Digital Twin Applications for Advanced Reactors: Summary of EPRI 3002023904 and Ongoing Industry Efforts

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ABSTRACT

To ensure successful construction and operation of future nuclear power plants in the current Unites States (US) energy market, overnight construction costs (OCC) and operations and maintenance (O&M) costs must be significantly reduced. A variety of industry initiatives have identified Digital Twin (DT) technology as a key opportunity to achieve such cost reductions. While DTs are becoming increasingly popular in the non-nuclear industry, adoption of DT technology in the nuclear industry has lagged to date, partly due to uncertainties resulting from the unique regulatory environment and initial capital investments compared to other industries. The goal of this Electric Power Research Institute (EPRI) project was to complement ongoing industry efforts to research DT applications and provide guidelines to support stakeholders in understanding and adopting DT technology and its maturity stages (Figure 1), with a focus on advanced reactors (ARs). To that end, this project explored potential benefits, challenges, capabilities, and use cases of DTs across the AR lifecycle by performing an in-depth literature review of AR DT applications and engaging stakeholders to summarize the industry perspective and lessons learned in recent years. Main contributions of this EPRI project included:

- Develop a list of DT use cases relevant to ARs, identify criteria that could be used to evaluate and prioritize them, and then use those criteria to select two use cases to further develop in this study: construction sequence simulation and predictive maintenance.
- Provide a framework for DT development, illustrate the development processes for two selected uses cases, and provide use-case-specific observations, best, practices, and recommendations.

The research findings are documented in the publicly available EPRI 3002023904 report (EPRI, 2022). This paper provides a brief overview of the main steps of the project and summarizes the key insights, best practices, and areas of future research identified.

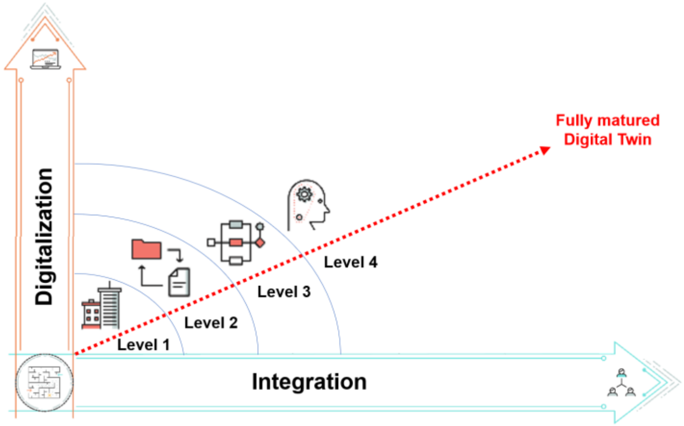

Figure 1. Digital Twin Maturity Trend.

RESEARCH CONTEXT

This project is part of EPRI's Advanced Nuclear Technology (ANT) program, whose mission is to reduce the risk and uncertainty of constructing and operating new nuclear power plants. According to EPRI 3002015935 (EPRI, 2019), nuclear power could become a more financially attractive option if cost saving solutions were developed to address the five top cost drivers identified in that report. Figure

2 shows the top five cost drivers and the ongoing ANT research activities initiated to address them. The figure identifies DTs as a potential solution to mitigate construction duration, which was found to be the most significant cost reduction strategy in EPRI 3002015935 (EPRI, 2019). DTs have potential applications in each of the other top cost-driving areas and can help reduce OCC, which makes up approximately 60% of the levelized cost of electricity (LCOE) of nuclear plants. DTs also have potential to reduce O&M costs, which are responsible for another 15-25% of LCOE (EPRI, 2019). One of the principal motivations for this project was thus to investigate how DT technologies can contribute to the overall nuclear industry's goals of reducing OCC and O&M costs, while focusing specifically on AR applications. The study is one of many EPRI initiatives (Figure 2) that share the same principal motivation of investigation ways to make nuclear power attractive compared to other sources of power generation.

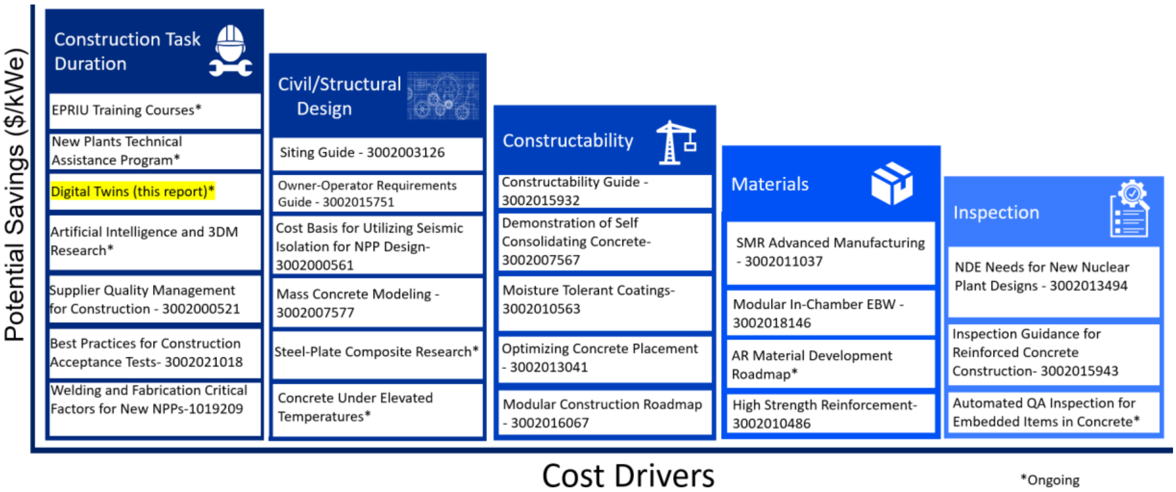

Figure 2. Ongoing research within EPRI's Advanced Nuclear Technology program (EPRI, 2019).

DIGITAL TWIN DEFINITION

The concept of DT originated in the 1970s in the US space and aerospace sector. In simple terms, a DT is a digital representation of a physical asset or process used to monitor, simulate, predict, and/or control its behaviour. Many assert that a DT must also collect data about the physical asset or process to update the digital representation, while others contend this physical-to-digital connection is not essential to DTs. A simple example that includes the data collection element could be a pump instrumented with various sensors that provide real-time input to a digital model used to predict component wear. An example of a DT without the data collection element could be a 3D CAD model of a site excavation used to simulate the construction sequence prior to breaking ground. Many research groups have attempted to develop a comprehensive definition of DTs, and new definitions will continue to emerge over time, across different industries, and as new DT applications are identified. Dr. Grieves's conceptualization of DT (Grieves, 2016) is perhaps one of the most helpful. He observed that, as technology matures, digital models tend to become more detailed and accurate, more integrated with each other, and more integrated with their physical counterparts. He conceived of a DT as the end state of this trend in which models are sufficiently detailed, comprehensive, and integrated with their physical asset that they will be able to provide the same useful information that could otherwise be obtained by examination or testing of the physical asset. This concept is illustrated in Figure 1, in which DT maturity is represented as a result of increasing integration and digitalization levels. Figure 1 divides the "space" of integration and digitalization into four "maturity levels," which can be conceptualized, for instance with the four analytics maturity categories covered in Kuhn et al. (2018): description, diagnostic, predictive, and prescriptive. This conceptualization is helpful because it clarifies that each evolutionary step toward producing more detailed, accurate, and integrated digital representations is a productive step toward realizing the potential benefits of DTs. It also helps to redirect effort away from unproductive attempts to develop a universal definition for DTs because it clarifies that there is no one unique definition, but rather a spectrum of potential DT manifestations and corresponding definitions.

DIGITAL TWIN PURPOSE AND NUCLEAR INDUSTRY ADOPTION OUTLOOK

A DT provides insights into various aspects of the asset or process (e.g., performance, efficiency, operations and maintenance cost) without affecting its operation or state (e.g., no downtime needed for offline inspection or testing). This capability can be leveraged to achieve a variety of benefits, for example:

- Faster deployment of new assets and systems.
- Improved operational efficiency and reliability.
- Optimized allocation of resources and manpower.
- Refined maintenance schedule.
- Reduced design, construction, operation, maintenance, and decommissioning costs.
- Improved integration of industrial systems.
- Better-informed decision making.
- Reduced exposure to high-risk environments (e.g., high radiation areas).

With the above potential benefits, in the past two decades DTs have been able to demonstrate value and have been rapidly gaining attention in the commercial industries. The trend has been fueled by rapid advancements in digital technologies such as artificial intelligence (AI), augmented reality (AuR), data science, distributed computing, and internet of things (IoT). Today, many industries are successfully employing such technologies for advanced system controls, autonomous operations, and predictive maintenance programs, which are often mentioned by AR stakeholders as important strategies for reducing OCC and O&M costs of future reactors. Example of industrial DT applications include aircraft and automobile manufacturing and fleet control, metal additive manufacturing, logistic and supply chain management, port loading operations, gas and wind turbine service optimization, and environmental monitoring. While many AR stakeholders are hopeful that existing and emerging DT technologies could help catalyze adoption of such strategies in the nuclear industry, the nuclear industry has only recently begun to recognize the untapped potential for DTs to achieve efficiencies over the entire lifecycle of an NPP. The next generation of ARs presents a unique opportunity to reap the potential benefits of DTs for multiple reasons:

- Recent technological advances are enabling an increasing number of DT applications and are driving the DT development and implementation costs down.
- Since ARs are still under development, they have less logistical inertia than the current existing nuclear power plant (NPP) fleet in adopting and integrating new technologies like DTs. Early adoption of DTs into the AR design phase could lay the groundwork for significant cost savings and benefits over the course of the full lifecycle.
- Many AR designs include harsh environments that could place new constraints on access by operations and maintenance personnel (e.g., very high radiation areas, extreme operating temperatures); DTs could provide “virtual access” to the plant without exposure to the extreme environments, thereby enabling safe operation of these novel plant designs.
- Regulatory frameworks for ARs are still under development across the world and could evolve to facilitate the adoption of DT technologies in AR designs.

Consequently, there may be a more favorable regulatory perspective to the adoption and use of DTs for ARs than for the current operating fleet, as evidenced by the recent US Nuclear Regulatory Commission (NRC) and Department of Energy (DOE) activities to promote knowledge sharing across industry stakeholders through a series of workshops, publications, and grants dedicated to DTs in ARs (e.g., USNRC (2020, 2021a, 2021b, 2021c), USDOE (2019)).

While momentum in the AR industry is building, some gaps are slowing the adoption of DT technology. Perhaps the most impactful gaps include the lack of a common conceptual framework, scarcity of business cases, limited diversity of existing DT use cases, and uncertainties in technology readiness and regulatory impact. Early nuclear DT studies have also indicated a need to adopt a “transformative approach” to successfully incorporate DTs in ARs, as new systems and processes will be required to implement the DT. For example, necessary DT hardware might impose requirements on the plant structural design that would not otherwise exist. Conventional workflows will likely need to be transformed as new DT development strategies are established.

To complement ongoing industry efforts and provide specific guidelines for AR stakeholders to understand and adopt DT technology, this EPRI project explored potential benefits, challenges, capabilities, and possible use cases of DTs across the various NPP lifecycle stages: Design, Construction, Commissioning, Operations, Maintenance, and Decommissioning. The project aimed to document best practices and establish recommendations for leveraging the advancement in DT technologies, with the goal of helping the industry answer the question related to the "added value" of DT technology adoption in nuclear projects, particularly in ARs. This paper focuses on a subset of the topics discussed in the EPRI 3002023904 and summarizes two of the main contributions of the report: 1) develop a list of DT use cases relevant to ARs, and 2) propose a generalized framework for AR DTs. The conclusions section provides a useful list of the main takeaways from this research study.

INDUSTRY PERSPECTIVE

This study began with a review of relevant literature and a series of industry engagement activities including interviews, workshops, and formation of a Technical Advisory Group (TAG). The TAG included participants from utilities and AR developers, including General Electric Hitachi (GEH), Kairos Power, Rolls-Royce, Terrapower, Southern Nuclear, X-Energy, and OPG. The industry engagement helped the research team develop an intimate understanding of the AR industry's interests, needs, perceived opportunities, and pain points, as well as the status of ongoing DT-related activities. The main talking points identified from the TAG interactions are discusses in Section 2.5 of EPRI 3002023904. Such interactions were instrumental to identify useful AR DT use cases and define the generalized AT DT framework.

IDENTIFICATION, EVALUATION, AND PRIORITIZATION OF USE CASES FOR ARs

Appendix A of EPRI 3002023904 (EPRI, 2022) provides a list of twenty-nine DT use cases relevant to ARs compiled during this research project. Although many use cases certainly have applicability across several NPP lifecycle stages, each use case is nevertheless classified by the lifecycle stage to which it is considered most applicable, as shown in Table 1.

Table 1. AR Use Cases Compiled in Appendix A to EPRI 3002023904 (EPRI, 2022)

Lifecycle Stage	**No. of Use Cases**
Design	4
Construction	4
Commissioning	2
Operations	11
Maintenance	6
Decommissioning	2
Total	**29**

For each use case, Appendix A to EPRI 3002023904 provides the following:

- A brief description of the use case, including the intended functionality and objectives, and references to related research and development efforts in the literature.
- The use case application area(s), which can be one or more of the four broad areas defined in EPRI 3002020014 (EPRI, 2020): Informed Decisions, Design Optimization, Configuration Management, and Health Monitoring.
- The target benefits of the use case.
- High-level requirements to successfully implement the DT.

Each TAG member was invited to assist in identifying the cases that were the most attractive and beneficial for AR technologies. TAG members were asked to consider example issues and DT characteristics such as technology readiness, utility/values, scalability, regulatory certainty, and AR applicability. The use cases were evaluated by the TAG to help the research team prioritize two cases for further development in the research project. Based on the TAG feedback and a few follow-up interviews with TAG members, the research team developed a use case evaluation framework (detailed in Section 3 of EPRI 3002023904) and selected two cases for further evaluation: 1) construction sequence simulation (CSM) and 2) predictive maintenance (PdM). CSM DTs provide an opportunity for reducing design and construction costs and delays (which are best aligned with the current stage of AR development), the underlying technologies such as construction cost estimating and scheduling, BIM, and probabilistic simulation are all relatively mature relative to many other use cases, and they require relatively little physical asset integration and metrology (e.g., sensors, network systems). Therefore, they are likely more straightforward to implement than many other cases. PdM DTs are expected to be key to keep ARs operational and safely cost effective over decades of asset lifetime, and the potential payback is very strong over such a long period of time (long term high reward). The nuclear industry has also invested substantially into PdM (e.g., EPRI's Preventative Maintenance Basis Database, EPRI 3002005428 (EPRI, 2015), and therefore PdM DTs have comparatively rich data resource to draw upon for integration with other DT elements such as real-time instrumentation monitoring, mechanics-based modelling. The following section presents the generalized AT DT framework developed in EPRI 3002023904 (EPRI, 2022). Specifics pros and cons of both CSM and PdM DTs are tested against the generalized framework and evaluated in Section 4 of EPRI 3002023904.

GENERALIZED DIGITAL TWIN FRAMEWORK

At the time of this report, there is not one agreed upon methodology for the development of DTs. The development process of a DT depends on the requirements, use case, available resources, and available technology architectures. As these inputs evolve over time, new development frameworks are expected to arise in the future. Considering the current state of knowledge, EPRI 3002023904 proposed the generalized framework in Figure 3, which is broken down seven unique steps:

A. Gathering Requirements
B. Scoping DT
C. Procuring Resources
D. Implementation of DT
E. Connecting the DT
F. Monitoring the DT
G. Scaling the DT
X. Prerequisite of DT

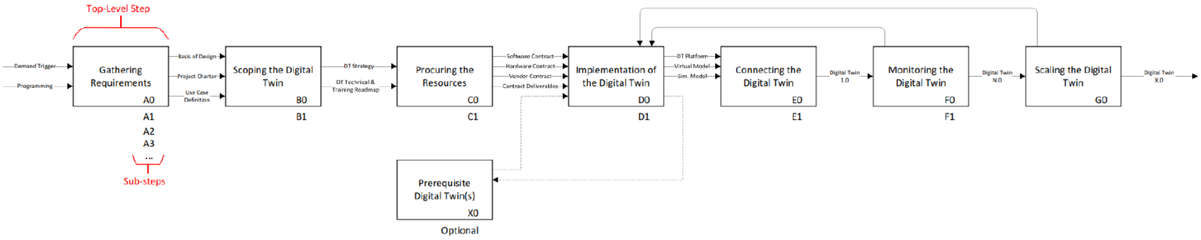

Figure 3. Digital twin development – generalized IDEF0 diagram.
(See Figure 2-4 of EPRI 3002023904 for an enlarged version of this figure)

The framework in Figure 3 provides one generalized structure for the minimum viable DT at any point throughout the digital lifecycle of a facility. This diagram has been created by utilizing the IDEF0 methodology. IDEF0 is functional modeling methodology commonly utilized to analyze, develop, and reengineer processes. This methodology provides the necessary means to evaluate the inputs (arrows on the left), outputs (arrows on the right), requirements (arrows on the top), and resources (arrows on the bottom) necessary for the development of DTs. Each step in Figure 3 is described in detail in Section 2.3 of 3002023904, which also provides an example application for a hypothetical smoke and fire detection and response systems developed in a silo and built assuming their physics analysis are integrated into the overall design, construction, testing, and commissioning of a facility. Section 4 of EPRI 3002023904 tests this framework for CSM and PdM use cases and summarizes their pros and cons. The following section summarizes the conclusions from such exercise and from the overall research efforts (literature review, TAG engagement, and use cases evaluation).

SUMMARY AND CONCLUSIONS

To ensure successful construction and operation of future nuclear power plants in the current U.S. energy market, OCC and O&M costs must be significantly reduced. A variety of industry initiatives have identified DT technology as a key opportunity to achieve such cost reductions. DTs are becoming increasingly popular in the non-nuclear industry as recent advances in the underlying technologies are enabling more complex applications and the associated hardware and software are rapidly becoming more affordable. Adoption of DT technology in the nuclear industry has lagged to date, partly due to uncertainties resulting from the unique regulatory environment and initial capital investments compared to other industries. However, the nuclear industry has recently begun to recognize the untapped potential for digital twins to achieve efficiencies over the entire lifecycle of an NPP, particularly for ARs, as demonstrated by several ongoing projects working to facilitate digital twin adoption. The goal of the project was to complement ongoing industry efforts to research DT applications and provide AR-specific guidelines to support stakeholders in understanding and adopting DT technology. To that end, this project explored potential benefits, challenges, capabilities, and use cases of DTs across the AR lifecycle and made progress on the following key issues related to DT adoption for ARs:

- Lack of a common conceptual framework and standardized procedures for DT development.
- Scarcity of successful, nuclear-specific DT demonstrations and business cases.
- Uncertainties in regulatory impacts and readiness of enabling technologies.
- Inertia in conventional business practices and workflows that might inhibit key features of DTs such as integration across technical disciplines, data sharing among various stakeholders, and digitization of workflows.

To investigate the preceding issues and develop insights, the project consisted of the following steps:

- Perform an in-depth literature review of AR DT applications and engage stakeholders to summarize the industry perspective and lessons learned on the following questions:
  - What is a DT, and what are its basic elements and enabling technologies?
  - What are the steps to develop and implement a DT?
  - What are the costs and potential benefits of DTs?
  - What are the most promising use cases relevant to various AR lifecycle stages?
  - What are the industry needs, gaps, and challenges to solve to facilitate DT adoption for ARs?
  - What are some best practices when developing a DT?
- Develop a list of DT use cases relevant to ARs, identify criteria that could be used to evaluate and prioritize them, and then use those criteria to select two use cases to further develop in this study: construction sequence simulation and PdM.
- Provide a framework for DT development, illustrate the development processes for two selected uses cases, and provide use-case-specific observations, best practices, and recommendations.

The rest of this conclusion section summarizes key insights, best practices, and areas of future research identified as part of this project, organized in Tables 2, 3, and 4, respectively.

Table 2. Key Insights

ISSUE	**INSIGHTS AND CONTRIBUTIONS**
DT definition, digitalization, and integration	This project proposes a working definition of AR DTs yet acknowledges that such definitions are diverse and vary across industries and over time. Considering the diversity of definitions, it is helpful to consider Michael Grieves's conceptualization of a DT; he observed that, as technology matures, digital models tend to become more detailed and accurate, more integrated with each other, and more integrated with their physical counterparts. He conceived

	of a DT as the end state of this trend in which models are sufficiently detailed, comprehensive, and integrated with their physical asset that they will be able to provide all the same useful information that could otherwise be obtained by examination or testing of the physical asset. This conceptualization is helpful because it clarifies that each evolutionary step toward producing more detailed, accurate, and integrated digital representations is a productive step toward realizing the potential benefits of DTs.
DT elements	DT elements can be thought of as building blocks (such as hardware, software, networks, and processes) that enable DT functions. Because DTs come in various forms based on their requirements and intended uses, their underlying elements also vary significantly. Section 2.2 of EPRI 3002023904 proposes a categorization of DT elements into six functional areas: collect, alert, react, process, visualize, forecast. The functional areas and elements are offered as a conceptual framework and taxonomy to support planning, development, and implementation of DTs.
Generalized DT development framework	The nuclear industry lacks a common conceptual framework and standardized procedures for DT development. The available options for building DTs are plentiful, though many have limitations, such as being use-case-specific or not being scalable. Section 2.3 of EPRI 3002023904 proposes a generalized DT development framework that can be applied at any point throughout the digital lifecycle of a facility, system, or component. The proposed conceptual framework can be used to evaluate the inputs, output, requirements, and resources necessary for the development of DTs. The framework aims to facilitate knowledge transfer across industry stakeholders while being flexible enough to be adopted for any DT use case.
AR industry perspective	The research team engaged various AR industry stakeholders through a series of interviews, teleconferences, webinars, and other correspondence to collect feedback on their perspective on DT technology. Section 2.5 of EPRI 3002023904 summarizes interests, trends, concerns, and issues that stakeholders identified as important. AR stakeholders generally agree that the main motivation for DT research is to achieve significant reductions in OCC and O&M costs. As such, they are principally interested in DT applications with the potential to reduce costs and risks in the design/construction and O&M stages. The main DT implementation challenges identified during this research are covered in Section 2.5.3 of EPRI 3002023904. One important challenge for the industry moving forward is the need to integrate DT development with conventional nuclear plant workflows. As DTs are introduced into existing design/construction/etc. processes, the norms, business practices, and attitudes will need to adapt to accommodate and support the new technologies before their benefits can be realized. EPRI 3002023904 provides some tools and resources to make progress in this regard. Other key challenges are described in Section 5.4 of EPRI 3002023904 along with future research opportunities to address them.
DT technology readiness	The research team reviewed literature and engaged industry stakeholders to assess technology readiness and identify important resources. The results are summarized in Section 2.6 of EPRI 3002023904. This effort provides insights into DT underlying technologies and offers a discussion on technology readiness and outlook of future technology development.
DT costs and potential benefits	Costs and benefits of DTs greatly depend on the use case and underlying technologies to develop and monitor the twin, and the literature currently lacks documented examples of successful DT implementation for nuclear applications. Recognizing this limitation, Section 2.7 of EPRI 3002023904 provides basic rough-order-of-magnitude cost information and expected benefits across various types and maturities of DTs. Because AR stakeholders identified DT costs and benefits as the most important aspects influencing use case prioritization, future research should investigate DT costs and benefits.
DT use cases for ARs	Twenty-nine DT use cases applicable to ARs are described in Appendix A, spanning a wide range of applications over the AR plant lifecycle. These cases provide a basis for AR stakeholders to build on and identify new applications. Two use cases from Appendix A were selected for further evaluation in this study: Construction Sequence Simulation and PdM. The use case evaluation process and criteria (Section 3 of EPRI 3002023904) offer a set of considerations and issues that readers can use to assess their own potential use cases.
DT development examples	Using the conceptual DT development framework proposed in this study (Section 2.3 of EPRI 3002023904), the two prioritized use cases were analyzed further to provide additional detail, illustrate the development process, and provide use-case-specific observations, best practices, and recommendations. These examples provide readers interested in DT development with an approach for considering the various steps, requirements, and constraints involved in developing a DT.

Table 3. Best Practices.

TOPIC	**RECOMMENDATION**
Follow an organized process.	Chances of successful DT development and implementation increase if an organized process is followed. The conceptual framework and DT functional areas covered in Section 2 of EPRI 3002023904 provide an opportunity to formulate an efficient work breakdown structure and optimize resources. Establish specific DT goals, requirements, quantifiable metrics, and inputs/outputs to minimize chances for misinterpretations.
Think ahead.	Experience with conventional NPPs suggests that changes to assets and processes might be lengthy and costly to implement. Plan to maintain the DT and keep it current. Design DTs to be sufficiently flexible to accommodate. future updates with minimal costs (for example, use standardized hardware and data formats). Define DT and WBS to be sufficiently specific at the beginning of the project to minimize chances for future changes.
Focus near-term use cases on low-risk and high-reward applications.	Prioritize low-risk/high-reward DT use cases and then move to more complex applications as experience is gathered. Use cases focusing on non-safetyr elated systems have less significant consequences of failure and are therefore less risky. Use cases addressing OCC and O&M cost reductions might be more interesting than other cycles in terms of potential return on investment. Use cases incorporating the DT early in the power plant design stage will likely result in higher long-term returns.
Identify opportunities to minimize development risks.	Scalability and intersystem issues might emerge as the DT is employed across various components and systems. Start small and then scale up on digitalization and integration to minimize risk. Subsequent development can move toward automation. Leveraging existing solutions could minimize efforts/risks. Prioritize integrated and standardized solutions as well as user-friendly interfaces.
Engage all stakeholders early in the process, define their responsibilities, and plan for disruptions.	Depending on the scale and scope of the DT, a variety of stakeholders might be involved in the DT development and deployment process. These could include regulators, contractors, vendors, utility staff, grid operators, and so on. Each of these entities could have one or more engineering teams collaborating on the project (such as civil, mechanical, electrical, software), each providing a unique set of requirements and outputs for their specific scope. To maximize the chances of successful implementation of a DT, engage stakeholders early in the process and define clear responsibilities. Section 2.7.1.3 of EPRI 3002023904 lists common DT personnel roles. Plan and budget for inefficiencies in conventional business practices and workflows resulting from disruptions due to DT technology adoption.
Construction sequence simulation.	A few key use-case-specific best practices are summarized here from Section 4.1.5 of EPRI 3002023904: • 3D model geometries should be sufficiently segmented to represent the intended LOD. • WBSs should be developed based on a singular classification method to have a holistic schedule of values. • While proceeding through the development and usage of the construction sequence DT, a best practice is to create and log new versions of all models, datasets, and DTs. • Keep current and existing records in a cloud-based repository to give other team members transparency and accessibility.
PdM	A few key use-case-specific best practices are summarized here from Section 4.2.5 of EPRI 3002023904: • Ease of use should be a main consideration; many platforms are overly complicated and have a user experience that few truly understand. • Design platform security to ensure reliability and prevent unauthorized access. • Interoperability and integration of the specific technology platforms used • during the AR lifecycle.

Table 3. Areas of Future Research

TOPIC	**RECOMMENDATION**
Business cases	Results from the literature review and stakeholder engagement indicate a scarcity of business cases for DTs in general and specifically for ARs. One of the main reasons is that early research studies have focused on DT capabilities and functions, while cost/benefit analysis data is rarely prioritized and/or shared publicly. In addition, the existing business

	cases typically cover specific DT use cases and cannot be easily grouped into categories from which statistics or trends can be derived. The widely varying scale and scope of DTs also make extrapolation of limited datapoints very challenging. Notwithstanding the lack of established business cases in the literature, this research filled some gaps in cost/benefit analyses (see Section 2.7 of EPRI 3002023904). Results from this project and other industry efforts (for example, EPRI 3002015935 (EPRI, 2019), GEMINA (USDOE, 2019) could help prioritize future studies aiming to prove that DTs can result in significant cost savings. For example, future research could investigate business case proofs-of-concept for AR applications and track costs, benefits (projected savings over time, opportunities for economies of scale), challenges (assumptions, lack of models), and lessons learned (most appropriate applications to reduce potential overruns). Initial business case studies could focus on simple applications with less demanding vetting requirements and then scale to more complex problems.
Cybersecurity and Data Ownership	Many DT applications depend on an abundance of sensors and data and often rely on wireless networks for data collection and sharing. Until a mature level of standardization and security is achieved in hardware and software supporting data transmission across the DT ecosystem, DTs might remain expensive and limited in functionality in the nuclear industry. Aspects such as cybersecurity and data ownership (for example, intellectual property, export control) will likely become increasingly important in the future as DTs grow in complexity and scale. Future pilot studies could investigate these aspects and identify solutions for a range of data transmission strategies. Because cybersecurity and data ownership are areas that require unique expertise and experience, SMEs in these areas will need to support industry stakeholders to scope out potential issues and solutions.
Technology Readiness	This study investigated the state of technologies enabling DT applications (see Section 2.6 of EPRI 3002023904). Some technologies and solutions are considered mature for practical applications, whereas others require further development. This study identified some technology aspects that require additional research to reach a sufficient level of readiness for successful deployment at an NPP and could be prioritized in future research efforts: • Data repositories – As DTs are developed and integrated for more assets and more data is collected and processed in increasingly sophisticated data-driven and physics-based models, demands for computing resources, data storage, and data management (such as compression, reduced order modeling, optimization of data collection) are expected to increase dramatically. These will likely become areas where innovation is required to enable larger, more integrated, and more detailed DTs. • Data structures – DTs require deployment of an instrumentation network, data processing software, data storage hardware, and development of physics-based and/or data-driven models for performance prediction and optimization. As multiple DTs are employed across various components and systems, scalability and intersystem performance issues might emerge from the use of different data protocols. Common semantic data structures could facilitate DT adoption. • Sensor integrity – In the case of ARs, sensors will have to be deployed in harsh environments characterized by conditions such as high radiation levels, high temperature, or high probability of mechanical damage (for example, in construction environments). Consequently, sensing networks for AR DT applications will have to be sufficiently robust, reliable, and resilient to such operational conditions. • DT integration platforms and standardization – DT integration platforms and tools have generally been deployed only for first-of-a-kind applications, although there are exceptions, such as BIM. No mature DT integration technology is available for broad commercialization across a variety of use cases. The lack of commercially available integration platforms is exacerbated by a lack of standardization of various DT elements and components. Future research could focus on developing standard integration platforms, protocols, and conceptual frameworks that are broadly applicable across a variety of use cases.
Training, Verification, and Validation	Many DT use cases for ARs rely on high-fidelity simulations to predict and optimize the physical asset performance. As such, advanced models and algorithms (such as AI/ML) are expected to play a crucial role in the successful implementation of DTs. Stakeholders identified training, verification, and validation of advanced models and algorithms as three critical aspects to produce reliable data and robust uncertainty quantification. ARs are still

	under development and lack historical data, which could affect training, verification, and validation efforts. Future research could review opportunities to streamline these efforts, for example: • Develop industry standards and guidelines for V&V of advanced algorithms, including specific measures, tolerances, analysis, and file formats. • Develop industry consensus on V&V process. For example, define stakeholder responsibilities throughout the DT lifecycle, identify actions in case of nonconformances, and establish data sharing protocols. • Augment existing training databases using physics-based simulations.
Regulatory Certainty	Regulatory certainty (including and beyond V&V) will be critical to the successful adoption of DT technology in the nuclear industry. Continued, ongoing engagement among regulatory bodies (for example, the NRC), technical research organizations (such as EPRI), policy advocates (such as the Nuclear Energy Institute), plant owners, and AR developers will be essential to ensure that the regulatory readiness keeps pace with DT technology development and deployment. Future studies could investigate options to develop infrastructure to support regulatory decisions associated with DTs and increase knowledge sharing. Examples include cross-sectoral committees focusing on specific AR DT gaps and collaborative development of industry standards.

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