.e., ARUGULA) that clarify technology implementations for control systems. Clear categories can aid decision makers on needed and mature vs. unneeded and immature technologies. The categories may also prevent confusion in adopting new features of existing technologies such as CBPs.

The authors believe that near-term solutions such as digitalization may drive human factors research toward advanced reactor deployment quicker than long-term solutions like automation. This does not obviate the importance of automation research; in fact, it stresses the importance of doing such research to support future reactors. Regardless, digitalized solutions are needed now.

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