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A Graded Approach to Simulators: Feature Requirements Mapping to Simulator Types for Nuclear Plant Control Room Research Use Cases

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ABSTRACT

Simulators function as test platforms for validating a broad spectrum of nuclear power plant operations. This spectrum encompasses tasks ranging from updating existing control rooms to fundamentally designing new ones, incorporating innovative operational concepts. The Simulator Feature Framework introduces a generic list of features to ensure that future simulators facilitate research endeavors that cater to both immediate plant modernization needs and the future deployment of advanced reactors (Gideon and Ulrich, 2023). Conducting research via control room simulators requires different simulator types, each varying in fidelity. Integrating the complete set of features outlined in the Simulator Feature Framework into all simulator types could escalate acquisition costs and decrease their commercial appeal for research purposes. A nuanced strategy is required to align simulator types with specific features that adequately underpin the intended research applications. This paper maps five simulator types to the feature categories within the Simulator Feature Framework. By connecting feature categories with simulator types, simulator vendors can incorporate capabilities suitable for distinct simulator tasks without obligatory inclusion of all features. This graded approach harmonizes the cost of simulator acquisition with the anticipated research benefits. Moreover, this alignment equips researchers with a foundational standard for assessing simulators' compatibility with research objectives across varying levels of fidelity. Two use cases are provided to consider simulators for advanced control room development and human reliability analysis data.

Keywords: Simulator-based research, Simulator types, Main control room, Nuclear power plant

INTRODUCTION

The light water reactor (LWR) is the predominant design of nuclear power plants (NPPs) in the U.S., with most plants commercialized between the early1970s into the early 1990s. The U.S. Nuclear Regulatory Commission (NRC) has granted operating license extensions from the original 40 years to enable continued operation for another 20–40 years (Boring et al., 2013). Control room modernization is critical to support nuclear plant life extension. The U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) program supports general research to enable plant life extension and control room modernization. Digital instrumentation and control technologies play a significant role in control room modernization. Therefore, the DOE LWRS program supports research to enable enhancement and outright replacement of control rooms.

Overcoming heavy upfront capital investment for building nuclear power plants and the negative public perception towards nuclear safety are the primary drivers of new advanced nuclear reactor designs. Advanced nuclear reactors are nuclear fission reactors with significant improvements over the most recent generation of nuclear fission reactors (Arostegui and Holt, 2019). The basis of improved advanced reactors includes enhanced safety, security, waste management, and versatility, as well as reduced reactor size and development cost. The Bipartisan Infrastructure Law (BIL), adjudged the single most significant investment commitment of the U.S. federal government to energy system modernization and decarbonization (Steinberg et al., 2023), is a recent example of legislative policy support to overcome investment barriers to clean energy research and development. With nuclear energy as the largest source of carbon-free electricity in the U.S., developing advanced reactors and modernizing existing nuclear power plants to support life extension will be critical to ensuring BIL programs yield the expected return on investments.

Simulators serve as testbeds for validating broad aspects of operations ranging from modernizing existing control rooms to the outright design of new ones using novel concepts of operations. The need for empirical research on the safety and efficiency of control room modernization and advanced concepts of operation is a critical imperative. Hence, simulators with adequate capabilities are needed to support control room simulator-based research. Here, research refers to both academic human-in-the-loop studies to explore control room concepts and applied operator studies that validate features of control rooms being deployed.

The Simulator Feature Framework is an initial effort to develop a generic list of features to ensure future simulators enable research to support immediate and future plant modernization and advanced reactor deployment needs (Gideon and Ulrich, 2023a). Results from a preliminary validation study show the Simulator Feature Framework's effectiveness as a baseline for assessing the functionalities of simulators in NPP control room research (Gideon and Ulrich, 2023b). However, control room simulator-based research requires different types of simulators with varying levels of fidelity. Designing all types of simulators to include the entire feature set specified in the Simulator Feature Framework may increase the acquisition cost and decrease their commercial appeal for research purposes. There is a need for a graded approach to map simulator types to specific features adequate to support intended research use cases. In this paper, five types of simulators are characterized and mapped to specific feature categories of the Simulator Feature Framework.

TYPES OF SIMULATORS

Simulators mimic real processes in part or in full using devices to represent the physical, dynamic, operational, and decision-making elements of the modeled system (Stanton, 1992). Three common characteristics of simulators include an attempt to represent, control, and omit non-essential elements of a real system (Gagne, 1962). The fidelity of a simulator refers to its degree of similarity to the simulated equipment. There are two dimensions of fidelity, namely physical fidelity, and functional fidelity (Stanton, 1996). Physical fidelity, sometimes referred to as the simulator scope, is the degree to which the simulator looks like the real equipment. Functional fidelity is the degree to which the simulated equipment acts like the operational system. Physical and functional fidelity may be conceptualized as breadth and depth of representation of the original equipment, respectively. The breadth of representation refers to the number of systems of the real equipment included in the simulation. The depth of representation is the degree to which a represented system behaves like the real operational system. Breadth and depth of representation are orthogonal dimensions and may be combined to varying degrees in different types of simulators.

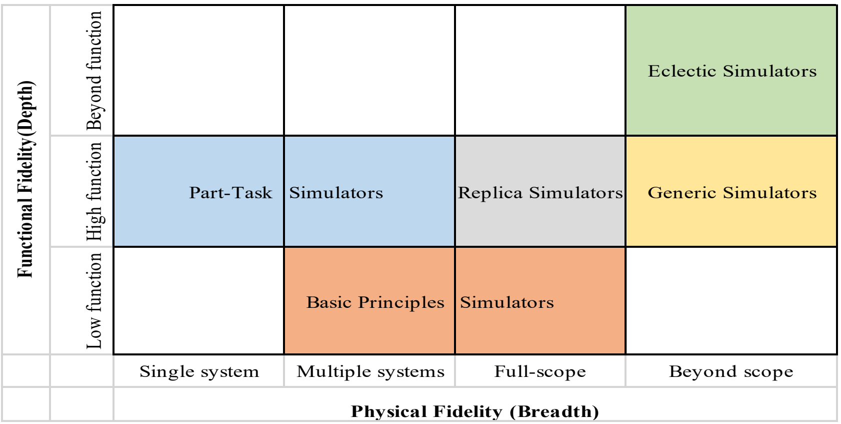
There are five major types of simulators based on the degree of representation of the real world (Clymer et al., 1981):

- *Replica simulator:* A replica simulator has full scope and high functional fidelity. This type of simulator is an exact representation of the human-machine interface (HMI) of a specific NPP control room with corresponding multisensory environmental elements. Replica simulators go by other names, such as plant-specific, full-scope, full-scale, or full-task simulators.
- *Generic simulator:* A generic simulator has a high level of functional fidelity but has physical systems representative of a generic class of simulators rather than a replica of a given plant control room design.
- *Eclectic simulator:* An eclectic simulator is closely representative of a specific NPP control room but includes non-representative features. It has physical and functional fidelity that goes beyond that of the specific control room that it represents. For this reason, eclectic simulators are also referred to as other-than-full-scope simulators.
- *Part-task simulator:* A part-task simulator represents only specific tasks relevant to aspects of a given plant operational system. For example, a part-task simulator may exist for demonstrating a subsystem of the plant such as the turbine control system. Part-task simulators have a low level of physical fidelity and a high level of functional fidelity.
- *Basic principles simulator:* A basic principles simulator demonstrates fundamental plant behavior as an overview. A basic principles simulator depicts high-level system functions via plant overview displays showing operating modes of the main plant systems only, with little or no detailed representation of underlying systems. These types of simulators have a high-level of physical fidelity and a low level of functional fidelity.

The characterization of the five types of simulators may be expanded to include graded levels of physical and functional fidelity (see Table 1). Contemporary simulators primarily consist of underlying software simulation models driving the HMI. The software models may range from reduced order models (ROMs) to full physics-based simulations. Boring et al. (2023)

highlight that simulators are fundamentally different from simulations in that simulators are designed for training with human operators, requiring synchronous interactivity between operators and models. Simulations are primarily asynchronous models that do not respond to real-time emerging contexts and are not suitable for training purposes. Synchronous interactivity with operators is a requirement for simulators.

Table 1. Types of simulators based on a graded level of physical and functional fidelity.



Functional Fidelity (Depth)		Physical Fidelity (Breadth)			
		Single system	Multiple systems	Full-scope	Beyond scope
	Beyond function				Eclectic Simulators
	High function	Part-Task	Simulators	Replica Simulators	Generic Simulators
	Low function		Basic Principles	Simulators	

REQUIREMENTS MAPPING TO SIMULATOR TYPES

The Simulator Feature Framework is an initial effort to develop a generic list of features to ensure future simulators enable research to support immediate and future plant modernization and advanced reactor deployment needs (Gideon and Ulrich, 2023a). The framework is comprised of eight feature categories and thirty supporting capabilities developed by reviewing published simulator-based research. The reader is referred to Gideon and Ulrich (2023a) for more in-depth discussions of the simulator features. This section highlights a graded approach that maps simulator types to specific features of the Simulator Feature Framework (Table 2). Designing all types of simulators to include the entire feature set specified in the Simulator Feature Framework may increase the cost of acquisition and decrease their commercial appeal for research purposes. A graded approach to map simulator types to specific features adequate to support intended research use cases presents an opportunity to tailor simulators to the diverse research needs of users. Mapping feature categories to simulator types enables simulator vendors to include capabilities adequate for different simulator types without necessarily including all features, thereby making simulator acquisition cost commensurate to intended research benefits.

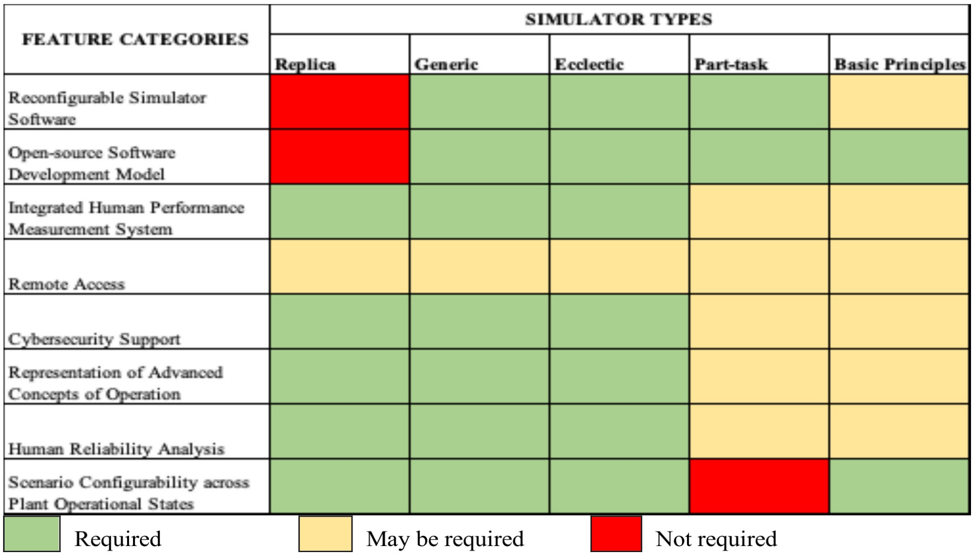
RESEARCH USE CASE MAPPING TO FEATURE CATEGORIES

For the sake of this paper, research use cases mapped to two simulator feature categories are discussed: representation of advanced concepts of operation and human reliability analysis (HRA).

Representation of Advanced Concepts of Operation

Contrary to projections in the wake of the nuclear renaissance of the early 2000s, nuclear power output as a percentage of global electrical energy generated has declined from 17.5% in 1996 to 10% in 2019 (Schneider and Froggatt, 2020). Traditional nuclear power plants are economically less competitive than alternative carbon-neutral energy sources such as renewables. The combined effect of the fitfulness of renewable energy sources and a lack of cost-effective storage systems presents an opportunity for nuclear energy as a complementary counterpart. However, substantial upfront capital investment cost and the inability of nuclear power plants to ramp power generation up and down in response to grid dynamics (i.e., load following) continues to pose significant economic barriers. NPP vendors and utilities are responding to this challenge with greater plant flexibility, including non-electrical uses during periods of reduced grid demand.

Table 2. Feature requirements mapping to simulator types.



FEATURE CATEGORIES	SIMULATOR TYPES				
	Replica	Generic	Eclectic	Part-task	Basic Principles
Reconfigurable Simulator Software	🟥	🟩	🟩	🟩	🟨
Open-source Software Development Model	🟥	🟩	🟩	🟩	🟩
Integrated Human Performance Measurement System	🟩	🟩	🟩	🟨	🟨
Remote Access	🟨	🟨	🟨	🟨	🟨
Cybersecurity Support	🟩	🟩	🟩	🟨	🟨
Representation of Advanced Concepts of Operation	🟩	🟩	🟩	🟨	🟨
Human Reliability Analysis	🟩	🟩	🟩	🟨	🟨
Scenario Configurability across Plant Operational States	🟩	🟩	🟩	🟥	🟩

🟩 Required 🟨 May be required 🟥 Not required

In the U.S., the combined effect of the high demand for electricity and the quest for clean energy gives the impetus to maintain the existing fleet of NPPs. At the same time, efforts continue to ramp up toward more effective and economically viable designs in the form of advanced reactors. Economic competitiveness is at the core of most advanced reactor designs, including enhanced safety, security, waste management, versatility, and reduced reactor size and cost. In particular, reducing the size of reactors will enable offsite assembly, thereby driving down upfront capital investment costs. Process automation and remote operations, common operational features of advanced reactors, are anticipated to reduce staffing costs and operational overhead significantly. Ultimately, reduced capital investment and operational cost, which constitute significant cost drivers in nuclear energy economics, will shorten investment break-even time and bolster the economic competitiveness of smaller-sized reactors. Small modular reactors (SMRs), microreactors, and fission batteries are advanced reactor designs with significant size reduction. Several other advanced reactor designs are in the works (International Atomic Energy Agency, 2020) with capabilities to use nuclear steam as process heat for industrial processes like hydrogen production (Ulrich et al., 2021a), load following, and diverse novel capabilities creating the groundwork for integrating advanced reactors into a modernized national electricity generation system.

There is a major shift in the concepts of operation of advanced reactors in many dimensions. Boring (2023) highlighted eleven major changes in the concepts of operation of advanced reactors and the shift in the role of operators. Unfortunately, the human factors component of advanced reactor control room design has not received as much attention as core technology. Given the limited budget of reactor vendors, which include many new start-ups, it might seem plausible from a business point of view to prioritize reactor technology design above and beyond human factors engineering (HFE), deferring the development of control room concepts of operation to support these advanced reactors to the later stages of the design process. The potential long-term cost of deferring the design of advanced concepts of operation may outweigh the perceived benefits driving such a development approach, as the cost of addressing HFE deficiencies at a later stage may be substantial. The focus, then, should be how to balance the parallel design of advanced reactors and their supporting concepts of operation cost-effectively.

A graded approach to simulators presents an opportunity for parallel and iterative design verification of control concepts, preventing potential costs associated with rework during late development and licensing applications. Basic principles simulators may serve as effective tools for verifying advanced concepts of operations in the early phase of advanced reactor development in a cost-effective manner while deferring integrated system validation (ISV) using full-scope simulators to later stages. For example, the Rancor Microworld Simulator, a ROM basic principles nuclear control room simulator, has been demonstrated to be effective in supporting basic human factors and reliability research (Ulrich, 2017). In an ongoing effort at Idaho National Laboratory (INL), Rancor is supporting the development and verification of advanced reactor concepts involving extraction of excess nuclear heat through a thermal power dispatch (TPD) system to support a secondary industrial process such as hydrogen production (Ulrich et al., 2021b). Further down the development life cycle, the full-scope simulator at the Human System Simulation Laboratory (HSSL) at INL may be used for operator-in-the-loop ISV on a much larger scale. Using a graded simulator categorization scheme enables reactor vendors to choose different simulator types containing unique features required to support the development and verification of advanced concepts of operation across the entire development life cycle of advanced reactors.

Figure 1 illustrates a continuum of control room development activities that make use of simulators (Boring, Ulrich, & Lew, 2022). At the conceptual or formative phases of development (i.e., the so-called As Low As Reasonable Assessment or ALARLA phase), the main goal may be to derive qualitative insights to inform the early design. This phase can generally make use of a low fidelity simulator. Appropriately, a low fidelity simulator can be more easily developed, ensuring control room design can be developed early in parallel with design engineering activities. At the other end toward the completion of design activities (i.e., the so-called Nuclear Oriented Detailed Operator-System Evaluation or NODOSE phase), high functional and physical fidelity are necessary to support quantitative validation activities. Overall, the simulator serves as a prototype for the control room, and the design phase determines the requirements for the simulator.

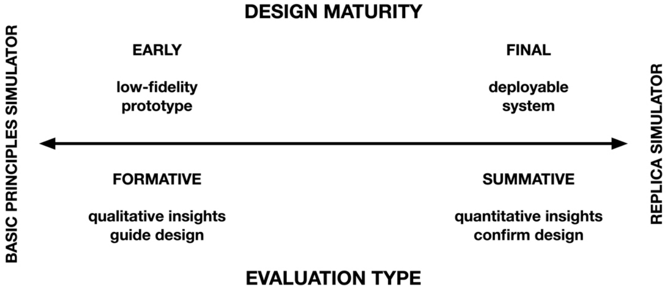


Figure 1: Design maturity vs. evaluation type (after Boring, Ulrich & Lew, 2022).

Simulators for Human Reliability Analysis

Collecting operator performance data is an essential activity for HRA modeling to understand the evolution of operator actions during event scenarios and to establish error rates for such actions. Despite the importance of data, such data have been elusive to collect. One challenge is the need for large samples of operators for typically low-frequency events. For example, an HRA method may predict a human error probability (HEP) equal to 0.001, meaning an error is posited every 1000 occurrences of a task. To validate this HEP, does that mean collecting data on 1000 runs of operators in a simulator to expect to see the error occur organically? Does it mean running 1000 crews of operators? Both would require extensive and unrealistic data collection efforts. Another approach to reduce the sample size is to seed an error (Boring et al., 2016) by setting up a context that more frequently leads to errors, potentially introducing confounds in the data and removing the goal of measuring organic errors.

Two large-scale data collection efforts exist for such purposes, among smaller efforts (Chang et al., 2022). The U.S. Nuclear Regulatory Commission leads a research effort called Scenario Authoring, Characterization, and Debriefing Application (SACADA; Chang et al., 2014) that collects operator performance data from NPP training simulators. Training objective elements (TOEs) are defined by the trainers at the plants and then classified as human errors when they are performed in an unsatisfactory manner. In addition to classifying TOEs as successful or erroneous outcomes, additional contextual information like performance influencing factors is cataloged, allowing mapping between contexts and error outcomes. By aligning with routine training, SACADA serves as a way to collect data over time, and human performance data are logged in a database to establish HEPs according to specific operational contexts.

Another large-scale HRA data collection effort is undertaken by the Korea Atomic Energy Research Institute. The Human Reliability data Extraction (HuREX; Jung et al., 2020) framework collects data from various full-scope training simulators in South Korea. The process of collecting data involves analysts reviewing video recordings, simulator logs, questionnaires, and operating procedures. Procedural tasks are classified according to a cognitive framework that ultimately catalogs basic human actions, contextual influences, and error rates.

Chang et al. (2022) compares some of the tradeoffs of SACADA and HuREX. SACADA is suitable for integration into plant training, but its data may exhibit some inconsistencies due to how training personnel subjectively categorize the TOEs and errors. HuREX, in contrast, has greater data consistency because of its use of a team of highly trained analysts to record the data. However, this process is labor intensive and best suited for specific research topics rather than long-term data collection. For example, HuREX has been used extensively for collecting human performance data specific to digital control interfaces in NPP control rooms. For both SACADA and HuREX, there is the challenge that the data collected do not match the traditional unit of analysis in HRA, namely, the human failure event (HFE). Rather, the data are more fine-grained at the task level. This challenge has been previously identified as an issue (Boring, 2014) in the emergence of dynamic HRA approaches like the Human Unimodel for Nuclear Technology to Enhance Reliability (HUNTER; Boring et al., 2022). Dynamic HRA, which uses simulation approaches, operates at the task rather than the HFE level. While there are challenges translating simulator data efforts like SACADA and HuREX to HFEs used in conventional HRA, these data sources are actually perfectly suited to dynamic HRA applications.

From a simulator perspective, both SACADA and HuREX are challenged by the use of full-scope simulators with operating crews. While this approach clearly produces the most generalizable results, it also remains data-limited in the complexity of collecting large data samples. As of 2022, SACADA and HuREX had collected approximately 18,000 and 45,000 data points, respectively (Chang et al., 2022). These data are a tremendous asset toward validating HEPs. However, it is possible to collect more data by simplifying the simulator to allow student operators, such as in a recent study using the Rancor Microworld Simulator. For example, a single study involving 20 students and 20 operators collected 16,675 human performance data points (Park et al., 2022a), which have subsequently been used to inform the modeling of scenarios in the HUNTER framework and to validate results (Park et al., 2022b). While there remain differences between the HRA data generated by the simplified simulator vs. the full-scope simulators, understanding the possibility of having different types of simulators for HRA research holds considerable promise toward collecting the data necessary to validate HEPs, overcoming the decades-old challenge of data paucity in the field.

CONCLUSION

It is important to remember that not all simulators are used for research. The majority of simulators in NPPs are used for training of reactor operators. However, there is a strong need for research applications, from first principles research on human-system interaction in control rooms to design validation work for control room modernization or advanced concepts of operation. Some research will support training development and design objectives, while other research may support larger research questions like the causes and frequency of human errors in complex operational contexts. Accordingly, there is no one-size-fits-all solution to simulators for research needs. The Simulator Feature Framework helps to classify different simulator requirements to ensure that the simulator type is commensurate with the ultimate research need. This alignment ensures that research is not forestalled due to the unavailability of the perfect simulator solution. It also helps to ensure that simulator costs can be kept in check appropriate to the type of research activity being performed. The two use cases provided in this paper illustrate the graded approach for simulator use in research. The first use case demonstrated how different types of simulators support different stages of control room development, from lower fidelity during the formative stages to full-scope during the final design evaluations. The second use case showed how different simulators could be used to address the tradeoffs of data collection for HRA. A major takeaway is that simplified simulators are of particular value in areas where using full-scope simulators is not cost-effective, realistic, or otherwise practicable.

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