



Program on Technology Innovation: Digital Twin Applications for Advanced Reactors

2022 TECHNICAL REPORT

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ABSTRACT

To ensure successful deployment and operation of new nuclear power plants (NPPs), the U.S. nuclear industry must develop solutions to reduce overnight construction costs (OCCs) and operations and maintenance (O&M) costs. The industry's activities to address this priority, which have included EPRI research and U.S. Department of Energy grants and programs, have identified digital twin (DT) technology as a key opportunity for significant savings.

For the project described in this report, a main goal is to investigate how DT technologies can help reduce OCCs and O&M costs while focusing specifically on applications pertinent to the next generation of advanced reactors (ARs). More specifically, the report complements ongoing industry efforts to research DT applications and presents insights and guidelines to support AR stakeholders in understanding and adopting DT technology.

ARs present a unique opportunity to reap the potential benefits of DTs because they are still under development and can incorporate DTs early in the design phase. Early adoption could maximize cost savings over the course of a plant's life. Moreover, regulatory frameworks for ARs are still under development and could evolve to facilitate the adoption of DT technologies in AR designs. The report focuses on AR applications to leverage the momentum, interest, and opportunity for parallel development of DT and AR technologies. The following issues must be addressed before DT benefits can be fully realized:

- 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 digitalization of workflows

The project that is the subject of this report aims to make progress, offer insights into each of the preceding issues, and propose opportunities and priorities for future research. The report explores potential benefits, challenges, capabilities, and use cases of DTs across the NPP lifecycle.

Keywords

Advanced reactor (AR)
Construction sequence simulation
Digital engineering
Digital transformation
Digital twin (DT)
Predictive maintenance

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PRIMARY AUDIENCE: Advanced nuclear reactor industry stakeholders, such as utilities, advanced reactor (AR) developers, and regulating agencies, that are interested in understanding, evaluating, and selecting digital twin (DT) applications for their plants

SECONDARY AUDIENCE: Light water reactor industry stakeholders, consultants, and research groups involved with DT applications

KEY RESEARCH 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 some best practices when developing a DT?
- What are the most promising use cases relevant to various AR lifecycle stages?
- What industry needs, gaps, and challenges must be solved to facilitate DT applications for ARs?

RESEARCH OVERVIEW

This report explores potential benefits, challenges, capabilities, and use cases of DTs across the AR lifecycle and aims to make progress on the following key issues related to DT adoption:

- 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 digitalization of workflows

KEY FINDINGS

- The chances of successful DT development and implementation increase if an organized process is followed and specific DT goals and requirements are established. The conceptual framework and DT functional areas covered in Section 2 provide an opportunity to formulate an efficient work breakdown structure and optimize resources.
- Plan to maintain the DT and keep it current, and design DTs to be sufficiently flexible to accommodate future updates with minimal costs (for example, use standardized hardware and data formats). Define DT and work breakdown structures to be sufficiently specific at the beginning of the project to minimize chances of future changes.
- Prioritize low-risk/high-reward DT use cases, and then move to more complex applications as experience is gathered. Use cases focusing on non-safety-related systems have less significant consequences of failure and are therefore less risky. Use cases incorporating the DT early in the plant design stage will likely result in higher long-term returns. The evaluation framework presented in Section 3 and the use cases listed in Appendix A could be leveraged for use case prioritization.
- Engage all stakeholders early in the process, define their responsibilities, and plan for disruptions in conventional business practices and workflows resulting from DT technology adoption.

- DT technology is mature enough to transition from theory to practical applications for selected use cases. Several enabling technologies and use cases are vetted and viable; however, there are several areas where further research and development are needed to ensure full implementation and adoption.
- Costs and benefits of DTs greatly depend on the use case and underlying technologies to develop and monitor the DT, and the literature currently lacks documented examples of successful DT implementation for nuclear applications. Results from this project and other industry efforts could help prioritize future studies aiming to assess whether DTs can result in significant savings for ARs.

WHY THIS MATTERS

This research complements ongoing industry efforts and provides specific guidelines for AR stakeholders to understand and adopt DT technology. The project documents best practices and establishes recommendations for leveraging the advancement in DT technologies, with the goal of helping the industry determine the added value of DT technology adoption in nuclear projects, particularly ARs.

HOW TO APPLY RESULTS

Stakeholders can leverage the following materials in this report:

- Section 2.1 defines DTs to help the reader understand the concept.
- Section 2.3 presents the generalized framework for DT development.
- Appendix A lists potential AR use cases, and Section 3 proposes a use case evaluation framework for use case prioritization.
- Section 4 tests the generalized framework for two use cases (construction sequence simulation and predictive maintenance).
- Section 2.5 explores the key challenges and needs identified by AR industry stakeholders for adoption of DT technology.
- Section 5 compiles best practices and recommendations for DT adoption and development.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- EPRI's DT research is managed through the Advanced Nuclear Technology program, whose mission is to reduce the risk and uncertainty of constructing and operating new nuclear power plants. Contact Hasan Charkas for more information.

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ACRONYMS AND ABBREVIATIONS

AI	artificial intelligence
ANT	Advanced Nuclear Technology
AR	advanced reactor
AuR	augmented reality (N.B.: In this report, <i>AuR</i> is used instead of the more common <i>AR</i> to avoid confusion with the acronym for <i>advanced reactor</i> .)
ARPA-E	Advanced Research Projects Agency-Energy
AWP	advanced work package
BIM	building information modeling
BOP	balance of plant
CAD	computer-aided design
CDE	common data environment
CDT	construction digital twin
CMIS	configuration management information system
CMMS	computerized maintenance management system
COTS	commercial off-the-shelf
CSDT	construction sequence digital twin
CWP	construction work packages
DDT	design digital twin
DE	digital engineering
DOE	U.S. Department of Energy
DT	digital twin
EPC	engineering, procurement, and construction
EPRI	Electric Power Research Institute
ETL	extract, transform, load
FGM	federated geometric model
FTE	full-time equivalent
GEMINA	Generating Electricity Managed by Intelligent Nuclear Assets

GIS	geographic information system
GUI	graphical user interface
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
IBM	International Business Machines Corporation
ICT	information and communication technologies
IDEF0	ICAM definition for function modeling, where ICAM stands for “Integrated Computer Aided Manufacturing”
INDE	integrated nuclear digital environment
IoT	Internet of things
ISO	International Organization for Standardization
IWMS	Integrated Workplace Management System
IWP	installation work packages
LCOE	levelized cost of electricity
LiDAR	light detection and ranging
LOD	level of development
LWR	light water reactor
MBSE	model-based systems engineering
ML	machine learning
MOS	metal-oxide semiconductors
MR	mixed reality
NASA	National Aeronautics and Space Administration
NLP	natural language processing
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
O&M	operations and maintenance
OCC	overnight construction costs
PCS	plant chemistry simulator
PdM	predictive maintenance
PM	preventive maintenance
PMBD	Preventive Maintenance Basis Database (EPRI)
PMDT	predictive maintenance digital twin
PMIS	project management information system

QA	quality assurance
QR	quick response
RF	radio frequency
RFI	request for information
ROI	return of investment
SME	subject matter expert
SSC	structure, system, and/or component
TAG	technical advisory group
UX/UI	user experience/user interface
V&V	verification and validation
VR	virtual reality
WBS	work breakdown structure

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INTRODUCTION

1.1 Background

In simple terms, a digital twin (DT) is a digital representation of a physical asset or process used to monitor, simulate, predict, and/or control its behavior. Some stakeholders advocate that a DT must also collect data about the physical asset or process to update the digital representation, whereas others contend that this physical-to-digital connection is not essential to DTs. A simple example that includes the data collection element is a pump instrumented with various sensors that provides real-time input to a digital model used to predict component wear. An example of a DT without the data collection element is a 3D computer-aided design (CAD) model of a site excavation used to simulate the construction sequence prior to breaking ground. Section 2.1 provides a more detailed discussion on the available definitions of DTs.

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

- Faster deployment of new assets and systems
- Improved operational efficiency and reliability
- Enhanced simulation of potential scenarios and outcomes
- Optimized allocation of resources and labor
- Refined maintenance schedule
- Reduced design, construction, operation, maintenance, and decommissioning costs
- Improved integration of systems
- Better-informed decision-making
- Reduced operator exposure to high-risk environments (such as high-radiation areas)

Consistent with the preceding potential benefits, DTs have been able to demonstrate value in non-nuclear industrial applications. Examples include aircraft and automobile manufacturing and fleet control ([1] and [2]), metal additive manufacturing [3], logistic and supply chain management [4], port loading operations [5], gas and wind turbine service optimization ([6] and [7]), and environmental monitoring [8]. In the nuclear industry, the use of DTs has lagged to date, in part due to uncertainties resulting from the unique regulatory environment and large initial capital investments compared to other industries. However, the industry has recently begun to recognize the untapped potential for DTs to achieve efficiencies in various stages of the nuclear power plant (NPP) lifecycle.

The next generation of advanced reactors (ARs) presents a unique opportunity to reap the potential benefits of DTs for multiple reasons. First, recent technological advances are enabling an increasing number of DT applications and are driving the DT development and implementation costs down. Second, because ARs are still under development, they have less logistical inertia than the current existing NPP fleet in adopting and integrating new technologies, such as 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. Moreover, many AR designs include harsh environments that could place new constraints on access by operations and maintenance personnel (such as areas with very high radiation or 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. Furthermore, 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 might 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 U.S. 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 (for example, see [9], [10], [11], [12], [13]).

Although momentum 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 proven business cases, limited diversity of existing DT use cases, and uncertainties in technology readiness and regulatory impact [10]. Early nuclear DT studies have also indicated a need to adopt a “transformative approach” to successfully incorporate DTs in ARs because new systems and processes will be required to implement the DT. For example, necessary DT hardware might impose requirements on the plant structural design (such as additional space claim) that would not otherwise exist. Conventional workflows will likely need to be transformed to ensure that additional DT-related design requirements are adequately captured and integrated into the plant design.

To complement ongoing industry efforts and provide specific guidelines for AR stakeholders to understand and adopt DT technology, this EPRI project explores 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 aims to document best practices and establish recommendations for leveraging the advancement in DT technologies, with the goal of helping the industry identify the potential value added that DT technology can provide to nuclear projects, particularly in ARs.

1.2 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 NPPs. According to the EPRI report *Advanced Nuclear Technology: Economic-Based Research and Development Roadmap for Nuclear Power Plant Construction* [14], 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 (see Figure 1-1). DTs offer a potential solution to mitigate construction duration, which was found to be the most significant cost reduction strategy in that report [14]. As will be shown in the present report, DTs have potential applications in each of the

other top cost-driving areas as well. Moreover, beyond the potential to reduce overnight construction costs (OCCs), which make up approximately 60% of the levelized cost of electricity (LCOE), DTs have the potential to reduce operating and maintenance (O&M) costs, which are responsible for another 15–25% of LCOE [14]. One of the principal motivations for this project is, therefore, 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 advanced reactor applications. This report is one of many EPRI initiatives that share the same principal motivation.

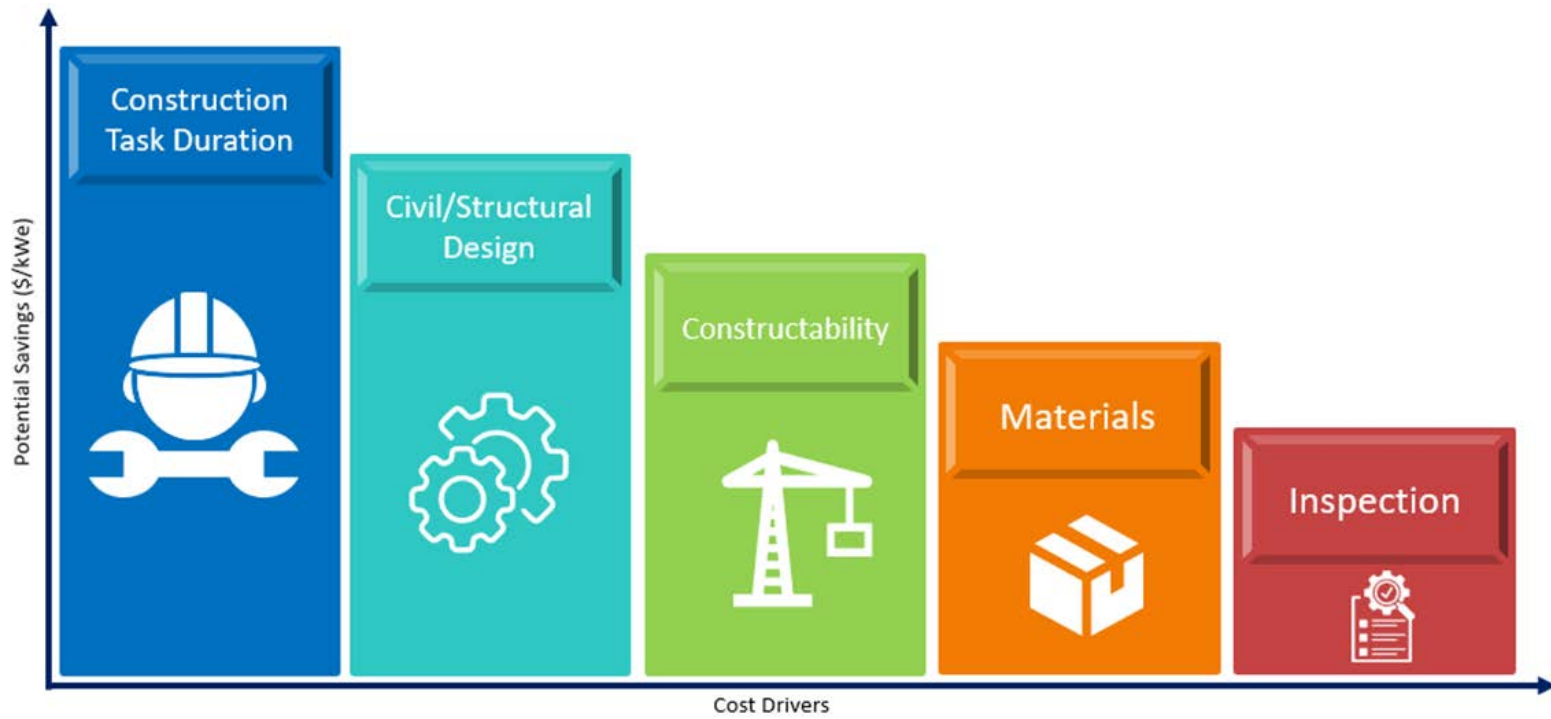


Figure 1-1
Ongoing research in EPRI's ANT program

1.3 Objectives

The project objectives are as follows:

- Summarize available resources, tools, software, sensing technologies, and monitoring strategies for implementing DTs for ARs.
- Propose preliminary industry guidelines for DT development and a conceptual framework to streamline DT adoption in the nuclear industry.
- Provide insights on the costs and potential savings of implementing DT technology to optimize activities across the plant lifecycle.
- Review available and potential NPP use cases, and summarize benefits and challenges for possible implementation in future NPP projects.
- Summarize key insights, best practices, and recommendations for implementing DTs across the AR lifecycle and identify areas of potential future research.

1.4 Scope and Approach

The scope of this project includes the following main steps:

- Section 2: Literature review and industry engagement. 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, Kairos Power, Rolls-Royce, Terrapower, Southern Nuclear, X-Energy, and Ontario Power Generation. The literature review and industry engagement activities provided insights in various areas as summarized in Section 2, including the following:
 - Diverse industry perspectives on how to define a DT, what DTs should do, and their essential functions and elements
 - Approaches and processes for developing DTs
 - Industry motivations and perceived opportunities and challenges for deploying DTs for ARs
 - The current state and future trends in DT technologies
 - Expected costs and benefits of DT technology adoption
- Section 3: Identification, evaluation, and prioritization of DT use cases for ARs. The next research step involved developing a list of DT use cases relevant to ARs, identifying criteria that could be used to evaluate and prioritize them, and then using those criteria to select two use cases to further develop in this study. Appendix A describes all 29 AR DT use cases compiled as part of this research. The TAG members were surveyed to provide inputs on benefits and challenges of each use case as well as the various considerations and issues relevant to use case prioritization and selection. The two prioritized use cases are construction sequence simulation and predictive maintenance.

- Section 4: Further development of prioritized use cases. Using an approach introduced in Section 2 for DT development, 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.
- Section 5: Conclusions. Key insights, best practices, and areas of future research derived from this research are summarized in Section 5. The findings can be used by AR industry stakeholders to identify, evaluate, and prioritize potential DT use cases, inform the design and development of DTs, and prioritize future research and development activities to facilitate the adoption of DTs.

1.5 Research Contributions by Stakeholders

Several issues must be addressed before DT benefits can be fully realized in the nuclear industry. To solve these broad, multifaceted issues, contributions are required from many stakeholders across various disciplines. This report explores potential benefits, challenges, capabilities, and use cases of DTs across the NPP lifecycle. Table 1-1 lists the main research contributions.

Table 1-1
Research contributions and benefits

Contribution	Benefit
Propose a generalized conceptual framework for DTs and their constituent elements and functions.	Facilitate knowledge transfer across industry stakeholders.
Offer an example process for DT development.	Provide readers interested in DT development with an approach for considering the various steps, requirements, and constraints involved in developing a DT.
Engage with AR industry stakeholders to identify key interests, needs, perceived opportunities, and challenges, including those derived directly from ongoing DT-related activities. Summarize observations, trends, concerns, and issues that stakeholders consider important.	The industry stakeholder perspective serves to: <ul style="list-style-type: none"> • Identify and prioritize issues warranting attention during DT development and further research to facilitate DT adoption for ARs. • Provide an update on the latest technology advancements. • Augment findings from other industry workshops and complement ongoing EPRI research.
Perform a literature review and engage industry stakeholders within and beyond nuclear to identify and evaluate potential DT use cases for ARs.	Twenty-nine DT use cases applicable to ARs are identified as part of this research (see Appendix A), spanning a wide range of applications over the entire plant lifecycle. These cases provide a basis for AR stakeholders to build upon and identify new applications. The use case evaluation process and criteria offer a set of considerations and issues that readers can use to assess their own potential use cases.
Perform a literature review and engage industry stakeholders to assess technology readiness and identify important resources.	Increase awareness of DT underlying technologies and discuss technology readiness and outlook.
Provide insights on costs and potential benefits of implementing DT technology.	Acknowledging the lack of proven nuclear-specific business cases in the literature, this research nevertheless offers high-level insights into costs and anticipated benefits of DTs.

2

LITERATURE REVIEW AND STAKEHOLDER INPUT

The following list summarizes the topics covered in this section:

- Section 2.1 presents common DT definitions and how the concept has originated and evolved over time.
- Section 2.2 analyzes the various “elements,” or component parts and functions, that compose a DT.
- Section 2.3 introduces a generalized framework for the development and implementation of DTs.
- Section 2.4 focuses on the digital thread, that is, the flow of data across use cases, lifecycle stages, and systems that integrates various DTs.
- Section 2.5 summarizes the AR industry perspective, including the TAG input on perceived needs, opportunities, and challenges.
- Section 2.6 discusses the current, emerging, and future states of DT technologies and solutions, respectively.
- Section 2.7 introduces a high-level discussion on costs and benefits for different professionals involved in the process and for different NPP lifecycle stages.

2.1 Digital Twin Definition

The working definition of a DT used in this report is from “Quick Insight Brief: Digital Twin Activities at EPRI” [15]:

... a digital replica of physical and functional characteristics of the assets that provides information to systems or personnel to make tactical or strategic operations decisions. A DT can be developed when there is a key interactive connection between a physical system and the corresponding virtual model. When measured data from the physical system is provided to a virtual model, a DT is formed, and this enables the DT output to be much more tuned to the physical systems’ performance and can be used to adjust operations or inform future decisions.

Notwithstanding this definition, the research team who wrote this report recognize that many different definitions have been proposed in the literature over several decades, dating back to the origins of the DT concept in the National Aeronautics and Space Administration’s (NASA’s) Apollo program in the 1960s [16]. Dr. Michael Grieves is widely recognized as the first to have formalized the idea of a DT in a 2002 presentation discussing a conceptual model for product lifecycle management [17]. The model was officially referred to as *digital twin* for the first time

in a subsequent 2011 publication [17], following the suggestion of John Vickers at NASA. The definitions of DTs and their components have evolved over time and vary across industries, depending on the specific DT scope and scale.

In 2015, Grieves noted that a DT consists of three main components: a virtual representation, a physical product, and a bi-directional data connection between the virtual and physical [18]. In 2019, Wang et al. built on the Grieves definition to note that “[a] digital twin can be regarded as a paradigm by means of which selected online measurements are dynamically assimilated into the simulation world, with the running simulation model guiding the real world adaptively in reverse” [19].

In 2021, the Digital Twin Consortium [20], a community of industry, government, and academic professionals who gathered with the sole objective of enabling the implementation of DTs, proposed the following definition and characteristics of a DT:

a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.

- Digital twin systems transform business by accelerating holistic understanding, optimal decision-making, and effective action.
- Digital twins use real-time and historical data to represent the past and present and simulate predicted futures.
- Digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in IT/OT systems [20].

Patterson et al. [21] were perhaps the first to postulate the concept of a DT in the context of an NPP. The paper describes an integrated nuclear digital environment (INDE) that would contain a chain of interconnected data from physics simulations, in-service monitoring, and plant inspections. The proposed INDE framework was expected to lead to shorter design and development times, reduced cost, and increased operability, reliability, and safety. The INDE shares many attributes of DTs as defined by various authors above and is therefore a helpful concept in understanding how DTs can be manifested in nuclear applications.

Although the preceding working definition from EPRI’s Quick Brief [15] is adopted for this project, the research team also acknowledges that new definitions will continue to emerge over time, across different industries, and as new DT applications are identified. Considering the diversity of definitions, it is helpful to consider Dr. Grieves’s conceptualization of a DT [22]. 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 2-1, in which DT maturity is represented as a result of

increasing integration and digitalization levels. Figure 2-1 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. [23]:

- Level 1 – Descriptive: Collect, display, and store information about the current or past state of a system. An example could be a 3D heat map of current radiation dose rates in a plant.
- Level 2 – Diagnostic: Perform analytics to determine trends or “why” the system is or was in a specific state. A trend or regression analysis, for example, might find a correlation between certain types of work done in a system and the nearby dose rates, which might suggest causality.
- Level 3 – Predictive: Combine descriptive information and diagnostic analytics to predict what is likely to transpire in the future. Predictive analytics can, for example, include rapid simulation of various scenarios to identify those with the greatest likelihood of desirable outcomes.
- Level 4 – Prescriptive: Combine descriptive, diagnostic, and predictive capabilities to either inform decisions about which actions should be taken, or automatically control those actions. Prescriptive DTs can recommend interventions or automatically interact with physical counterparts (that is, the initial stage of virtual to physical convergence through cognitive actions).

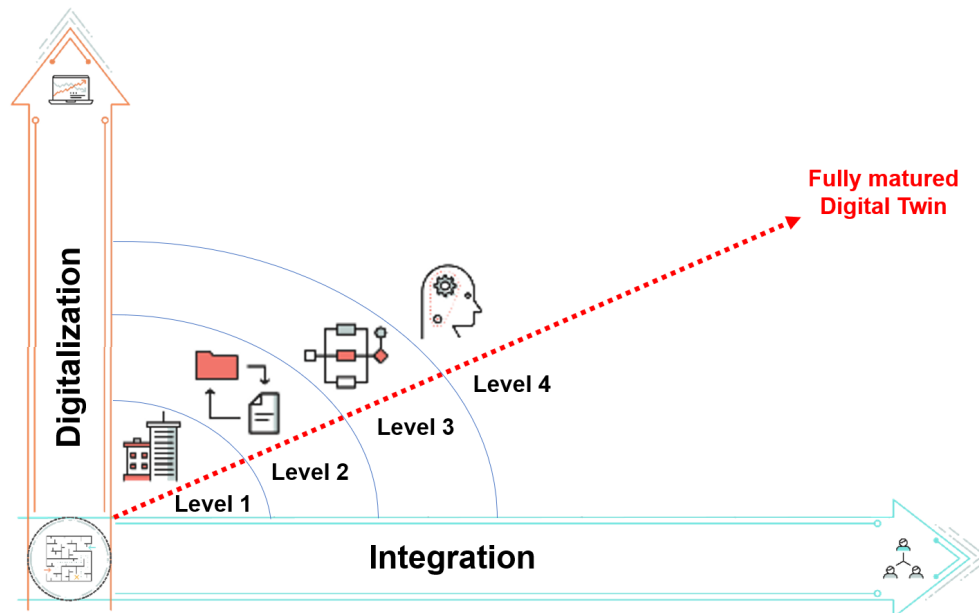


Figure 2-1
DT maturity trend

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.

2.2 Elements of DTs

A great deal of research has gone into defining and studying the building blocks of a DT. This section takes a more granular look at what a DT consists of (that is, its “elements”). DTs come in various forms based on their requirements and intended uses, and therefore the elements can vary widely across DTs. The DT elements covered in this report are only some of the most common elements that have been considered. As technology evolves, elements will change along with them (such as high-bandwidth connectivity systems). Elements of DTs can be hardware, software, or processes.

The EPRI report *Quick Insight Brief: Elements of Digital Twins and Project Updates* provides a definition of five basic DT elements—monitoring systems, advanced modeling and simulation, data analytics, data repository, and DT platform and integration systems [24]. This list of five elements is expended considerably in this section, and those with commonalities or linkages are grouped together into six functional areas illustrated in Figure 2-2: collect, process, visualize, alert, react, and forecast.

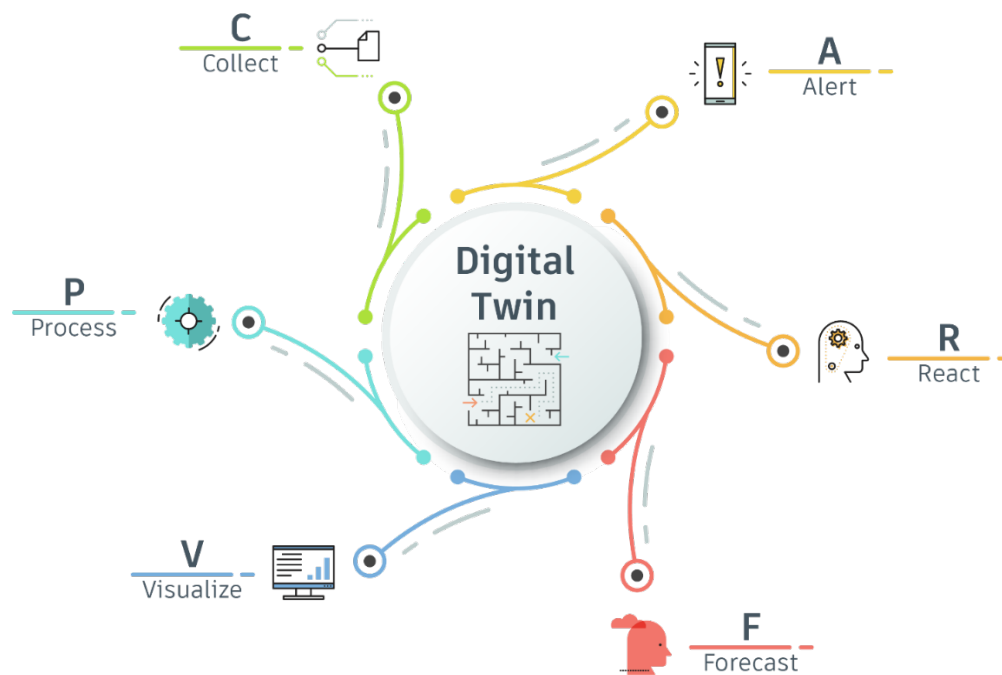


Figure 2-2
Functional areas of a DT

Following are some of the most common DT elements, each categorized under its most relevant functional area:

- **Collect:** Elements related to capturing and hosting data.
 - Cloud data repository: A virtual repository continuously updated with new telemetry data from instrumentation on the asset, asset maintenance data, plant operational data, and so on.
 - Digital engineering (DE): A multidisciplinary data integration into a single source of truth repository to track and manage facility lifecycle events.

- Building information modeling (BIM): A digital representation of physical and functional characteristics of a building.
- Geographic information system (GIS): A system designed to capture, store, manipulate, analyze, manage, and present spatial or geographic data.
- Generative design: The algorithmic generation of design options based on given constraints and requirements.
- Laser scanning: LiDAR-enabled data collection that produces “point clouds.”
- Photogrammetry: Photographic data captured, processed, and stitched together.
- Internet of Things (IoT): The extension of Internet connectivity into physical devices and everyday objects.
- Private networking: Advancements in connective technology (such as 5G) display potential in the creation of high-bandwidth, secure private networks. These networks will establish a private connection from the private cloud repository to IoT devices.
- **Process:** Elements related to computation, analysis, and/or modification of information.
 - Finite element analysis solver: A computerized method to solve differential equations to compute the model response to a set of boundary conditions and loads (such as forces, displacements, temperature changes).
 - Extract, transform, load: Three general processes used when moving data from one or more sources to another. Extract, transform, load processes can be classified as self-service (*ad hoc*) or enterprise data exchanges.
 - Artificial intelligence (AI): A broad division of computer science with several subdisciplines dedicated to the study of machine intelligence and human-machine interactions.
 - Machine learning (ML): A set of algorithms or computational methods to achieve a previously unprogrammed result, relying on data to train or teach the algorithms based on pattern recognition. ML can be used to perform predictive analytics.
 - Natural language processing (NLP): A branch of AI focused on developing algorithms that can comprehend and operate on written or spoken natural human language. Common applications of NLP are text and speech processing, syntactical analysis, natural language understanding, and document data extraction.
 - Edge computing: The pre-processing of data on a hardware device prior to data transfer to the cloud. Most IoT sensors and hubs are edge computing devices. Compared to waiting for a server to queue a transaction, perform the transaction, and return the results, edge computing provides more expedient results. It also requires less centralized computing resources.
- **Visualize:** Elements related to the end-user interface with other DT elements, including:
 - Viewer: Displays a translated version of the digital model in 2D or 3D.
 - Virtual reality (VR): A fully digital environment as viewed by the device user. It is a 3D simulation of events or experiences that can relate to the real or a simulated world.

- Augmented reality (AuR): A technology that superimposes a computer-generated scene on a user’s view of the real world, thus providing a composite view. It is a multidimensional overlay to a real-world environment.
- Mixed reality (MR): A combination of VR and AuR. Virtual and real objects interact with each other (for example, both virtual and real shadows are captured in the user’s view) and cannot be distinguished.
- **Alert:** Elements related to the notification of events, often from a system to an external view for users, including:
 - Management: Data-driven operations provide managers and executive decision-makers with timely means to monitor and respond to high-level key performance indicators.
 - Operations and Maintenance: DT information provides operators real-time visibility into system and component states, trends, and anomalies to facilitate risk mitigation and optimize operations.
 - Notifications: Email, SMS, or pager messages sent based on specific trigger events from within the environment.
- **React:** Elements related to the responses to events communicated between the physical and DTs.
 - Planning: Planners and schedulers are often tasked with anticipating the need for, or outcomes of, preventive maintenance and upgrades to systems. By connecting the functional areas (such as collect, process, visualize, and forecast [see Figure 2-2]), planners can develop more accurate plans based on more timely, accessible, and meaningful information.
 - Business intelligence: Provides a visual analysis of historical, current, and predictive business information. Business intelligence platforms should be connected to the collection and process functional areas.
 - Plant operations manager: Software aiming at mitigating risk during plant operations by improving communications across the workforce, ensuring safety compliance, and minimizing equipment downtime.
- **Forecast:** Elements related to the prediction of physical events via analysis of the DT.
 - Simulation: Advanced modeling and simulation tools used to fill in data gaps and predict the future response based on the current state, including uncertainty assessments of available data and predictions.

A given DT use case might not require all of the preceding functional areas or elements; conversely, another use case could require elements not listed. Thus, the elements of a given DT are fundamentally use-case-specific.

2.3 DT Development

At the time of this report, there is no universally accepted methodology for the development of DTs. The development process depends on the requirements, use case, available resources, and readiness of underlying technologies. Although the development process typically follows the flow and aggregation of information through a facility's lifecycle, DTs are not required to encompass the entire facility. It is possible to create a DT of a single system or component. This section proposes a generalized framework for DT development that is scalable, applicable to individual components or entire facilities, and can be used at any point during a facility's lifecycle. For example, a DT can be created for an asset that has been in operation for several years.

Figure 2-3 displays a simplified DT data flow applicable to a construction project. This brief example provides a simplistic DT development methodology. The data aggregation begins during the design stage represented by the virtual project data, which is then augmented with construction data. Toward the end of construction, the as-built or as-constructed data are integrated into the DT platform, and the sensors that have been placed during construction can be enabled. Once a virtual facility representation and sensor data are flowing, many DT platforms can learn and keep track of this historical data in a database, often referred to as a *historian*. Historian data coupled with the sensor data flow and baseline simulation results enable predictive analysis. This scenario illustrates how components, systems, data, and technology are integrated to develop a DT.

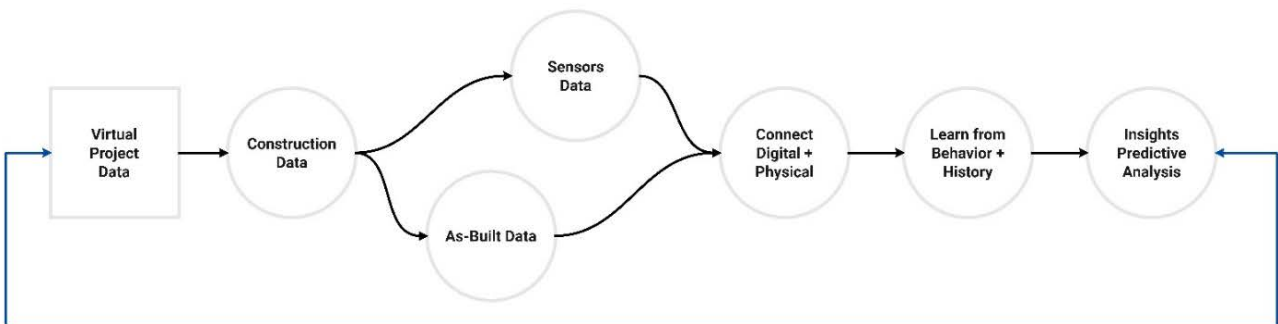


Figure 2-3
Simple DT development process

Generally, DT development can be segmented into eight top-level steps, as shown Figure 2-4. The diagram has been created following the IDEF0 (Integrated Computer Aided Manufacturing [ICAM] Definition for Function Modeling) methodology [25]. IDEF0 is functional modeling methodology commonly used to analyze, develop, and reengineer processes. It provides a 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) applicable to the development of DTs.

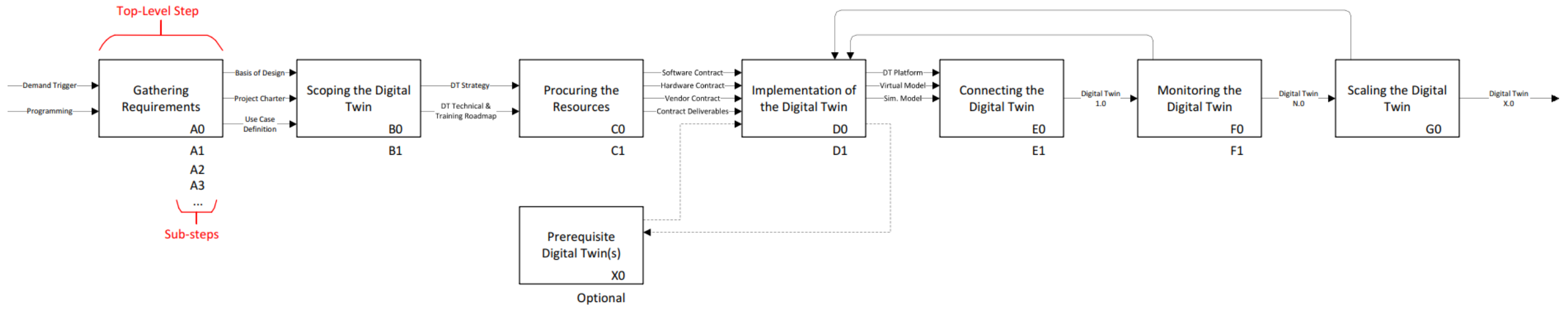


Figure 2-4
Generalized IDEF0 diagram of DT development

When adopting and applying this framework, it is important to first gather and define requirements (A0). The requirements can be refined and verified in subsequent steps. Sometimes, development of a DT requires prerequisite DTs; Figure 2-4 represents this by the Prerequisite DT(s) (X0) step feeding back into the Implementation of the Digital Twin (D0) step. As multiple, interdependent DTs are developed and connected, they support and are supported by the digital thread, as described in Section 2.4. For instance, when developing a cost estimate, inputs could include a geometric model (such as a design digital twin [DDT] or construction digital twin [CDT], as described in Section 2.5.2.1), a model-based systems engineering (MBSE) model, and a cost database. In this case, if a cost estimate indicates that a particular equipment model is higher-performing and less expensive than the specified model, the DT could feed these data back to the DDT to update the necessary equipment identification, and it could feed back to the cost database. Other examples that could require a DDT include physics simulations, logistical simulations, stress analysis, MR training experiences, and various maintenance scenarios.

Connecting the DT (E0) represents the steps necessary to integrate the physical asset and digital representation defined in the previous step. This could include the development of a visual knowledge graph with sensor telemetry data streaming in. Some DTs may skip this step during their early iterations of simulation. After developing the connections of the digital and physical, the next stage is to monitor or analyze the DT (F0). This typically involves dashboards for data visualization; however, this can be a phase when deeper analysis against historical data or other simulation inputs and/or resources is performed. For example, certain simulation platforms are interoperable with multiple databases to facilitate comparison of new versus historical data. An example use case could be to predict wear patterns by comparing current versus historical vibration levels of a pump. The last stage, scaling (G0), integrates a singular DT into numerous other DTs. The loops from (F0) and (G0) back into (D0) represent an improvement process in which findings from early monitoring and scaling activities are fed back into the DT development as new upstream requirements.

The eight top-level steps covered in the preceding are expanded in Sections 2.3.1–2.3.7 using a sample illustration. If a top-level step contains substeps, they are represented in Figure 2-4 by displaying a corresponding alpha character and numeral (such as A1, A2, A3) to the bottom right of the box. Only the first substep is presented in Figure 2-4 for Steps B0 to F0 for simplicity. Sections 2.3.1–2.3.7 provide common examples of these substeps. Not all the substeps presented in Sections 2.3.1–2.3.7 are required to develop a DT. For the purposes of illustrating these steps, the following DT problem statement will be used: smoke and fire detection and response systems are developed in isolation and should have their physics analysis integrated into the overall design, construction, testing, and commissioning of a facility.

The IDEF0 notation typically requires resources (arrows on the bottom) and requirements (arrows on the top); however, they are not included on several steps illustrated herein to provide flexibility in the framework. Also, any resource or requirement arrows displayed can be modified as necessary to meet the needs of the development process.

2.3.1 A0: Gathering Requirements

Block A0, Gathering Requirements, focuses on the overall capture of the high-level necessity of the DT (see Figure 2-5). The organizational vision of the DT is also considered and developed while gathering the requirements.

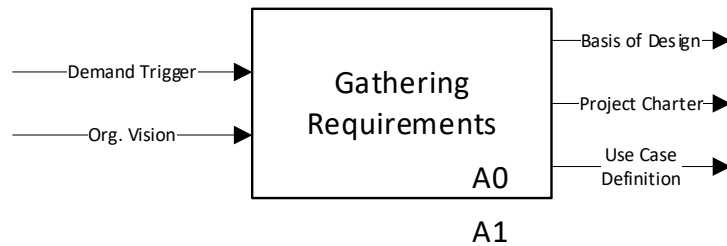


Figure 2-5
Gathering requirements, IDEF0

While working on the subprocesses associated with the A0 block, it is important to contemplate what use cases the DT will address (see Figure 2-6). For example, referencing the previous problem statement, a sample use case could be to use the design 3D model in the computational fluid dynamics simulation of the smoke path so that the geometric model does not need to be recreated and can be updated quickly when changes occur.

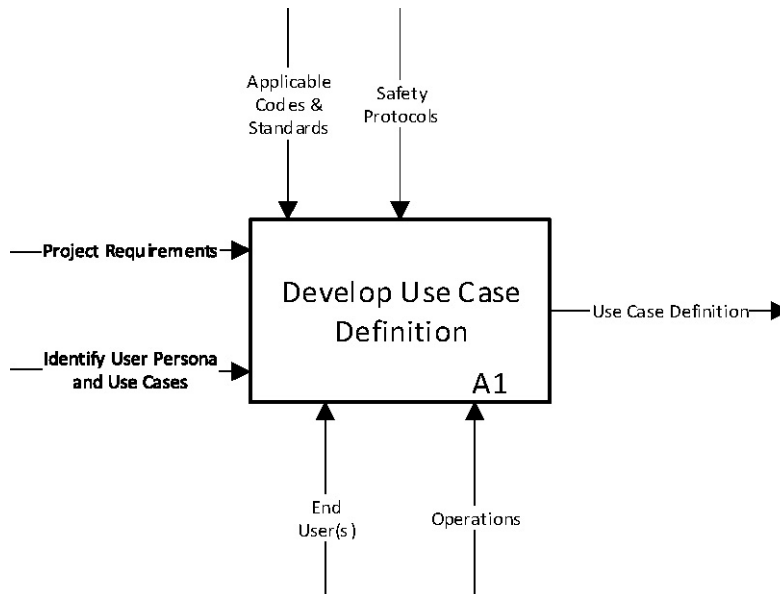


Figure 2-6
Gathering requirements IDEF0 A1: develop use case definition

The costs of DT development should be weighed against the potential benefits before investing significant resources in development. For instance, a fire simulation platform might not be interoperable with the native design geometry platforms without significant investment in developing the integration. This development cost could exceed the projected return on investment (ROI) of the DT. The integration development is a one-time cost, but it would also need to be maintained; therefore, the cost of maintaining features and elements developed should also be considered (see Figure 2-7).

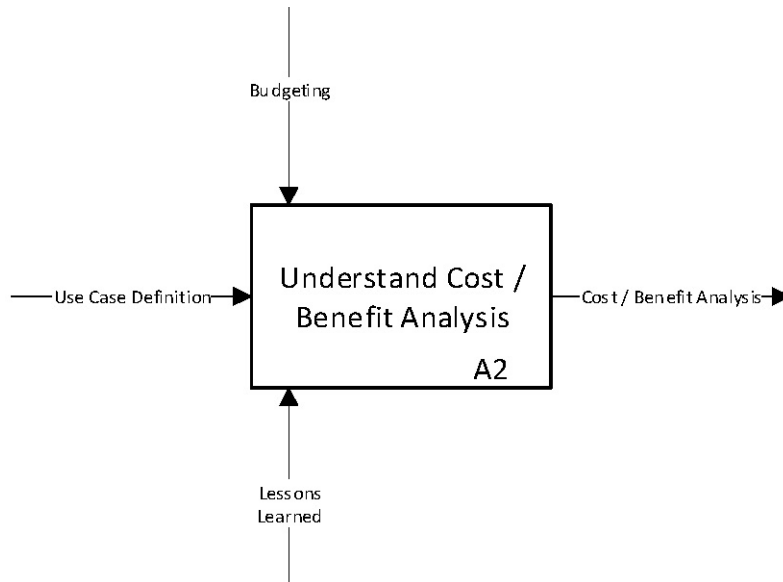


Figure 2-7
Gathering requirements IDEF0 A2: understand costs versus benefits

Once the use cases are defined and costs and benefits understood, it is important to develop the basis of design with regard to the technology platform(s), necessary resources, and general timeline for development (see Figure 2-8). At the conclusion of this stage, a project charter and design basis documents can be used as guides throughout the remainder of the development process.

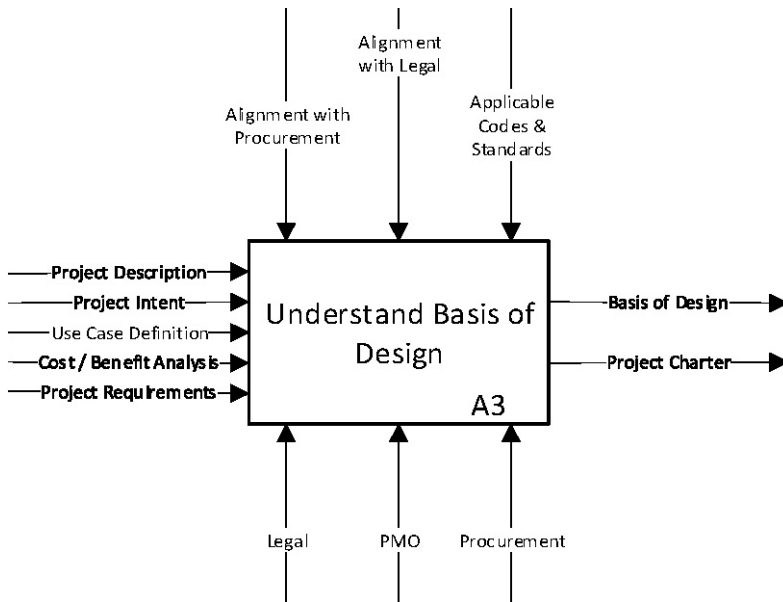


Figure 2-8
Gathering requirements IDEF0 A3: understand basis of design

2.3.2 B0: Scoping the DT

Upon development of the project charter and basis of design, attention should be given to the systems design of the DT. This step typically relies on an MBSE process to design the performance, behavioral/functional, and architectural model of the DT. Figure 2-9 is a diagram of the scoping step.

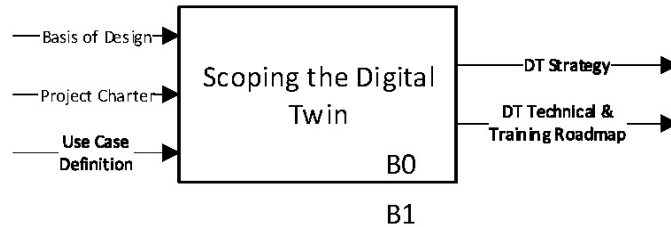


Figure 2-9
Scoping the DT, IDEF0

To establish the strategy (see Figure 2-10), tools that leverage general-purpose system architecture modeling language for systems engineering applications, such as System Modeling Language, can be used, although this is not required. The strategy could be developed using other non-systems engineering means, such as Microsoft Office;¹ however, the value that a dynamic systems model provides will not be available. A strategy of the fire-and-smoke system example could be that it must use the video surveillance system to detect fire(s) and smoke.



Figure 2-10
Scoping the DT, IDEF0 B1: establish strategy

After establishing the strategy, it is then recommended to develop a roadmap and associated performance metrics defining what and how the strategy will be implemented (see Figure 2-11). This could include both functional and nonfunctional requirements to be used when identifying, reviewing, and procuring the necessary technologies in the next step. A functional requirement for the fire-and-smoke system example could be that the operational alerting system should send mobile alerts to the technicians. A nonfunctional requirement could be that the system must have a high availability of at least 99.99% uptime.



Figure 2-11
Scoping the DT, IDEF0 B2: develop roadmap

¹ Office is a registered trademark of Microsoft Corp.

2.3.3 C0: Procuring the Resources

The next main step is to procure the necessary resources to achieve the vision and constraints identified in the first two steps, A0 and B0. These substeps have been divided to separate software, hardware, and integration personnel. To carry our example forward, the development team could need to procure sensors, additional video cameras, cabling, cloud server provisioning, software system, and specialty contractors (see Figure 2-12).

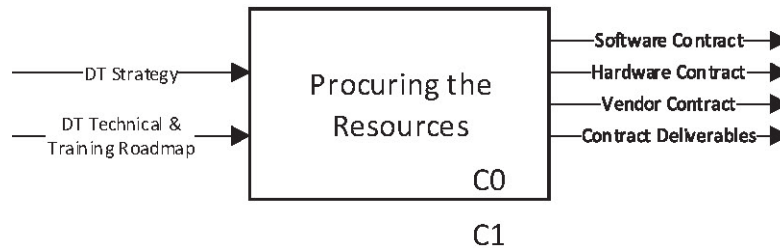


Figure 2-12
Procuring the resources, IDEF0

Prior to approaching vendors, the strategy and roadmap should be simplified and aligned to the overall vision (see Figure 2-13). Furthermore, the outputs of this first stage would rely on the framework curated in the strategy. The separation of hardware (such as the video cameras) and the software platform should be considered. Some vendors might provide both hardware and software in a discounted manner; to develop an accurate and fair procurement strategy, the line items should be separated.

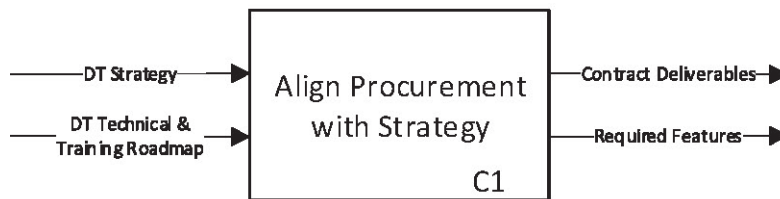


Figure 2-13
Procuring the DT, IDEF0 C1: align procurement with strategy

Each organization has unique vendor procurement methods and policies, some of which focus on preventing and controlling loss of intellectual property. Depending on the scale and complexity of the DT, data sharing across multiple vendors could become cumbersome. The highest ROI might be achieved by involving vendors early in the development process to identify potential issues and solutions.

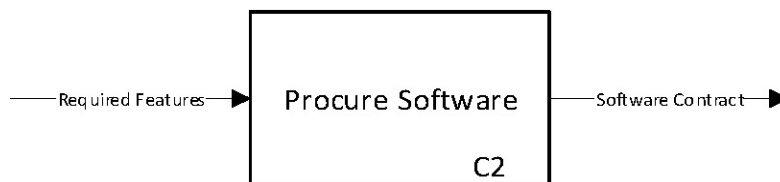


Figure 2-14
Procuring the DT, IDEF0 C2: procure software

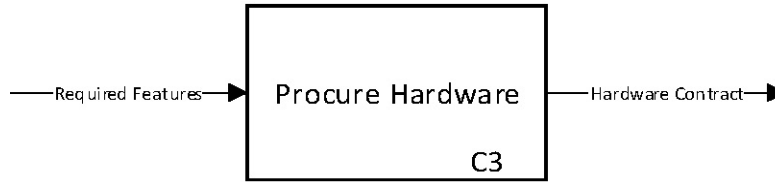


Figure 2-15
Procuring the DT, IDEF0 C3: procure hardware

When working with new technologies, consulting or integration assistance can help ensure project success. If an integration vendor is selected, it is recommended that they have a single point of contact within the DT development team. This would typically be the project manager or product owner. Additionally, it is important to have the integration scope well defined during stages A0 and B0. Figure 2-16 is a diagram showing the process involved in procuring an vendor.



Figure 2-16
Procuring the DT, IDEF0 C4: procure integration vendor

2.3.4 D0: Implementation of the DT

After considering the vision, requirements, and procurement of the DT, the next step is implementation (see Figure 2-17). Developing a single DT will often have inputs from other DTs and/or model processes. In Figure 2-4, this is denoted by the prerequisite DT(s) (X0), being circularly connected to D0. However, this is not always the case, and the geometry and linked data can be developed during this stage. The fire-and-smoke system example would now be implemented with the assistance of the specialty contractors to install and test the sensor array.

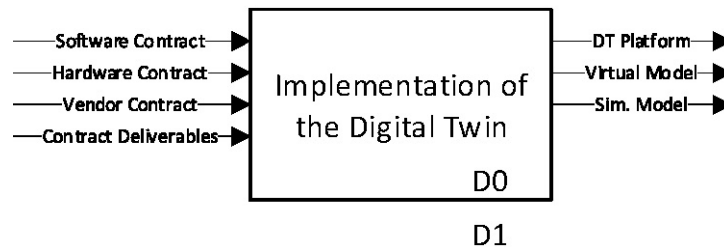


Figure 2-17
Implementation of the DT, IDEF0

The first step in implementing the DT is to implement the platform that will aggregate the component parts of the DT (see Figure 2-18). This could be a common data environment (CDE) where all the documentation files and integrations are managed.

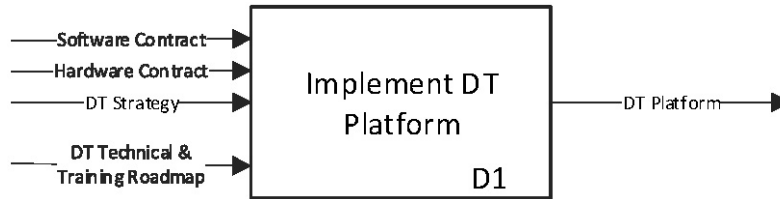


Figure 2-18
Implementation of the DT, IDEF0 D1: implement DT platform

Developing the model of the DT (see Figure 2-19) refers to the curation of a 3D and data representation of the physical elements. This could include data collection from the field by laser scanning or photo collection.



Figure 2-19
Implementation of the DT, IDEF0 D2: develop model

Developing the simulation of the DT (see Figure 2-20) refers to the curation of the physics model and algorithms necessary for ongoing analysis.



Figure 2-20
Implementation of the digital twin, IDEF0 D3: develop simulation

2.3.5 E0: Connecting the DT

This step could also be called *integration of the DT*. Once the digital and physical entities are integrated, the DT is launched for stakeholders to begin interacting, interpreting, and acting on the results. The DT platform must be able to accept the integration of multiple sources of data through direct and indirect connections. To continue our previous example, the fire prevention and detection system, operational system, and cameras might have been installed during construction, and the simulation model has been developed based on the design 3D models. It is now time to connect the physical to the digital. In this example, the connections to the physical would be made using application programming interfaces or integration platforms as a service to send signals between the simulation and operational system. Figure 2-21 is a diagram showing the process of connecting the DT.

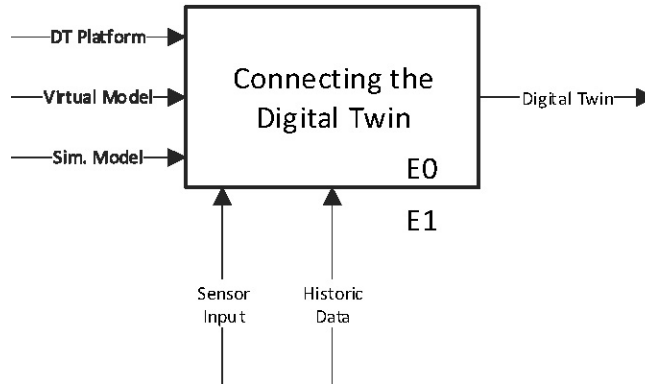


Figure 2-21
Connecting the DT, IDEF0

Updates to the DT should be mostly complete once this substep is initiated. This stage includes training operators and end users of the DT. The data model would begin to flow and grow as more time series data are aggregated into the historian system. The launch step is shown in Figure 2-22.

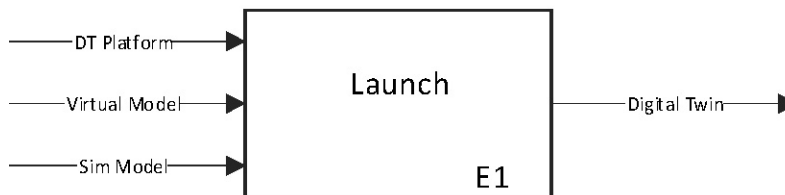


Figure 2-22
Connecting the digital twin, IDEF0 E1: launch

2.3.6 F0: Monitoring the DT

Upon connecting the DT visuals to the physical components or monitoring systems, users can observe the results and changes in subsystems that might influence the overall system. This stage, illustrated in Figure 2-23, also includes the maintenance and operation of the DT.

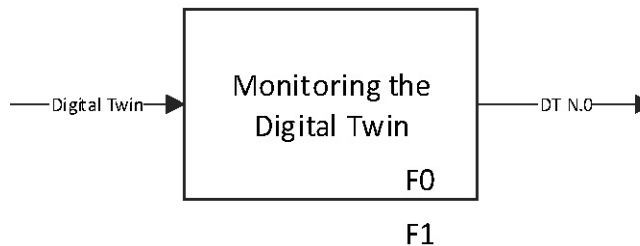


Figure 2-23
Monitoring the DT, IDEF0

Once the data begin to flow, they should be monitored and tested for reliability and further calibration of the system (see Figure 2-24).

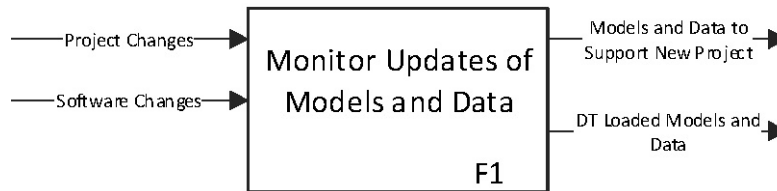


Figure 2-24
Monitoring the DT, IDEF0 F1: monitor updates of models and data

If a twin is developed during the construction or commissioning phases of a project, the data are likely to be in flux until those processes are complete. For this reason, a step to constantly iterate on the representation of the virtual is included in Figure 2-4. Figure 2-25 shows the process of monitoring the handover of data to the DT platform.

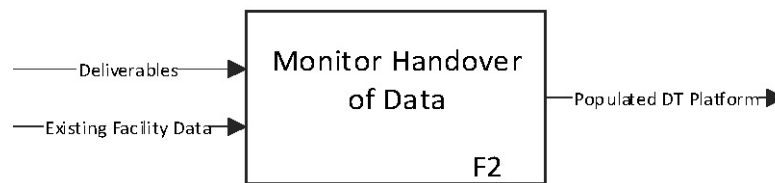


Figure 2-25
Monitoring the DT, IDEF0 F2: monitor handover of data

Figure 2-26 shows the final substeps in the F0 block. At this point, the initial vision should be revisited and revised as needed to account for lessons learned during the initial implementation of the DT.

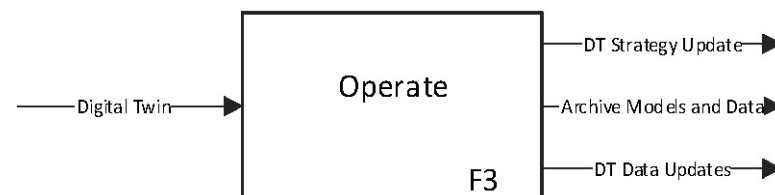


Figure 2-26
Monitoring the DT, IDEF0 F3: operate

2.3.7 G0: Scaling the DT

Block G0, Scaling the DT, will not be applicable to all DTs. Scaling will be applicable only in situations where the DT developed will need to be integrated with other DTs or expanded to include additional components, systems, or facilities within the scope of the DT. If this is the case, it should be a requirement captured during the requirements gathering stage. The input to this stage is represented at N.0, where N denotes the number of iterations the DT has run through the implementation. The output of this stage is represented as X.0, where X depicts the next generation of the DT (see Figure 2-27).

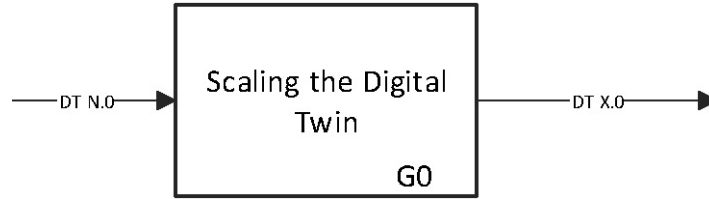


Figure 2-27
Scaling the digital twin, IDEF0

Scaling the DT will often mean that multiple DTs will be integrated; however, this could also present the expansion of the created DT. For instance, the fire systems could be integrated with the seismic analysis systems. Or, if the fire system were only implemented in one zone, the DT could be expanded to include additional zones. These integrations lead us to the development of the digital thread.

2.4 The Digital Thread

The digital thread can be thought of as a line of data, information, or geometry flowing through the DT elements. For example, the DT Consortium defines the digital thread as

A mechanism for correlating information across multiple dimensions of the virtual representation, where the dimensions include (but are not limited to) time or lifecycle stage (including design intent), kind-of-model, and configuration history; the mechanism generally relies on stable, consistent real-world identifiers [26].

An example of a digital thread could be the asset name of an element that is used during the design process, then with the possible addition of a tracking code (QR code or similar) for use in tracking construction logistics; finally, the same asset name could be used in the computerized maintenance management system (CMMS) for maintenance tracking purposes.

The digital thread can link multiple DTs across different lifecycles. Figure 2-28 illustrates the digital thread connecting the data flows between the unique DTs (in orange) into a more complex aggregate system. Each DT is independent but influences the next DT. As previously explained, the scale of DTs varies based on the context (subcomponents, components, subsystems, systems, system of systems, plants, fleets, and so on). The DT can start small and then scale up if doing so provides value and satisfies a need. The prioritization of project-specific use cases can dictate where to begin linking and expanding the DTs (as indicated in Figure 2-28 by the arrows from the use cases pointing toward the digital thread). As more DTs are connected and aggregated, the quantity of information flowing through the digital thread widens and is maximized during the final operations stage of a facility. If DTs are scaled during operation, the digital thread will widen accordingly.

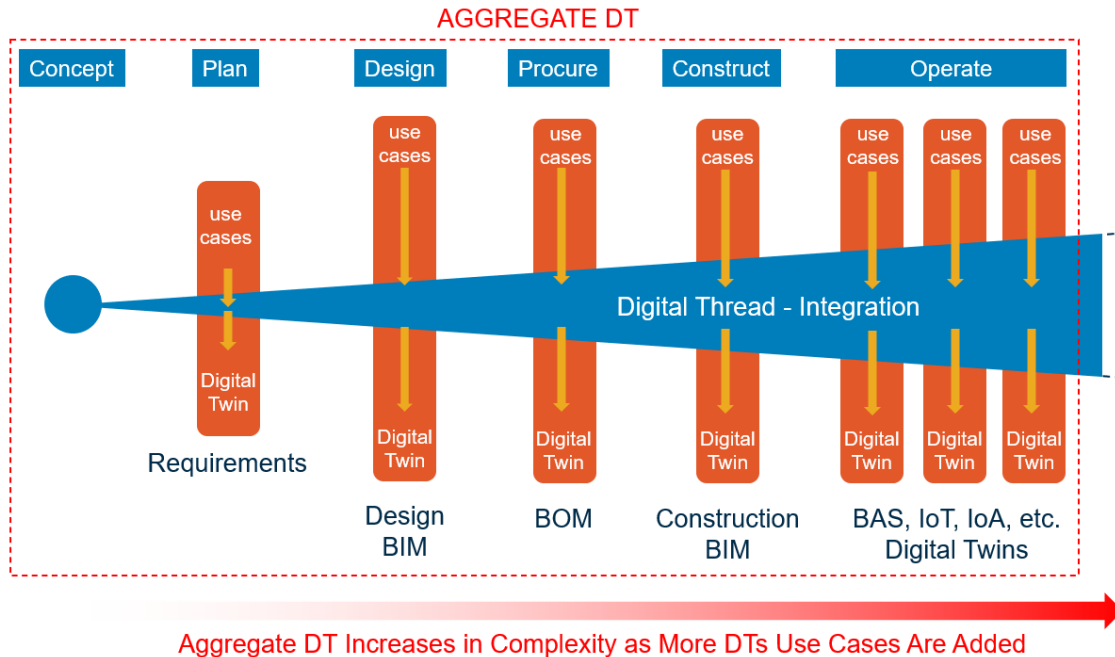


Figure 2-28
The digital thread through a facility's lifecycle

2.5 AR Industry Perspective

The research team engaged various AR industry stakeholders as well as engineers involved with DT applications in other industries (such as transportation, oil, and gas) through a series of interviews, teleconferences, webinars, and other correspondence. 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. This section summarizes key insights, trends, concerns, and issues that stakeholders identified as important. Following is a sample of the interactions that the research team had with industry stakeholders:

- Various interactions with the TAG members introduced in Section 1.4 throughout the project:
 - Early in the project, the TAG advised the research team on expected challenges in the AR lifecycle and opportunities for DT technologies to facilitate solutions.
 - TAG members responded to a survey to help prioritize DT use cases for further investigation in this project, as described in Sections 3.2 and 3.3. They also provided general feedback on the DT use case characteristics that are most important to the AR industry.
 - TAG members provided valuable feedback on the generalized DT development framework covered in Section 2.3.

- Near the end of the project, in a final meeting with the TAG, the research team presented the preliminary conclusions and insights from the project and collected additional feedback on the TAG’s perspective.
- Finally, TAG members reviewed and commented on this report prior to final publication.
- Meetings with EPRI managers leading parallel research activities related to AR technologies, costs, and digitalization solutions (such as managers from EPRI Nuclear Maintenance Application Center, Radiation Safety, Plant Modernization, and ANT).
- Interactions with attendees of DT-related industry conferences and workshops (such as NRC workshops [9], [11]), including organizers, presenters, and audience.
- Meetings with U.S. national laboratory personnel leading DT research activities (for example, Idaho and Oak Ridge National laboratories).
- Conversations with stakeholders in other industries (such as transportation, oil, and gas) to get additional perspectives on the current state of DT technology and how other industries are using or planning to use DTs.

Section 2.5.1 introduces the main AR stakeholder motivation for investigating the potential of DT technologies (that is, reducing costs of NPP construction and operation). Section 2.5.2 explores opportunities to reduce costs and risks. Sections 2.5.3 discusses potential implementation challenges for DT adoption. This industry feedback helped to shape the course of the research focus during this project and should continue to influence the development and deployment of DTs in the AR industry.

2.5.1 A Key Driver: Cost Reduction

It is widely regarded among AR stakeholders that the cost profile associated with deploying and operating a new light water reactor (LWR) is untenable in the current U.S. energy market. This is evidenced by the premature shutdown of 12 nuclear reactors from 2013 to 2021 and seven more scheduled to be decommissioned by 2025 [27]. This trend has been attributed largely to the O&M costs of the current U.S. fleet of LWRs; indeed, most of these premature reactor closures cited operating losses, cheaper energy alternatives, or excessive equipment replacement costs as major factors contributing to permanent shutdown [27]. The industry has responded with a variety of initiatives to fund and investigate alternative solutions to invert this trend. For example, the goal of the DOE-funded ARPA-E GEMINA program is to reduce the fixed O&M costs² of ARs in the United States to about \$2/MWh, compared to about \$13/MWh for the existing fleet of LWRs, which represents approximately 80% of a LWR’s total generating cost [13]. The program contends that achieving this O&M cost reduction is essential for ARs to be economically competitive with other alternatives, such as natural gas. The ARPA-E-GEMINA program identified DT technology as a key opportunity to achieve this goal.

² Fixed O&M costs are the costs of power plant operation and maintenance that are incurred regardless of whether the plant is generating electricity (such as regular maintenance, inspections) [70].

Many industries are employing AI, advanced data analytics, distributed computing, powerful physics simulation tools, and other technological breakthroughs to advance autonomous, efficient, and low-cost O&M [13]. Advanced system controls, autonomous operations, and predictive maintenance are often mentioned by AR stakeholders as primary strategies in reducing O&M costs of future reactors. Many AR stakeholders are hopeful that existing and emerging DT technologies could help catalyze the adoption of these strategies.

Although AR industry attention on DTs has thus far focused largely on O&M cost reduction (for example, ARPA-E GEMINA [13]), there is also a recognition that DTs could improve efficiency in other lifecycle stages. The high capital cost of constructing new LWRs has often been further exacerbated by budget overruns and costly delays due to nonconformances identified during the design and construction phases. These often require expensive evaluations and/or corrective actions in the nuclear regulatory environment. AR stakeholders are interested to learn whether DTs can offer solutions to reduce nonconformances and the cost of corresponding corrective actions to enable a more streamlined and economical deployment of new NPPs.

2.5.2 Opportunities to Reduce Costs and Risks

AR stakeholders engaged during this project were principally interested in DT applications with the potential to reduce costs and risks in the design/construction and O&M stages. These concerns and interests are summarized in the following.

2.5.2.1 Design and Construction

AR stakeholders noted that on recent LWR construction projects, construction activities began before the design was 100% complete and final. This is common practice in conventional commercial and industrial construction, but it created unique challenges when implemented in the nuclear regulatory environment. Whereas conventional construction practices rely on an iterative and *ad-hoc* request-for-information (RFI) process to refine and clarify the design as construction progresses, the strict regulatory and licensing requirements at a nuclear construction site precluded efficient use of a similar process. For example, in a conventional construction project, if an inspector finds that a structural element is not in strict conformance to the design drawings, it is common for the builder to submit an RFI to the structural engineer to assess the consequences of the nonconformance. The structural engineer can often easily assess that the design included sufficient conservatism such that the governing code requirements are not compromised despite the nonconformance. In contrast, a nonconformance discovered at a nuclear site often triggers a lengthy quality assurance (QA) process that can include additional inspections, nonconformance reporting, detailed reanalysis, and potentially physical modifications or an amendment to the plant's licensing basis. These outcomes have proven very costly in terms of direct labor and downtime. Stakeholders therefore emphasized the need to move toward a process in which the design is 100% complete, optimized, and validated for accuracy and constructability before any construction begins.

Many potential DT applications have been conceived that could facilitate progress on this front. Following are several representative examples:

- A DDT of the plant, which would digitize and integrate various design information (for example, geometry, cost and schedule information, structural analysis), could enable rapid design iterations. This could help, for example, to rapidly assess consequences of nonconformances during construction.
- A DDT could serve as a common platform for the various trades to obtain and provide detailed design information. This could be used to advance the design to a greater level of development (LOD) prior to starting construction. For example, the design could conceivably be matured to LOD 400 (that is, as defined in AIA E202 [28]) prior to beginning construction by incorporating trade design information like shop/fabrication drawings into a BIM model. This would help to mitigate the need for design changes during construction resulting from ambiguity in a less-mature LOD design.
- Construction sequence simulations leveraging the DDT can be used to assess and optimize the design for constructability (for example, clash analysis, equipment layout planning). The idea of a construction sequence digital twin (CSDT) is further developed in Section 4.1.
- Parts orders and material stocking activities could be automated and monitored in real time as construction proceeds. This could help to mitigate the risk of construction delays associated with supply of construction modules and materials.
- The AR industry has also identified the need for improved configuration management in the design phase. A data-centric configuration management information system (CMIS) (for example, [29], [30]) integrated with design tools into a DT framework enabled by digital thread traceability (see Section 2.4) can ensure that design changes get broadcasted into the rest of the system to facilitate rapid detection of potential issues. Similarly, any changes in the configuration of a structure, system, and/or component (SSC) could trigger a design check to confirm that the configuration change does not result in an inadequate design.
- DTs also have potential applications for automated quality control of prefabricated parts and construction modules, some of which are envisioned by AR developers to be additively manufactured. Improved quality control and traceability could help to preclude costly delays resulting from delivery of nonconforming procured parts and modules. Similarly, automated inspection of concrete construction, steel erection, and other trades using scene capturing technologies (such as LiDAR, structured light) could capture as-built configurations in real time and feed the DDT to enable rapid evaluation and requalification of nonconformances (EPRI 3002023902 [31]).
- DTs could also be used to enable remote virtual monitoring and inspections to augment other means of ensuring compliance with regulatory and licensing requirements.

2.5.2.2 Operations and Maintenance

Stakeholders regard DT technologies as important in automating O&M in advanced reactors. Current AR concepts involve new, unique, and extreme environments where frequent ingress and egress of personnel might be undesirable and unsafe. Some stakeholders envision automated, robotic maintenance to be a central enabling technology of ARs, which would elevate human operators to an oversight role carried out remotely. Such autonomous/robotic O&M would also result in a leaner and more efficient workforce, which stakeholders identified as a critical

strategy to reducing O&M costs as envisioned by the ARPA-E GEMINA program. Stakeholders advised that DTs could be an essential element to such automated and robotic maintenance programs. For example:

- A DT of the plant could be used as a virtual environment in which to train and commission autonomous AI/ML algorithms prior to physical deployment (that is, prior to generating instructions for operating the physical asset).
- A DT could be leveraged to autonomously analyze a number of future scenarios based on current and past plant conditions and optimize fluid and gas parameters based on the analysis outcomes (for example, water chemistry model and control [15]; fire detection and response [32]).
- Autonomous personnel tracking could enhance plant security and reduce operation costs.
- Turbines across multiple plants could be instrumented to track fleet operation and maximize power output [33].

DTs could also facilitate development and deployment of predictive maintenance (PdM) programs, which could enable a more efficient use of the equipment throughout its lifetime by reducing unnecessary maintenance and minimizing premature replacement. Recognizing that the nuclear industry has already made significant progress toward developing PdM programs (for example, see [34], [35], [36], [37]), AR stakeholders envision that digital twins will improve current PdM methods and technologies. The idea of a PdM DT is further developed in Section 4.2.

2.5.3 Implementation Challenges for DT Applications in ARs

DT technology relies on several engineering domains, such as mechanical and electric hardware, onboard and off-product software, power and telecommunications networks, systems integration and interoperability, data storage solutions, and data science (AI/ML). As such, implementation challenges are likewise varied. The following subsections summarize salient implementation challenges identified during the industry engagement effort.

2.5.3.1 DT Integration in Conventional Workflows

Stakeholders who had been involved in piloting DTs in early design stages noted that DT implementation must be intentionally planned into the design workflow before substantial design activities begin. They found that inertia in conventional design workflows, combined with design project cost and schedule constraints, can be a barrier to the kind of integration and digitalization that is needed to deploy DTs during the design phase. The same is likely to be true as DTs are deployed in other lifecycle stages. Many NPP lifecycle processes (design process, construction process, commissioning process, and so on) have evolved over many decades and have been optimized to suit the tools and resources available. As DTs are introduced into these processes, the workflows, norms, business practices, and attitudes will need to adapt to accommodate and support the new technologies before their benefits can be realized.

2.5.3.2 Model Training

Some of the most useful applications envisioned for DTs pertain to performance prediction and optimization of the underlying asset or process. These capabilities will be powered by ML/AI algorithms trained to predict the asset behavior or the process outcome based on historical and current data. Stakeholders noted that the quality of these predictions depends on the quality of “training data” (that is, data fed to the algorithms to identify and learn patterns). To ensure unbiased training, the training data must have adequate coverage of the domain in which the ML/AI algorithms are expected to operate. ARs are still under development, with little or no prior real-world operational experience. As such, compiling high-quality training data presents a challenge for AR DTs, particularly in the beginning. This is expected to be less of an issue as more operational experience is gathered and more training data are collected, which can be fed back to train algorithms. In many cases, synthetic training data can also be produced by simulation using high-fidelity physics-based models, although this might require increased effort and costs.

2.5.3.3 Regulatory Certainty and Regulator Engagement

Stakeholders identified verification and validation (V&V) of DT components, and in particular any ML/AI algorithms, as a key area requiring engagement with the regulator to facilitate deployment of safety-related equipment. ML/AI algorithms are probabilistic in nature (that is, they use inference to predict likely outcomes), whereas current V&V approaches are deterministic in nature (that is, they ensure that the correct operation is being performed and performed correctly). In some cases, it might not be feasible to validate that an AI/ML algorithm is indeed performing the correct operation correctly. This is due to the “black box” nature of technologies like artificial neural networks and deep learning, where “hidden layers” of operations are performed without the opportunity for observation or scrutiny by the user. Therefore, new V&V approaches could be required to provide reasonable assurance that such advanced analytical tools generate reliable results and insights (see, for example, ASME Verification, Validation and Uncertainty Quantification Subcommittee 70 work on ML V&V [38]).

Also, ML/AI algorithms are expected to operate on large volumes of data collected over time. Stakeholders were uncertain whether this scenario may result in a regulatory liability, that is, when data potentially indicating a nonconformance were collected but not acted on because the associated ML/AL algorithm did not infer an anomalous state. There is also regulatory uncertainty regarding the extent to which a DT serving as a “single source of truth” repository (see Section 2.4 on digital thread) will be required to conform to nuclear QA criteria (such as 10 CFR Part 50, Appendix B [39]).

The regulatory framework for ARs is still under development. Regulatory uncertainty in V&V and similar issues might influence the scale to which DTs are implemented by AR developers. Stakeholders tended to agree that the best initial applications for DTs are likely those that are less strictly regulated, such as balance-of-plant (BOP) systems rather than primary coolant systems or other safety-related systems.

Stakeholders also generally agreed that regulatory certainty (including and beyond V&V) will be critical to the successful adoption of DT technology in the nuclear industry [10]. Continued, ongoing engagement among regulatory bodies (such as 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.

2.5.3.4 Scalability and Intersystem Performance

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. Stakeholders expected that, as multiple DTs are employed across various components and systems, scalability and intersystem performance issues might emerge, such as many installed sensors that potentially use different data protocols, varying data acquisition methods (wired/wireless), capability of operators to ingest and interpret large volumes of data, and validation of integrated models and their interactions. Stakeholders also noted that computational power and data storage capabilities might limit some DT applications. As DTs are developed and integrated for more assets and more data are 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, and optimization of data collection) are expected to increase dramatically. These will likely become areas where innovation is required to enable larger, integrated, and detailed DTs. Stakeholders suggested that it might be prudent to limit the deployment of DTs to the most critical and high-value systems first, and then scale to larger systems and more detailed models as permitted by the available DT technologies.

2.5.3.5 Sensor Integrity

A crucial aspect of DTs is an instrumentation network collecting real-time data on the physical asset or process to update the virtual model. In the case of ARs, these networks will have to be deployed in harsh environments characterized by conditions such as high radiation levels, high temperature, and high probability of mechanical damage (such as in construction environments). Consequently, sensing networks for AR DT applications will have to be sufficiently robust, reliable, and resilient to such conditions. Stakeholders also noted that systems capable of detecting sensor faults will be important to ensure accurate inputs to DTs.

2.5.3.6 Cybersecurity and Wireless Sensor and Data Transmission

Many DT applications depend on an abundance of sensors and data. For non-nuclear applications, the industry generally conceives of DTs as being fed by wireless sensor data through the IoT. Wireless sensors have several advantages over wired sensors. For example, they can be moved from one location to another without having to move wires; they can usually be installed and operated more quickly; they can be monitored, reconfigured, and augmented more easily. However, most NPPs typically avoid transmitting critical data wirelessly for cybersecurity and reliability reasons; as such, using wireless sensors for data transmission might be challenging for NPPs. This issue would need to be addressed to enable deployment of use cases that rely on an abundance of remote wireless sensors. Alternatively, wired sensors could be used in some cases, but the additional cost and space claim of the necessary extra cabling could make such use cases infeasible for NPPs due to excessive costs or physical limitations.

2.5.3.7 Updating and Maintaining the DT

NPP assets evolve over time, for example, as new safety features are added and SSCs are modified and improved. The evolution is even more pronounced and rapid in the context of AR design, development, and prototyping efforts. The DT must be flexible to efficiently keep up with such changes, and stakeholders identified DT configuration control as a key area requiring research and development. Continuous updates to the model could be challenging in rapidly evolving, high-accuracy environments. For example, it might be preferable to have hardware components (such as sensors) that can be efficiently replaced, upgraded, or deployed in different environmental conditions, if needed. For many use cases, particularly those associated with the development, prototyping, and design stages of ARs, DTs will ideally be designed to minimize the costs required to keep them consistent with the physical asset's current configuration.

2.5.3.8 DT Standardization and Intellectual Property

Broad adoption of DTs can succeed only if a high level of standardization is achieved in the production and deployment process. Standardized DT codes, data structures, protocols, hardware, and manufacturing and qualification operations will allow stakeholders to communicate using a common language and facilitate scalability and intersystem cooperation. Until a mature level of standardization is achieved, DTs might remain expensive and fragmented in functionality.

Data ownership issues such as confidentiality, intellectual property, and export controls must also be addressed. A DT potentially provides much more proprietary information about a design than the physical asset itself (such as design calculations and analyses). If a DT is produced by a product developer, manufacturer, and so on, they might be reluctant to give customers unfettered access to the DT to protect intellectual property. However, this kind of data-sharing across systems, vendors, and organizations is essential to developing integrated DTs. Ideally, the various stakeholders in a project involving DTs will address how data will be shared, issues with intellectual property rights, and so on very early in a project to ensure its success.

2.5.3.9 Cost-Benefit Analyses and Business Case

Stakeholders are generally hopeful that DT applications can reduce costs and risks throughout the plant lifecycle. However, they recognize that demonstrating the scale of future cost/risk benefits for ARs is currently a challenge because only a very limited number of relatively immature DT applications have been deployed in the nuclear industry to date. Validation that DTs can mitigate major cost issues (such as O&M costs and construction overruns) will be a critical step for widespread DT adoption in commercial projects. Early DT implementation (that is, in the AR design process) is believed to be one of the main opportunities to realize the benefits of DTs, yet some stakeholders find it difficult to justify the associated development and deployment costs while lacking successful commercial examples to support objective business cases. Experience from other industries (freight, aerospace, multistory residential building construction, and so on) could provide useful insights. The results of the DOE ARPA-E GEMINA program and other early research activities could also provide preliminary insights on the ROI of various digital twin applications. Section 2.7 provides general insights on costs and benefits related to DT development and implementation.

2.6 State of DT Technologies

DT technologies are evolving rapidly. This section categorizes some of the most common DT technologies based on their specific development stage. Technologies considered ready for successful deployment in nuclear DTs are covered under Section 2.6.1 (“Current State”). Section 2.6.2 (“Emerging State”) lists technologies expected to become widely adopted in nuclear DT applications in the near future. Emerging technologies have often been successfully implemented in limited, narrow applications for years, but applying those technologies to new applications or scaling them to one or more DTs would be an innovation. Section 2.6.3 (“Future State”) presents technologies that will likely require several years before being vetted and deployed in nuclear projects.

2.6.1 Current State

2.6.1.1 Software Topology

The typical DT technology stack has numerous software platforms with a multitude of variables. These software platforms and variables are frequently disjoined due to a lack of a common information model or ontology.³ Although no two facility programs are the same, the technology stack must be developed in a repeatable way to enable the digital thread for the aggregate DT use case. Figure 2-29 illustrates a DT software topology.⁴ It shows an archetypal aggregation of common digital engineering tools throughout a facility’s lifecycle. The sample diagram in Figure 2-29 can be used to understand the relationship between different software platforms. For example, Figure 2-29 shows how planning, project controls, and design authoring tools are leveraged during the early lifecycle of a project. This common DT stack then proceeds to integrate simulation and immersive reality experiences to deliver a cohesive tool.

³ In computer science, ontologies are categorization systems similar to taxonomies. Taxonomies are typically a simple hierarchical arrangement of entities (e.g., transportation, land transportation, road, car). The main difference is that taxonomies take into consideration one type of relationship (unidirectional), while ontologies account for many different complex relationships between the entities (arbitrary format). See further discussion in [71] and [72].

⁴ In computer science, software topology is the schematic representation of interconnections between virtual (software) elements.

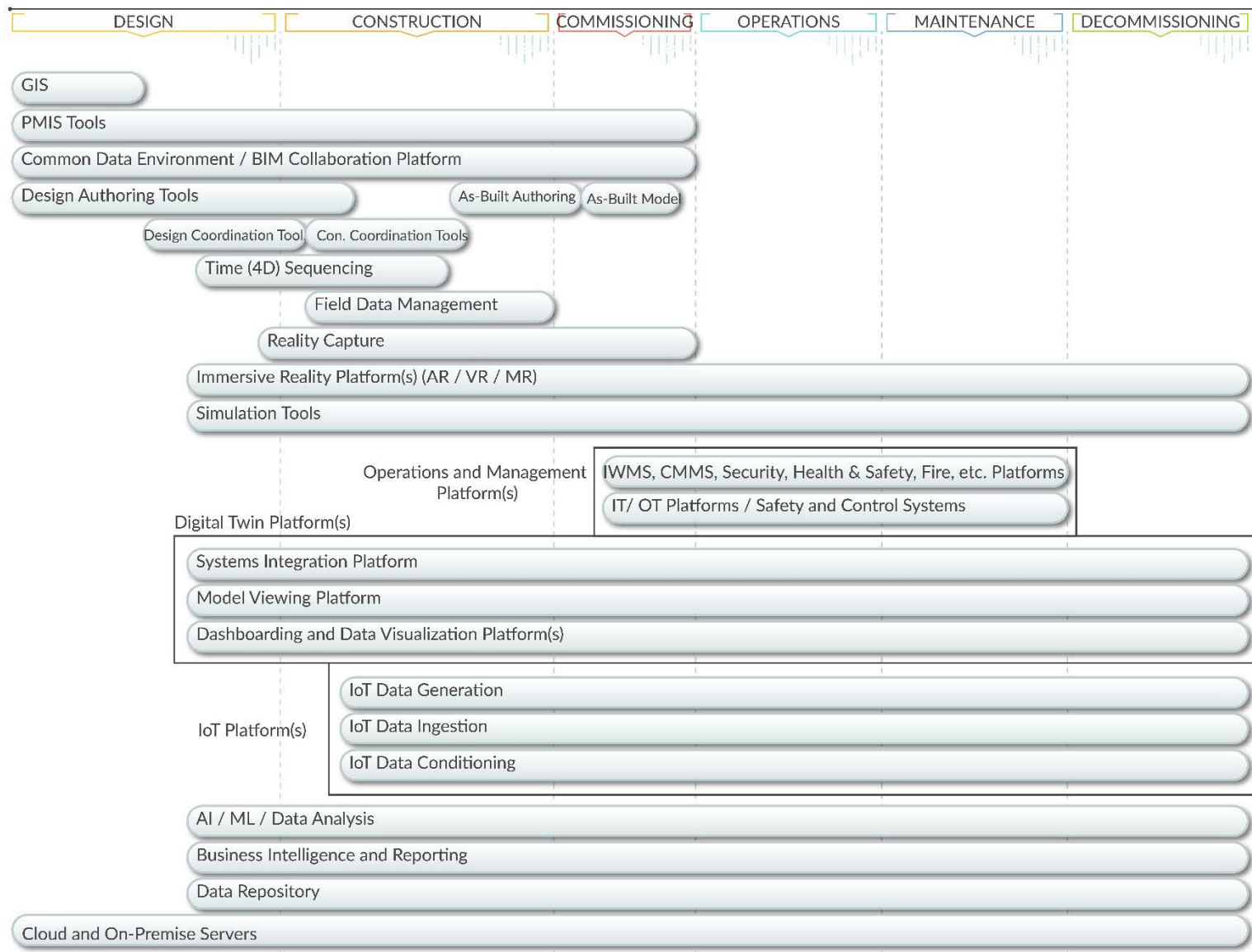


Figure 2-29
DT software topology

The lower half of Figure 2-29 depicts a common challenge regarding data analytics. The diagram shows that the business intelligence analysis and reporting can begin during the design phase; however, the resultant analytics are likely to be different calculations during the construction and operations stages. Similarly, the simulation tools could also vary throughout the lifecycle. The diagram is intended to illustrate what a software topology might look like for a DT that has been developed from early inception of a facility through decommissioning; it is not intended to identify specific tools nor how they could be integrated into the digital thread.

2.6.1.2 Sensors, Data Acquisition, and Monitoring

Broadly speaking, a sensor is a device that detects events or changes in its environment and sends the information to other devices (frequently computer processors) that indicate or control the system state. Contemporary sensors are generally used with other electronics, such as a logic controller and/or a human input device [40].

Sensors can be deployed to measure individual properties such as pressure and temperature, as a part of a package to provide multiple related properties, or in a mesh configuration to allow interaction with data from other sensors within the mesh. “Smart” equipment incorporates one or more of these types of sensors built directly into the equipment to provide performance data and enable the possibility of control.

Three example categories of specialized sensors for ARs are:

- Chemical sensors: Provide data about the chemical composition of the environment that is typically in liquid or gas phase.
- Biosensors: Detect chemicals or compounds related to a biological component.
- Metal-oxide semiconductor (MOS) sensors: Sensors based on MOS widely used to measure physical, chemical, biological, and environmental parameters. These include biochemical sensors, image sensors, and monitoring sensors.

Consideration of IoT data acquisition devices should not be limited to direct contact sensing devices. Non-contact equipment, such as video cameras, infrared imaging, and other low-voltage system components, can also be applied for data acquisition. For example, infrared imaging can be implemented to monitor absolute or relative temperatures of equipment or systems, which can then be fed back to the IoT platform for conditioning and analysis along with the other data streams.

2.6.1.2.1 Data Protocols

Data protocols enable the exchange of data in a structured and meaningful way. Without protocols, hardware would not be able to process the data received. Sensors are capable of not only collecting and relaying data, but also computing basic results “at the edge.” Sensors and gateways (a centralized hub of sensors) enabled with edge computing inherently lessen the need for computing resources at the controller or cloud. Furthermore, standard protocols enable “smart” devices and “connected” sensors to communicate with each other, for example, to respond if one or more of them malfunctions.

2.6.1.2.2 Device Infrastructure

When implementing an IoT system, an initial consideration is device provisioning, which refers to the process of connecting IoT devices such as sensors or smart equipment to the servers or platform with which it will communicate. IoT device provisioning includes enrolling a new device or sensor onto the topology, giving it a unique identification, and configuring it to send data to the system. Authentication is also part of the provisioning process. Authentication ensures that only secure and trustworthy devices are added to the network with the correct certificates and credentials.

Once provisioned, devices will require monitoring, updates, and, potentially, repairs. IoT device management software provides centralized, real-time information and bi-directional control of devices. There are numerous device management platforms available, including on-premises facility operating system frameworks, or secure cloud platforms, such as Azure IoT Hub, Azure IoT Central, Google Cloud IoT Core, IBM Watson IoT, and AWS IoT Device Management.

Common features of a device management platform include:

- Device discovery — A typical IoT architecture can involve hundreds or thousands of unique devices across various organizational units and user environments. When assets are instrumented with internet-enabled sensors, IoT device management platforms might allow for automated discovery and identification of each object, in lieu of requiring manual input of device identifiers.
- Device monitoring — A real-time device registry could provide any combination of details and data related to each device. This might include items such as product identification number, current location, active status, and battery life.
- Remote provisioning — Device management tools might help distribute individual or batch updates and security patches to devices.
- Remote device access — In addition to repairs and updates, administrators might benefit from basic remote access of connected devices. By taking control of device functionality, administrators can trigger events or perform actions without the need for physical intervention in the device environment.

Although *telemetry* typically refers to communication through wireless radio frequency, it also includes the use of other methods, such as local area network, optical link, or other wired communications-like power systems. Many modern sensors can take advantage of global system for mobile networks to receive and transmit telemetry data without being connected to local networks. Multiple concurrent technologies can be applied, depending on needs such as power consumption, data rate, and range.

2.6.1.3 Reality Capture

Laser scanning, 360° photography, and photogrammetry facilitate accurate comparison of physical as-built conditions to digital design information. An initial use case for laser scanning was implemented to capture existing spaces to enable designers to formulate solutions for new designs. Today, laser scans are also used by construction professionals to provide digital records of installation progress.

Reality capture has also shown promising applications to create a DT where no other 3D representation exists. For example, a laser scan of an existing asset can produce a point cloud, which is processed into a DT platform to support O&M. The platform is then able to bond asset component identifiers and associated metadata to portions of the point cloud. This leads to a viewable virtual experience that delivers outputs similar to DTs that are based on user-defined 3D geometry models.

2.6.2 Emerging State

2.6.2.1 Building Information Modeling and DTs

Sections 2.6.2.1.1–2.6.2.1.3 present examples of how BIM and DTs can assist with the development of aggregate DTs (as described in Section 2.5).

2.6.2.1.1 Advanced Work Packages

DTs can provide significant benefits by utilizing its data throughout the build process. Advanced work packages (AWPs) combine historical, BIM, DT, and simulation data to enable prescriptive, measurable, and verified construction execution. Studies have determined that AWP can increase field productivity by 25% and reduce the total installed cost by 10% [41]. AWP aids in construction-driven planning and optimization. Standard work packaging is not specifically construction-driven—planning is carried out in a much higher level and does not always account for the logistics and workforce planning. An AWP is a hierarchical structure of tasks: it begins with grouping activities into overall construction work packages (CWPs) to identify the critical path of the project. The CWP is then extracted into installation work packages (IWPs) by applying the associated resources to specify the executable construction tasks.

AWPs are sometimes thought of as construction-driven planning exercises; however, they can have far greater impact on the overall program. Historically, AWP have been implemented by engineering, procurement, and construction (EPC) projects between the procurement and construction phases and linked back to the engineering phase with the use of work breakdown structures (WBSs). Using BIM and MBSE, advanced work packages could be developed and further simulated during the design of the facility. Pre-fabrication and off-site manufacturing would also benefit from an integrated AWP approach.

2.6.2.1.2 Bill of Materials and Supply Chain Management

Processes surrounding bills of materials and supply chain management have traditionally been analog. Furthermore, these pre-digital processes are still mainly manual and conducted with little automation. BIM and DT enable the digitalization and automation of these process. The level of automation is dependent on the design organization's digital maturity. A DT of a supply chain simulates performance, value streams, and risks. This type of DT identifies where uncertainty and volatility exist and provides optimization solutions where possible.

2.6.2.1.3 Industrialized Construction/Manufacturing

DTs have an emerging capability to use data to enable prefabrication, off-site manufacturing, and modularization of facility components, which can enable more efficient and faster building methods. Components are designed and prefabricated off-site and then assembled and incorporated on-site. Many construction companies are applying this digital approach to aid in variability and risk reduction, speed, and quality of construction.

An emerging technology in the construction industry, 3D printing is currently being proven successful for large-scale applications such as residential housing; however, it might not be ready for implementation in critical infrastructure. By using 3D design and 3D printing for equipment in the field, builders can precisely layer materials from a digital model.

2.6.2.2 Visualization

Immersive experiences have rapidly transitioned from the gaming sector into commercial design, construction, and operations. The DT uses several visualization capabilities to enhance a user's understanding of the digital and physical environments. Additionally, immersive experiences offer more collaborative environments for remote workers:

- AuR supplements the physical world by assisting personnel with tasks such as visualizing or simulating procedures for maintaining and repairing equipment. For example, a tablet or headset can display design specifications and all associated data when pointed at a piece of equipment in the facility.
- VR can enable a person to immersively experience a DT's simulated environment. This can be performed with various headset technology. VR technology is already being used for training staff in nuclear plants for specific use cases (for example, to minimize radiation exposure during equipment maintenance operations).
- MR superimposes the virtual and physical worlds in one view. An example would be visualizing the 3D model in a real-world context. For example, MR can enable a user to view an AR facility's virtual representation at a physical, real-world site.

2.6.2.3 Generative Design

Generative design is the process by which computer simulations use ML to generate numerous possible scenarios for the design of a component, system, or facility. This technology is classified as emerging because it is not currently integrated into many systems engineering methodologies or design workflows.

2.6.3 Future State

2.6.3.1 Advanced Robotics

Robotics technologies are advancing rapidly throughout the industry, especially where precision and life safety are paramount. Cognitive robots and autonomous robotics can be applied to execute routine processes at minimal cost with high accuracy, including maintenance, repair, and overhaul in environments that would be harmful to a person. Using the digital thread, autonomous robots can execute operations and navigate from the DT.

Robotics in construction allow complex physical tasks to be performed with minimal human intervention and are becoming more common in the construction industry. There has been extensive development of methods to automate various trades. Robotics are being used for bricklaying, welding, and concrete pouring. Employing robots to perform typical human labor provides construction efficiencies, precision, reduced human labor, and enhanced safety.

2.6.3.2 Inspection Automation

The precision and data of the DT will help drive the automation of inspection using drones, cameras, and lasers to capture current conditions and automatically inspect elements. Similar automated data acquisition processes can be used to identify maintenance needs and nonconforming construction or operating conditions. AI and ML can be integrated to automatically identify problems in equipment and materials.

2.7 Costs and Benefits

Costs and benefits of DTs are highly variable, depending on the use case and technologies used to develop and monitor the DT. These sections provide a rough cost basis and benefits across all types and maturities of DTs.

All costs and associated ranges have been derived from various sources of software products and services. Costs are expressed as U.S. dollars unless otherwise noted.

2.7.1 Costs

The cost of a DT tends to be heavily front-end-loaded for personnel resourcing. As with any software implementation, there will be an initial cost as well as an ongoing cost. The cost of operating and maintaining a DT will reduce over time and level out when it is in deep operation. As time and technology progress, the costs, both initial and ongoing, should decrease. There will most likely be a quicker decline in software-related costs as more standardized DT platforms come to market with toolsets such as low- or no-code environments that allow end users to define and control the DT without support from specialized developers. The following is a list of typical one-time and ongoing costs throughout the DT lifetime:

- One-time setup costs:
 - Hardware purchase
 - Software purchase
 - Initial labor for DT development, testing, and deployment
- Ongoing operation costs:
 - Hosting fees for hardware and software
 - Maintenance/replacement/upgrade costs of hardware and software
 - Labor for DT maintenance/replacement/upgrade (for example, information technology [IT] personnel, equipment maintenance personnel)
 - Security, safety, and regulatory compliance requirements
 - Scaling the DT

Initial costs can be correlated to the first five steps of the development lifecycle (A0-E0), whereas the ongoing costs are correlated to the last two steps (F0–G0). Furthermore, A0–C0 are personnel resource-intensive, whereas D0-E0 are likely to have higher software and hardware costs. Finally, F0 will have a much more balanced usage of software, hardware, and personnel. G0 is highly variable, depending on the scope and extent of scaling a DT. Some applications might benefit substantially from economies of scale, but others could require substantial redesign and redeployment in order to scale to larger scopes.

To facilitate a rough order of magnitude estimation for the cost of a DT, Table 2-1 provides rough cost ranges of the development steps from Section 2.3. Numerous assumptions were made to develop these estimated costs per stage, including:

- A full aggregate DT is developed and used.
- Commercial off-the-shelf (COTS) software is used in lieu of developing a custom solution. COTS software will not solve all DT integration challenges; further, it typically requires some level of additional customization. If a DT platform is developed from scratch with limited platform integrations to existing operational systems, it would add significant development cost. Depending on the target use case, this cost could be in the magnitude of \$1,000,000 or more.
- The final costs will be based on the complexity of the DT, which provides for the variability in the estimated cost range (see Table 2-1).

Table 2-1
Estimated cost ranges per DT development stage

Stage	Estimated Minimum Value	Estimated Maximum Value
A0, Gather Requirements	\$120,000	\$140,000
B0, Scoping the DT	\$100,000	\$200,000
C0, Procuring the DT	\$80,000	\$160,000
D0, DT Implementation	\$1,600,000	\$3,200,000
E0, Connecting the DT	\$1,200,000	\$2,400,000
F0, Monitoring the DT	\$400,000	\$800,000
G0, Scaling the DT	\$600,000	\$1,200,000

Total Cost = A0 + B0 + C0 + (D0 + E0 + Total Cost of Iteration(s)) + (F0 * Number of Operational Years) + G0

The following sections identify the recommended categories of software, hardware, and personnel. Each section includes an estimated percentage. The formula provided is a generic approach to understanding the total cost for a DT over a period. This simplistic cost model can be used during stages A0 and B0 to validate the projected benefits against the costs by performing feasibility studies and/or cost-benefit studies.

Sections 2.7.7.1– 2.7.7.3 identify the recommended categories of software, hardware, and personnel. Each section includes an estimated percentage range for the development. Ongoing usage and maintenance costs are estimated to range from 3% to 10% of the total construction cost range for the development. Ongoing usage and maintenance costs are estimated to range from 3% to 10% of the total construction cost.

2.7.1.1 Software and Implementation Costs

Software and implementation costs of a DT can vary depending on the approach and scope. Initial COTS software costs are typically based on the number of users and data/resource usage. Initial software implementation of the DTs is typically estimated from 2% to 8% of the total construction costs of the facility. The common types of necessary software to develop DTs can be categorized, for example, as follows:

- Simulation and Analysis
 - Structural Analysis
 - Fluid Analysis
 - Environmental Analysis
 - Data Analytics
 - ML/AI Analysis
- GIS
- Design Creation/Automation
- CDE
- Systems Engineering
- Coordination (including Clash Detection)
- BIM/3D Modeling
- Visualization/Rendering/MR
- DT Platform
- Facility Management (integrated workplace management system [IWMS], CMMS)
- Other Operational Systems (ERP, MDM)

2.7.1.2 Hardware Costs

Hardware costs will vary based on several factors. Existing network topology and security requirements tend to drive the hardware section of the DT architecture. For instance, cloud infrastructure costs will be very different from a system completely based on edge-computing infrastructure. Initial hardware costs of the DTs are typically estimated from 3% to 6% of total construction costs. Regardless of the processing and storage options selected, hardware can be separated into at least of two categories: infrastructure, also known as *middleware*, and data acquisition.

Regarding infrastructure options, depending on the DT platform selected, these resources can be managed by the software platform provider with no additional costs beyond initial procurement. When building a DT platform from the ground up, there are three main compute options: on site, cloud, or remote resources. Each of these solutions has advantages and limitations, but their overall costs tend to be similar. For a newly constructed facility, a general rule of 1–3% could be applied for the cost of the infrastructure assets.

Data acquisition elements should be considered an extension, and not a replacement, of typical instrumentation and control (I&C) practices. Typically, I&C is a relatively small module of a plant’s maintenance and capital budget; however, it has a large impact on the plant’s reliability, performance, and safety [42]. Common industry standard sensors, such as environmental or presence, cost between \$100 and \$1,000. Specialty sensors, such as radiography, cost between \$10,000 and \$100,000. A major consideration of data acquisition elements is the need for wired versus wireless network connectivity. Wired networks are generally considered more reliable, but the cost continues to increase to follow materials prices. Wireless networks provide flexibility and cost advantages that cannot be achieved with wired networks. For example, studies have found that wired cabling costs can range from \$1,000 to \$2,000 per foot [43]. It might not be cost-effective or practical to instrument all the physical assets in a plant. Data acquisition elements generally fall within the range of 1–3% of the construction cost for a new facility.

2.7.1.3 DT Personnel Roles

Many personnel roles are involved the planning, development, use, and maintenance of a DT. In addition to traditional software development and implementation roles, it is recommended to include two new roles specific to the management of the DT program: the DT manager and DT integrator. The manager acts as a program manager to ensure that several smaller projects are moving toward the integration of a complete DT. After implementation, the manager transitions to managing the maintenance and future development. The integrator is responsible for establishing the connections between the physical assets and DT during the initial implementation. Later, the integrator manages and updates those connections. Initial personnel costs of the DTs are typically estimated from 3% to 6% of the total construction costs of the AR. The following are common personnel titles and estimated market costs:

- DT manager: \$300/hour
- DT integrator: \$250/hour
- Project manager: \$250/hour
- Product manager/product leader: \$250/hour
- 3D modeler: \$100/hour
- UX/UI designer: \$50/hour
- Data scientist: \$250/hour
- Data engineer: \$200/hour
- Full stack or mobile developers: \$175/hour

- DevOps: \$200/hour
- QA: \$150/hour
- Cybersecurity: \$225/hour

2.7.2 Benefits

When considering DT implementation, direct and indirect benefits should be considered. Direct benefits are measurable or quantifiable. Examples of direct benefits include positive revenue, profit, increased generation, and lower cost per kWh. Indirect benefits are more qualitative, such as improved brand value, environmental benefits, safety awareness, or customer satisfaction. Not all benefits are necessarily realized during the operation of a DT; many benefits can be provided during the planning, development, and implementation stages.

Examples of DT benefits during the planning and development stages are the reduction in prototypes and subsequent change management, virtualized and less costly tests and simulations, and the use of digital models to verify design and process studies. Examples of benefits during the implementation of DTs include better design, construction, and commissioning team collaboration; planning and scheduling; employee training; and the reduction in possible construction quality issues. Possible benefits during the operations stage include reduced maintenance costs, enhanced efficiency and productivity, real-time remote monitoring, and better financial decision-making.

3

IDENTIFICATION, EVALUATION, AND PRIORITIZATION OF USE CASES

Based on the literature review and stakeholder engagement described Section 2, the research team compiled a list of 29 potential DT use cases for AR applications. The purpose of the list is to provide candidate use cases for further development in Section 4, which illustrates the DT development process outlined in Section 2. The list also provides readers interested in developing DTs with a menu of ideas for potential AR-related applications, as well as references to literature describing related research and development efforts.

Section 3.1 and Appendix A identify and describe the 29 use cases. The cases were evaluated by the TAG to help the research team prioritize two cases for further development in Section 4. Section 3.2 outlines the TAG’s evaluation and corresponding results. Based on the TAG feedback and follow-up interviews with TAG members, the research team selected two cases for further evaluation: one related to construction sequence simulation and the other pertaining to PdM.

3.1 Use Case Identification

Appendix A identifies and describes the 29 DT use cases. Although many use cases have applicability across several NPP lifecycle stages, each use case is nevertheless classified by the lifecycle stage to which it is considered most applicable; see Table 3-1.

Table 3-1
Use cases per lifecycle stage

Lifecycle Stage	Number of Use Cases
Design	4
Construction	4
Commissioning	2
Operations	11
Maintenance	6
Decommissioning	2
Total	29

For each use case, Appendix A 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 [15]: Informed Decisions, Design Optimization, Configuration Management, and Health Monitoring
- The target benefits of the use case
- High-level requirements to successfully implement the DT

For example, Use Case 4.2, “Smart Chemistry Monitoring and Control,” describes a DT that improves the Operations lifecycle stage by optimizing chemistry controls and increasing reliability. It involves monitoring and modeling working fluid chemistry to enable early identification and mitigation of adverse trends and anomalies. Successful implementation will require the development of advanced chemistry monitoring and control platforms. Advanced platforms might include, for example, an improved plant chemistry simulator (PCS) module to represent plant-specific heat balance and physical models, and integration of real-time data feeds from tools such as SMART Plant Works (EPRI 3002020014 [15]). Similar details are provided in Appendix A for the other use cases.

3.2 Use Case Evaluation and Prioritization

The use cases in Appendix A were reviewed, evaluated, and prioritized with input from TAG members to select two cases for further development in Section 4. Each TAG member was invited to help identify the cases that were the most attractive and beneficial for AR technologies, as described in the following.

TAG members were asked to consider the example issues and DT characteristics described in Tables 3-2 to 3-6 when evaluating the use cases. Many of these issues are related to topics in Section 2.5 because they were synthesized based on engagement with industry stakeholders:

- Table 3-2, Technology readiness: Are the necessary hardware and software tools and components readily available, or are additional research and development needed before the use case can be implemented?
- Table 3-3, Utility/value: What kinds of benefits can be expected from implementing the various use cases?
- Table 3-4, Scalability: How flexible is the use case? Can it be deployed in a low-risk, low-cost manifestation at first, then scaled up to realize greater benefits?
- Table 3-5, Regulatory certainty: What regulatory uncertainties exist, and how might they be resolved when deploying the use case?
- Table 3-6, AR applicability: Does the use case address current needs and pain points specific to AR technologies?

TAG members were also invited to consider the rough-order-of-magnitude costs that can be expected for procuring and deploying the various elements of DTs. Section 2.7 of this report provides additional context and analysis of DT costs.

3.2.1 Use Case Evaluation Criteria Tables

Table 3-2
Technology readiness

Characteristic/Issue	Considerations
Sensor integrity	<ul style="list-style-type: none"> • Sensors need to be robust and reliable to perform in the harsh environments of the various AR lifecycle stages, such as rugged construction conditions, high radiation levels, and high temperature. • Multiple channels (typically three or four) are required to ensure sensor reliability. • Virtual sensing approaches could mitigate this concern, but the cost of implementation is uncertain. • Stakeholders have proposed data-driven methods to support diagnosis of sensor faults.
Wireless versus wired sensor deployment	<ul style="list-style-type: none"> • For nuclear applications, a wireless IoT sensor deployment strategy will need to overcome challenges associated with connectivity reliability, cybersecurity, and potential interference with other systems (for example, safety systems). • Wired sensors might be a viable alternative if the cost and effort of cabling are not prohibitive.
Data-driven models/ algorithms and training data	<ul style="list-style-type: none"> • The success of ML/AI algorithms in reliably predicting and optimizing the performance of the asset/process represented by the DT is highly dependent on the quality of training data and the extent to which the training data capture the domain of states in which the ML/AI algorithms are expected to operate. • ARs are emerging technologies limited to early-stage operational experience. Compiling high-quality training data in such cases presents a challenge. However, in many cases, training data can also be produced by simulation using high-fidelity, physics-based models, although this might require significant effort and cost.
High-fidelity, real-time, physics-based models	<ul style="list-style-type: none"> • Computational power demands and associated costs increase with increasing fidelity in simulations and as applications require results nearer to real-time. Therefore, DTs requiring high-fidelity, near-real-time simulation must provide substantially more value than DTs not requiring this capability to justify the higher costs. • High-fidelity, validated multiphysics-based models may require substantial research and development for certain AR applications where innovative materials and physical/chemical/nuclear processes are involved. • Computation time increases rapidly with increasing complexity, which can be driven by integration of physics-based models across multiple systems and components. Complexity also increases as models incorporate additional physics (such as integrated thermal and mechanical physics) and as the models are integrated with more sensor data. Enabling technologies will likely include data management/compression, model reduction, and similar simplifying techniques to offset the cost of increasing complexity.

Table 3-2 (continued)
Technology readiness

Characteristic/Issue	Considerations
Integrated digital framework	<ul style="list-style-type: none"> • A DT typically integrates several smaller disparate digital systems (for example, BIM versus a sensor data acquisition system). No universal digital framework is currently capable of enabling rapid development of DTs across all application areas by enforcing a common interface among different digital systems. This translates into significant development effort and cost for DTs built from interdisciplinary technologies. • Multiple platforms are available for certain applications (such as BIM platforms for integrating geometry and procurement information). Technologies will continue to be developed as use cases expand into new industries and DTs become more integrated and sophisticated.

Table 3-3
Utility and value

Characteristic/Issue	Considerations
Enabling technologies	<ul style="list-style-type: none"> • Some use cases might be indispensable in enabling certain AR reactor technologies as economically viable. These should be identified and prioritized.
Cost reduction	<ul style="list-style-type: none"> • Short term and long term.
Improved reliability	<ul style="list-style-type: none"> • Consistent operational throughput/output. • Increased operational life.
Optimized performance	<ul style="list-style-type: none"> • Maximized efficiency. • Maximized operational life. • Minimal maintenance burden.
Improved safety	<ul style="list-style-type: none"> • Many ARs are designed to be “walk-away safe.” DTs could be used to demonstrate these design capabilities in a cost-effective manner. Furthermore, DTs can be leveraged to improve safety beyond strictly preventing nuclear accidents, such as by reducing occupational hazards (radiation doses and so on) for plant personnel.

**Table 3-4
Scalability**

Characteristic/Issue	Considerations
Scope of application	<ul style="list-style-type: none"> • A DT can be developed at the level of the subcomponent, component, system, plant, or plant fleet. Many individual use cases can be developed at one level and then scaled to others. Not all levels, however, are feasible for all use cases. • Costs, complexity, logistics, technology readiness, and security concerns could all be impediments to scaling up to larger scopes of application.
Versatility and economy of scale	<ul style="list-style-type: none"> • Some costs of DT deployment might decrease on a per-use-case basis with each additional use case implemented (such as data center, personnel to develop and maintain integration platform), such that the marginal economic benefit increases with each additional use case deployed. • Several use cases have potential to deliver value across multiple lifecycle stages; others are more restricted to a single stage. • Some stakeholders outside of the nuclear industry have found through experience that a combination of DT use cases might need to be implemented together to achieve desired economic benefits.
First-of-a-kind versus n th -of-a-kind deployment	<ul style="list-style-type: none"> • DTs for the first generation of ARs might not be directly usable for successive generations. DTs that are readily modifiable could bring additional savings and benefits. • Costs and risks of developing a first-of-a-kind DT can be substantially diminished in subsequent deployments. For example, subsequent iterations might justify using fewer sensors based on experience or require more sensors to reduce uncertainty. • Benefits realized from implementing DTs across multiple similar assets can increase with each deployment. For example, trends and lessons developed from one plant can help to inform predictive capabilities at others.
Analytics maturity	<ul style="list-style-type: none"> • Most use cases can be scaled along a spectrum describing the maturity of the analytics capabilities used. This scale of analytics maturity has been commonly described in the literature using broad categories, such as those discussed in Section 2.1 (that is, descriptive, diagnostic, predictive, and prescriptive).

Table 3-5
Regulatory certainty

Characteristic/Issue	Considerations
Verification and validation (V&V)	<ul style="list-style-type: none"> • V&V of DT systems in general, and particularly of ML/AI algorithms driving them, might be required, consistent with typical nuclear quality assurance requirements. • Because digital twin, ML, and AI are emerging technologies, there might be few precedents available on successful V&V as well as new challenges encountered. For instance, ML/AI algorithms are probabilistic in nature, and V&V approaches for inherently probabilistic tools and methods are less well established than more traditional, deterministic, physics-based analytical tools.
Safety versus non-safety applications	<ul style="list-style-type: none"> • Industry stakeholders have expressed an expectation that DTs with advanced analytics capabilities will face more regulatory uncertainty when implemented on safety systems (such as reactivity control) than on non-safety systems (such as turbine control).
Degree of sophistication	<ul style="list-style-type: none"> • DTs can vary considerably in sophistication; they can be strictly descriptive or can include a broad spectrum of analytics capabilities, with autonomous control representing the most mature analytics capability. • Industry stakeholders have expressed an expectation that DTs with more sophisticated analytics capabilities (such as autonomous control) will face more regulatory uncertainty than simpler implementations (such as strictly descriptive).
Data vs. knowledge	<ul style="list-style-type: none"> • Many DT use cases involve collection, processing, analysis, and storage of large volumes of data pertaining to the plant state. • There might be practical limitations in organizing the large volume of data in a cost-effective and efficient form. As such, the plant operators' capability to comprehend and respond to all the available data at any given time in some cases might be hindered. • It is possible that collected data will indicate an anomalous condition that was not known to or acted on by operators or automated controls. • Some industry stakeholders have expressed uncertainty about how such a situation might be handled by regulatory authorities in which plant operators have data but not knowledge about potential adverse plant conditions/ states.

**Table 3-6
AR applicability**

Characteristic/Issue	Considerations
AR-specific systems, components, and challenges	<ul style="list-style-type: none"> • The focus of this project is DT applications for ARs. Many use cases are general and could be applied across various industries. For this project, preference should be given to use cases that address specific needs of the AR industry. • Use cases that are unique to ARs and/or the nuclear industry might require more development compared to others that could more easily adopt means and methods from other industries with mature DT technologies (manufacturing, aerospace, and so on).
Technology specificity	<ul style="list-style-type: none"> • Certain use cases could be more applicable to a particular AR technology than others.

3.2.2 TAG Questionnaire and Responses

The questionnaire in Appendix B asked participants to do the following:

1. Identify five highest-priority use cases, then rank them by the following considerations: technology readiness, expected cost, utility and value, scalability, regulatory certainty, and AR applicability. Also, rank them overall. Provide comments explaining the selection and rankings.
2. Explain which considerations were most important in the prioritization and why.
3. Advise whether other aspects, qualities, or characteristics of use cases should be considered going forward.
4. Identify AR-specific systems or features that could benefit from DTs but were not included in Appendix A.
5. Identify any additional use cases envisioned for ARs not included in Appendix A.
6. Share any expected challenges in implementing DTs for ARs.

Six TAG members representing four AR technology developers and one utility company provided the requested input. The questionnaire results and any additional TAG comments on the use case table were summarized and fed back to the TAG for further concurrence on use case prioritization. Table 3-7 shows 16 cases that were shortlisted by at least one TAG member (TAG members are identified in columns A–F of Table 3-7). Of the 16 shortlisted cases, the following three were shortlisted by at least three TAG members:

- 2.2 – Real-Time Construction Sequence Optimization and Front-Running Simulations
- 2.3 – Automated Construction QA
- 5.5 – PdM

Table 3-7
Top use cases

#	Use Case	TAG Member					
		A	B	C	D	E	F
1.2	Construction Sequence Simulation					X	X
1.4	Sensor Layout Optimization				X		
2.2	Real-Time Construction Sequence Optimization and Front-Running Simulations	X		X		X	
2.3	Automated Construction QA	X		X	X	X	X
2.4	Quality Control and Qualification of Off-Site Manufactured Components						X
3.1	Virtual Plant Simulator for Operations Training and Optimization				X	X	
3.2	Virtual Commissioning		X				
4.1	3D Mapping and AuR Visualization of Ambient Radiation Levels	X			X		
4.2	Smart Chemistry Monitoring and Control						X
4.4	Narrow-Band Dynamic Operating Envelope	X	X				
4.7	Fleet-Level Performance Optimization		X				
4.8	Mobile Access to Digital Configuration Management Information			X			
5.1	Robotic Maintenance	X				X	
5.2	Virtual Walkdown and Inspection			X			X
5.4	Sensor Fault-Detection		X				
5.5	Predictive Maintenance (PdM)		X	X	X		

Based on responses to Question No. 2 of Appendix B, Table 3-8 shows the considerations that TAG members ranked as most important when prioritizing use cases. The following are the three most important considerations according to TAG members:

- Cost
- Utility/value
- Technology readiness

Table 3-8
TAG top considerations

Consideration	TAG Member					
	A	B	C	D	E	F
Technology readiness	X			X	X	X
Cost	X	X	X	X	X	X
Utility/value	X	X	X	X		X
Long-term risk reduction			X			
Scalability				X		
Regulatory certainty						X
AR applicability					X	

3.2.3 Survey Findings

In addition to Tables 3-7 and 3-8, other survey response information, such as comments on individual use cases and answers to the remaining questions in the Appendix B questionnaire, was reviewed by the research team and incorporated into the AR industry perspective summary in Section 2.5. The collective feedback was used by the research team to select two use cases for further development in Section 4:

- Combined 1.2 and 2.2
 - 1.2: Construction Sequence Simulation
 - 2.2: Real-Time Construction Sequence Optimization and Front-Running Simulations
- 5.5: PdM

These two use cases (1.2+2.2 and 5.5) are described in Sections 3.2.3.1 and 3.2.3.2, respectively. Use Case 2.3 (Automated Construction QA) received the highest number of TAG votes but was judged less suitable for the illustrative purposes of Section 4 and was therefore not selected for further development, as explained in Section 3.2.3.3.

3.2.3.1 Use Cases 1.2 and 2.2 Discussion

Use Cases 1.2 and 2.2 are closely related and were selected for further development for the following reasons:

- Both focus on reducing construction costs and delays, which stakeholders indicated are essential to the success of the AR industry overall.
- The use cases focus on the design and construction lifecycle stages, which are best aligned with the current stage of AR development.
- TAG members were particularly interested in the potential for these DTs to aid in understanding the impact that decisions during construction will have on costs, safety, and satisfying design requirements.

- The underlying technologies, such as construction cost estimating and scheduling, BIM, and probabilistic simulation, are all mature relative to many other use cases.
- The use cases require relatively little physical asset integration and metrology (such as sensors, network systems), so they are likely more straightforward to implement than many other cases.
- The modeling and simulation tools and data could be beneficial to streamline and improve offsite primary manufacturing and production of subassemblies.

Because Cases 1.2 and 2.2 share many functionalities and features, developing 1.2 also entails significant progress toward developing 2.2. Therefore, the research team decided to combine them for the purpose of developing a shared framework in Section 4.

3.2.3.2 Use Case 5.5 Discussion

Use Case 5.5 (PdM) focuses on the maintenance lifecycle stage. It was selected for further development for the following reasons:

- TAG members expressed that PdM will be key to keeping ARs operational, safe, and cost-effective over decades of asset lifetime. The potential payback is therefore very strong over such a long period.
- Other industries and disciplines have already invested substantial resources in developing and demonstrating PdM technologies and capabilities (for example, monitoring-based maintenance credits in aviation allow increased mean time between repairs). These advances can be leveraged in the AR industry as well.
- The nuclear industry has also invested substantially in PdM (an example is EPRI's Preventive Maintenance Basis Database [PMBD] [44]). Therefore, this use case has a comparatively rich data resource to draw on for integration with other DT elements, such as real-time instrumentation monitoring and mechanics-based modeling.
- PdM DTs might require specific software and hardware, but once developed and implemented, they will likely be readily scalable across systems.

3.2.3.3 Use Case 2.3 Discussion

Use Case 2.3 (Automated Construction QA) was shortlisted by more TAG members than any other use case. However, it involves additional complexities compared to 1.2, 2.2, and 5.5. For example, the underlying technology is expected to rely on hardware and software that have yet to demonstrate successful implementation at large scale in the nuclear regulatory environment (for example, LiDAR, photogrammetry, their point-cloud integration with BIMs, nonconformance identification models). Conversely, 1.2, 2.2, and 5.5 rely on more mature and readily available technologies. In addition, the DT development process for 2.3 is expected to involve more steps and require more resources compared to 1.2, 2.2, and 5.5.

Although the TAG members expressed broad interest in Use Case 2.3, they concurred that this topic would likely benefit from work performed for 1.2, 2.2, and 5.5; as such, they indicated less urgency to further evaluate 2.3 in this study. EPRI is actively investigating automated processes for QA as part of a broader effort to identify and address major nuclear cost drivers (see EPRI 3002015935 [14]). For example, one EPRI project reviewed automated QA inspections for embedded items in concrete (EPRI 3002023902 [31]). That report examines the benefits and challenges (including costs and times) of three reality (or “scene”) capturing technologies for measuring the geometry of embedded elements prior to concrete pouring to streamline inspection efforts. Such research will be instrumental in developing the underlying technologies that could ultimately enable a DT use case like 2.3.

4

ENGINEERING THE DT

This section illustrates the DT development process for two use cases and provides use-case-specific observations and recommendations. The generalized DT development framework described in Section 2.3 is used to evaluate use case aspects such as inputs, outputs, benefits, challenges, and costs. Section 4.1 presents the case-specific DT development framework for Use Cases 1.2 and 2.2 (construction sequence simulation), and Section 4.2 covers Use Case 5.5 (PdM). Each section includes five subsections with details on the definition and description of the case, DT development process, observations, and best practices and recommendations.

4.1 Use Cases 1.2 and 2.2: Construction Sequence Simulation

4.1.1 Description

The Construction Sequence DT (CSDT) is a digital simulation of the physical and functional processes that are required to build a facility. Construction sequence analysis can be performed at the design stage and/or a construction stage. Use Case 1.2 (Construction Sequence Simulation) focuses on simulations during the design stage to forecast possible issues, whereas Use Case 2.2 (Real-Time Construction Sequence Optimization and Front-Running Simulations) is performed as construction progresses. Both cases focus on reducing construction costs and delays, which stakeholders indicated are essential to the success of the AR industry overall. Use Case 2.2 should provide additional confidence because near-real-time data can be fed to the DT as construction progresses.

By adopting a CSDT, repetitive and critical-path tasks can be analyzed and optimized. To simulate construction sequences and identify potential hurdles, the CSDT requires not only 3D geometry but also external data sources, such as schedules and cost databases. Front-running simulations provide near-real-time analysis of the likely outcomes of construction project events. These outcomes provide construction management with high-fidelity information to support optimal responses to construction deviations.

By integrating a schedule with the geometry, the resulting model is referred to as a *four-dimensional* (4D) model. The 4D models can be leveraged for logistical analysis of site components, installation sequencing, and optimization of installation. When developing this CSDT, it is necessary to capture the steps to complete each task (such as system startup, shutdown, disassembly, procurement, and delivery of materials), the resources to fit the system together, and the personnel to test and verify that that system has been constructed to the design requirements. All these tasks and subtasks can then be connected to the 3D virtual representation; each simulation platform achieves this in a slightly different way, but it typically includes grouping tasks together and assigning them to the geometry. When the relationships between the schedule and model have been established, algorithms can be applied to the build methods and the virtual model elements to evaluate multiple scenarios. These scenarios could

include the addition of work crews, temporary crane placement, or other variables to identify the optimal critical path. As the schedule changes due to supply chain limitations, weather, or other unexpected activities, the simulation can be updated with these inputs to provide an updated output and optimization of the schedule. To provide the most transparency to administrative stakeholders, animation videos and images can be exported from the simulation platform.

The result of integrating cost with the geometry is referred to as a *five-dimensional* (5D) model. Time can be a consideration of a 5D simulation; however, it is uncommon to include the schedule linkage with cost in current practice. These 5D models provide a view into the procurement and cost controls of a project. The granularity of the information provided by a CSDDT depends on the cost management database platform with which it is integrated. The most efficient cost simulation models include a WBS and work packages as parameters within the 3D model. A WBS relates similar building elements and systems to each other in a hierarchical manner and enables relating costs to the facility assets. The work packages are typically a grouping of building elements that are either installed simultaneously or have other close relationships in the system or WBS hierarchy. Work packages typically have manpower effort and cost associated with them. As an illustration, for a cooling system retrofit, the segments of piping, fittings, and associated instrumentation can be grouped together virtually under a common WBS code forming a work package. This work package is then linked to the cost database with the WBS code; therefore, as the costs of material and labor are updated, it can be represented in the virtual model as well. If the routing of the piping requires modification, the added or removed segments of the work package automatically update the overall cost calculation.

Each of these unique 4D and 5D outputs start with the same inputs. Additionally, by combining the 4D and 5D models, it is then possible to view a time-based project cost analysis. The resulting sequences provide guidance and direction for pre-task planning, instruction, and QA.

The targeted benefits of a CSDDT can include, but are not limited to, the following capabilities:

- Minimize ambiguity in design to preclude construction delays and costly design changes during construction
- Improve fidelity and optimization of construction cost estimates and schedules
- When integrated with cost models and schedules, alternative construction sequences/processes can be analyzed and optimized
- Enable simulation of prefabrication and modularization installation, including repair/replace scenarios
- Improve efficiency and safety of construction operations
- Early warning of personnel environmental health hazards during construction for improved safety
- Informed *ad hoc* decision-making based on knowledge of likely consequences of unplanned events that occur during construction and potential outcomes of mitigating actions

Although this section focuses on applying CSDDTs in the construction lifecycle stage, they can also be applied to operations and decommissioning activities. CSDDTs can be used, for example, during major component replacement or refueling.

4.1.2 Development Process

A structural example is used in this section to illustrate the process of developing a CSDT. Consider a scenario where a user seeks to optimize the design and construction of the foundations and structural elements. A CSDT can be created to analyze the general phasing and critical-path activities to ensure constructability and access. The sequence can initially use low LOD geometry model. Then, structural design software combined with critical path schedule can be used to validate the overall sequencing approach. If the process identifies issues such as conflicts with work durations and inspections in a given area, the design approach can be modified to correct the problem. Prior to construction, high LOD rebar fabrication models can be incorporated into a sequence to analyze installation, access, congestion, and regulatory adherence. The sequence of reinforcement installation can result in spatial clashes or inaccessibility that is not evident during design using traditional 2D plans or even 3D models.

Figure 4-1 shows the development process for a CSDT built to optimize the construction of foundations and structural elements. The case-specific DT development process in Figure 4-1 is based on the generalized framework presented in Section 2.3. This section focuses on development steps specific to the CSDT.

4.1.2.1 A0: Gathering Requirements

Requirements related to a CSDT define the relevant use cases and address the scope of physical assets that will be modeled—for example, the complete facility, multiple specific systems or subsystems, or individual components or subcomponents. The development team should understand how regulatory inspections and requirements constrain the construction process. Budgeting requirements must also be considered for DT development as well as construction, and relevant requirements can be informed by available DT standards at the time. The requirements are gathered from the design basis for the DT and can be documented in a project charter, which should include relevant use case definitions.

- Constraints/requirements
 - Enterprise DT guidelines: Organizational standards for definition, integration, and ontologies. These are internal guidelines to follow in the development of the DTs.
 - Regulatory requirements: Federal, state, and local regulations governing the safety, security, and standardization of ARs.
 - Budget: Defines the resources available for DT development and identifies any economic/business constraints that will define success of the CSDT (such as a minimum net cost saving for construction).
- Resources
 - Administration: Necessary to compile the design basis, project charter, and use case definitions.
 - BIM subject matter expert (SME): Provide insight into the feasibility of the proposed solutions.

4.1.2.2 B0: Scoping the DT

The next step is to specify the who, what, and when. Scoping and requirement gathering are closely related. Outputs of the definition should include a DT strategy and technical roadmap. For the structural system example, a possible definition of the CSDT could include a strategic objective to understand the structural installation sequence and optimize the regulatory reviews of rebar placement.

- Constraints/requirements
 - Enterprise DT guidelines: The same standards that were previously used to provide a framework are used to influence the data standards and model development.
 - Enterprise data guidelines: An ontology of the facility. This is important for the identification of model elements to be connected to the schedule. An example is a WBS unique identifier being linked to other model elements.
 - Budget: Provides a cap on the allowable duration and cost of defining the DT.
 - 3D model creation standards: Provide the necessary requirements for model development and management.
- Resources
 - Administration: Develops the DT strategy, technical, and training roadmaps aligned with the overall vision and use cases for the DT.
 - BIM SME: Provide insight into the feasibility of the proposed solutions.
 - Data flow/sources: Data sources should be documented and managed in accordance with the data standard. For instance, sources could include the DDT, the construction DT, the overall schedule, the supply chain schedule, the off-site manufacturing schedule, and cost tables.

4.1.2.3 C0: Procuring the Resources

Once the driving forces and strategic objectives are understood, the necessary resources to implement the DT should be procured. If aligned with the organizational vision and strategy, external vendors could be contracted to produce the CSDT because it requires a specialized skillset to integrate the models and databases. Outputs from the procurement stage include software and hardware contracts, vendor contracts, and the associated contract deliverables and milestones. In the previous structural example, procurement could include the need to acquire simulation software, such as Synchro and Primavera P6, as well as a contract with a specialty vendor to develop the CSDT.

- Constraints/requirements
 - Enterprise DT guidelines: During this stage, the standards are linked to the contract language for required adherence by the hardware, software, and any other vendors when building the CSDT.
 - Contracting strategy: Provided by the procurement management. This is inclusive of the procurement process, security reviews, and other necessary contracting methods.

- Resources:
 - Procurement: Personnel responsible for the contract review, negotiation, and execution of the software, hardware, and any other vendors.
 - Administration: Consults with procurement to align the contracts and deliverables with the overall goal of the CSDT.

4.1.2.4 D0: Implementation of the DT

During the implementation stage, the design and/or construction 3D models are aggregated and verified as being capable of integrating with other DT elements. Outputs from the implementation should be the Design DT (DDT) and/or Construction DT (CDT). The next step is to connect the 3D DT with the schedule and cost elements (E0). In this stage, the structural example will be verified to ensure that the structural slabs have been modeled in a way segregated into individual the concrete pours, that the steel elements have been modeled with separate connection plates and structural members with unique identifiers, and that the rebar has been modeled both in the longitudinal and latitudinal directions.

- Constraints/requirements
 - Enterprise DT guidelines: These standards must be verified and validated during the implementation of the CSDT.
 - 3D model creation standards: Provide the necessary requirements for model development and management. These standards must be verified and validated during the implementation of the CSDT.
 - Time/resources: A limiting factor in the development of any DT or associated platform.
- Resources
 - Schedule criteria: The basic framework for how the integrated schedules should be composed. This provides a flexibility for the various design, construction, and operations teams to use their own preferred scheduling tools.
 - Design criteria/3D models: The 3D design models are not required for all CSDT use cases; however, the design models are generally a starting point for early schedule decision-making.
 - Construction criteria/3D models: The 3D construction models are most important for the CSDT as they contain a higher level of geometric fidelity.

4.1.2.5 E0: Connecting the DT

The next step is to connect the 3D DT with the schedule and cost elements in the simulation platform. The output is the initial CSDDT. Additional outputs from this stage are animation video(s) and/or virtual reality experience(s) that are used to interrogate the DT during the next stage. For the structure example, the output could be a video of the structural elements showing how they are scheduled to be installed along with any temporary site elements, scaffolding, cranes, and so on.

- Constraints/requirements
 - Enterprise DT guidelines: Organizational standards for definition, integration, and data ontologies.
 - Time/resources: A limiting factor in the development of any DT.
- Resources
 - Data mapping: Relationships connecting between the models, schedules, and cost information.
 - Schedule: For the CSDDT, this could include the overall schedule, the supply chain schedule, the off-site manufacturing schedule, and cost tables.
 - Cost breakdown: Some CSDDTs can include cost analysis. In these cases, a cost database is connected to the model elements. This connection can be formed from the WBS identifiers or from their own cost breakdown structure attributes.

4.1.2.6 F0: Monitoring the DT

In this stage, the CSDDT is used to view and comprehend the construction process. A feedback loop also connects back to the Implementation section in Figure 4-1. The feedback loop updates models, schedules, and costs based on insights from monitoring and analyzing the CSDDT. After a period of using the CSDDT, the output can be considered Version 1.0; at this point, the CSDDT provides feedback to the design and construction teams for model, schedule, or cost updates. The next iteration of the CSDDT would move into the next sequential version. For the structural sample, as the construction schedule is modified, the master schedule would need to be adjusted, and the DT re-exported to see the updated schedule impact.

- Constraints/requirements
 - Enterprise DT guidelines: Organizational standards for definition, integration, and data ontologies.
 - Budget: The ongoing maintenance of a CSDDT is constrained by the budget for monitoring the DT.

- Resources
 - Field input: Field installation or construction task sequences may be changed due to variables such as weather or delivery logistics.
 - Schedule deviations: Tracking between the planned and actual activities; this relationship can be input back into the CSDT by updating the linked schedules or model components.
 - Cost differences: As the prices of construction elements deviate from the baseline, the differences should be captured and updated within the CSDT.

4.1.2.7 G0: Scaling the DT

The final stage in CSDT development involves upscaling the DT for use during operations. Figure 4-1 includes a feedback loop to the Implementation stage in case there are any model, schedule, or cost updates.

- Constraints/requirements
 - Enterprise DT guidelines: Organizational standards for definition, integration, and data ontologies.
 - Budget: The budget during the monitoring period might be more restrictive than other stages, but when considering potential scalability of the CSDT, the benefits of nth-of-a-kind deployments should be considered to ensure budgets are commensurate with potential value.
- Resources
 - Additional analysis – Includes additional simulation capabilities that could be developed with the CSDT. An example of this could be connecting the CSDT to automated schedule management.

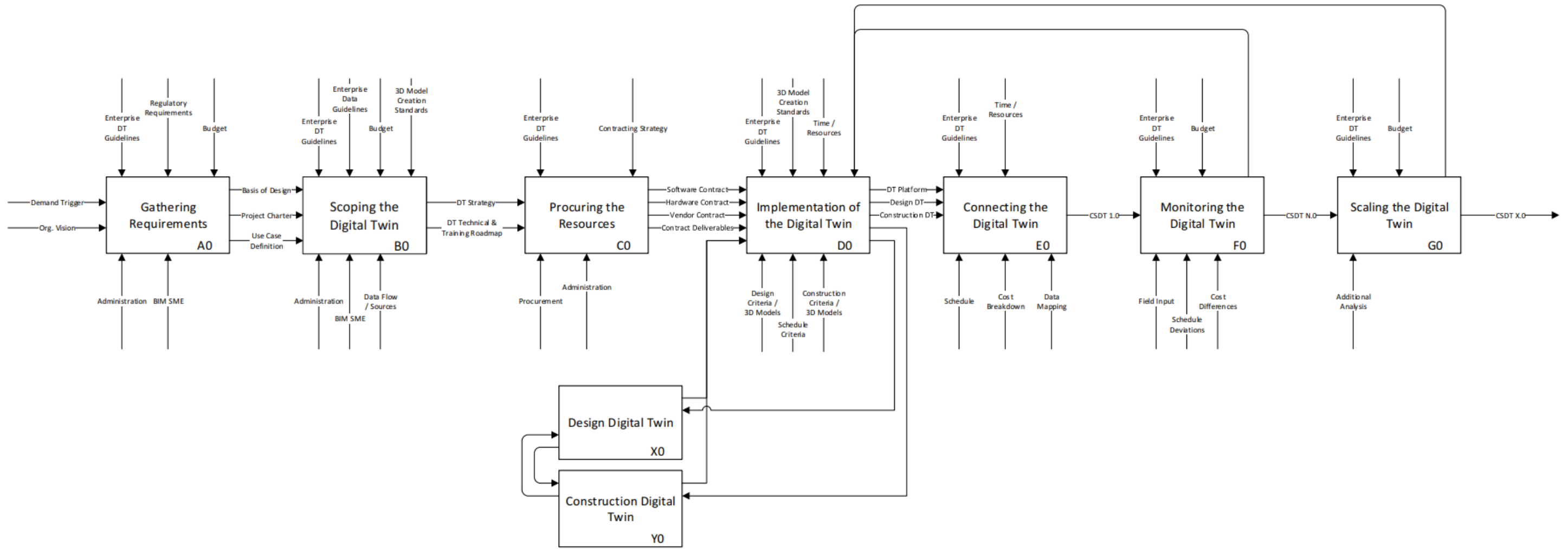


Figure 4-1
Use Cases 1.2 and 2.2 – construction sequence simulation – development

4.1.3 Use Case Definition

Table 4-1 maps the specific use case elements. It was developed following the use case prioritization process to display the definition of the use case. Table 4-1 should be used as a supplemental document when developing the design basis and project charter during Stage A0: Gathering Requirements.

Table 4-1
Use Case 1.2 and 2.2 definition—construction sequence simulation

Characteristic	Description
Use case identification	1.2 and 2.2
Use case name	Construction sequence simulation
End objectives	<ul style="list-style-type: none"> • Constructability, logistics, and sequencing verification to enhance cost and schedule compliance. • Integration of schedule and WBS, which provides feedback to the active installation tasking and potentially to an automated QA use case. • Support the testing and validation of options and the ability to iterate both design and construction possibilities. • Installation and construction sequences provide verified process and workflow for operational repair/replacement.
User/actor	Engineers, planners, general contractors, estimators, schedulers, controls group
DT summary	The CSDT is a digital simulation of the physical and functional processes required to build a facility. The CSDT typically models construction elements that are not included in the final facility but are critical to the construction, for example, temporary structures and hoisting. It is also common to have the CDT linked to the simulation for overall reference and logistical analysis of the building systems. The CSDT simulations produce a feedback loop to the DDT and CDT in the form of constructability, phasing, and logistical analysis.
DT inputs	<ul style="list-style-type: none"> • DDT – A DT representing the physical and functional characteristics of the real-world entities that make up the design of the project. The process of creating the DDT acts as a simulation of the facility performance (structural analysis, energy analysis, and so on) and construction feasibility (coordination, digital layout, sequencing). • CDT – A DT representing the physical and functional characteristics of the virtualized construction process. Specifically, these DTs are leveraged for simulating constructability (clash detection, digital layout, sequencing, and so on). • Other preconditions of the CSDTs can include design for manufacturing and assembly methodology, fully coordinated building information modeling, schedule, cost breakdown structure, and WBS.
DT outputs	<ul style="list-style-type: none"> • Video animation, navigational model, and/or VR experience. • The feedback loop can trigger the need for collision avoidance, sequence verification/modification, schedule adjustment, value engineering, and/or validated and repeatable repair/replace scenarios.

Table 4-1 (continued)
Use Case 1.2 and 2.2 definition – construction sequence simulation

Characteristic	Description
Systems used	BIM (such as Autodesk Revit), scheduling (such as Primavera P6), construction scheduling simulation (such as Synchro), structural analysis (such as Ansys), clash detection (such as Autodesk Navisworks), PMIS (Project Management Information Systems), construction sequencing/installation management (such as Autodesk Assemble).
Development steps	<ul style="list-style-type: none"> • Development of DDT and/or CDT • Develop and integrate cost breakdown structure and WBS (such as XLS, e-builder, Assemble, Kahua, BIM 360) • Incorporation of work breakdown and cost information into DDT and CDT based on individual sequencing simulation objectives (such as Assemble, Kahua) • Development of overall construction schedule and sequencing based on individual simulation objectives (such as P6, MS Project) <ul style="list-style-type: none"> ○ Rebar placement, concrete pour sequence, critical-pick ○ Prefab module assembly, module heavy-lift, module installation ○ Advanced resource planning ○ Site logistics and laydown areas ○ Safety and hazard mitigation ○ Site worker training ○ Project stakeholder communications • Above information is linked in a 4D construction sequencing/simulation/analysis/visualization platform such as Navisworks, Synchro, Fuzor, and so on, based on simulation objectives. <ul style="list-style-type: none"> ○ Models are loaded from collaboration platform/CDE ○ Schedule/sequence is loaded ○ Schedule and model elements are linked based on WBS ○ Sequencing/simulation/analysis/visualization is performed based on objectives
Usage/maintenance—basic flow	<p>Usage</p> <ul style="list-style-type: none"> • Outcomes of simulation are analyzed against expected results. Simulations can be exported without 4D software to enhance collaboration. • Simulations can typically be viewed on computers, television monitors, and VR headsets if exported in the proper format. <p>Maintenance</p> <ul style="list-style-type: none"> • As necessary, the feedback loop provided can encourage modifications to the DDT, CDT, logistics model, and/or schedule. • Feedback should always be managed in a single location so that no comments are missed. • It is often recommended to provide feedback with associated time stamp if viewing an animation.

Table 4-1 (continued)
Use Case 1.2 and 2.2 definition – construction sequence simulation

Characteristic	Description
Benefits (business impact)	<p>Accelerated schedule – Minimizes conflicts in field and resulting schedule impact. Reduction in field RFIs and resultant schedule impact. Up to 30%* schedule savings facilitates earlier on-line dates.</p> <p>Cost savings through efficiency gains:</p> <ul style="list-style-type: none"> • Reduction of change orders • Reduced RFIs • Better construction coordination • Time reduction • Schedule and construction simulation (“what if” scenarios) • Advanced planning—build it first in virtual space • Construction time and cost transparency to stakeholders
Cost analysis	<p>Software: \$ out of \$\$\$\$\$*</p> <p>Standard AEC platforms typically in use, less than \$100,000.</p> <p>Labor: \$ out of \$\$\$\$\$*</p> <p>Typically included in AE/GC contracts as project-level staff.</p> <p>Infrastructure: \$ out of \$\$\$\$\$*</p> <p>Can leverage DT framework, including CDE.</p> <p>Overall use case up-front costs: \$\$ out of \$\$\$\$\$*</p> <p>Cost savings metrics: Approximately 10%* reduction in RFIs Median response time 12 days \$100,000 labor hours/daily burn rate</p>

* Representative values from heavy-construction applications.

4.1.4 Observations

As the digital thread of a project is considered, there can be multiple CS DTs, and each DT can vary in scope, fidelity, and usefulness. The sequence analyses have been shown to provide time and cost savings in the field. The CS DTs also assist in ensuring the completeness of DDT and CDT prior to construction to minimize requests for information and preclude construction-stage design changes, requalification engineering assessments, and extended regulatory inspections.

The resulting outcomes of the CS DT are most likely to identify scenarios with the least desirable outcomes and adjust the construction plan to mitigate them. Construction sequence digital twins classify issues and provide feedback loops that are incorporated upstream in the DDTs and CDTs before impacting the cost or schedule. Furthermore, this process lends itself to the use of modular/prefabricated assemblies, which can further enhance the schedule and cost savings.

4.1.5 Best Practices and Recommendations

An important consideration for how to implement this use case into a project environment relates to how the 3D models are developed—specifically, how the geometry is segmented. For example, a floor slab must be modeled in several segments to match the pour sequencing to graphically represent how the preparation, pour, and curing processes will occur. This will inherently influence the LOD of the elements needed to perform the CSDT simulation (in other words, not all model entities will need to be modeled with their full subassembly breakdown, and other model entities will need more complexity added to them). When a project is planned, the LOD definitions should be included in the project execution plan such that they are related to the various model uses and outcomes. This will provide clarity of modeling requirements to the design teams and set the expectations of when the CSDT(s) would be developed and by whom.

WBSs should be developed based on a singular classification method to have a holistic schedule of values. It is best practice not to change the WBS during the process; it is an element that needs strong consideration prior to implementation.

While proceeding through the development and usage of the CSDT, a best practice is to create and properly label new versions of all models, datasets, and DTs. Additionally, it is best practice to keep them in a cloud-based repository to provide transparency and accessibility to other team members.

Advancements in reality capture and drone technologies have enabled rapid measurement of as-built construction conditions to facilitate comparison with 3D design models. This comparative analysis can be fed into the CSDT to analyze the construction deviation impacts on the schedule.

4.2 Use Case 5.5: Predictive Maintenance

4.2.1 Description

PdM is the use of condition monitoring to inform maintenance schedules. This eliminates unnecessary maintenance activities and identifies when additional maintenance should be performed to prevent unexpected failures. Systems are monitored to produce work orders as needed and inform root-cause analysis.

EPRI's *Predictive Maintenance Primer* [34] identifies three key benefits of PdM—human performance, O&M cost, and technical capabilities:

- PdM improves human performance by providing the information needed to consider or take action to “prevent injury, equipment damage, and/or improve the efficiency and effectiveness of the task” [34].
- *O&M cost* refers to the information “...that will result in overall reduced costs and/or an increase in revenue through additional or restored energy production” [34].
- According to the *Predictive Maintenance Primer*, technical capability is the targeted “...information that will lead to improved equipment reliability” [34].

As it has been noted, PdM is not a new concept. The technology platforms, sensor technology, and algorithms in use have all seen rapid and robust development. Further, the IWMSs that include PdM are interoperable with the “single source of truth” employed during a digital

engineering lifecycle. This presents an ability to fully populate a maintenance management system with equipment, systems, process definitions, documentation, and training materials during the commissioning and initial testing process of a nuclear facility. A link between the early phases of the project development lifecycle and operations removes the need for key personnel to manually enter data into the maintenance systems.

The organization of a predictive maintenance digital twin (PMDT) that begins during the design stage is very much a data exercise. This early information is simply the identification of the assets that will be included in maintenance activities. When assets are first identified, regardless of analysis type, they are given a unique identifier. Many engineers will liken this identifier to an equipment tag; however, asset identifiers need to be more specific than what the element represents and/or its functional location within its system. For example, the identifier for a pump will need to include what type of pump it is (for example, centrifugal), its general location (this is optional and dependent on the asset class), the system, and a numeric identifier if there are multiple pumps of the same type. Below is first an example of how an asset identifier could be structured, followed by an example using the originally presented structure:

Location – Asset Class Asset Class ID – System ID – Asset Sequence Number

REC-PUMP_CEN001-RECCOOL001-001

When the asset identifiers are created, they should be used as the primary key during design and construction. It is often recommended to use this identifier in the place of an equipment tag on plans and diagrams; this is necessary to ensure continuity between design and operational information. As data are generated during the design, procurement, and construction stages, they should all be associated with the same asset identifier. By maintaining this identifier during subsequent stages, the data related to the asset can then be imported into the IWMS platform at significant milestones to prevent a large and burdensome loading of data at the conclusion of the project. During the commissioning and testing of a system, the information, testing procedures, startup, shutdown, and so on can be linked directly into the IWMS for the PdM algorithms to begin early training. With the manual asset data provided, the equipment sensors can be integrated and linked to the asset identifier. This will accelerate the learning of the PdM algorithms to identify trigger states.

Early developments have also been made to generate a link between the IWMS and AuR headsets. Initial use cases for technicians in non-irradiated areas of the plant have been identified to support visual inspections and field maintenance activities.

Today, PdM platforms can consolidate operating experience data such as EPRI's PMBD, real-time instrumentation data, physics-based modeling, and machine-learning algorithms to assess current health and predict remaining life. Furthermore, PdM platforms can account for the direct and indirect costs of a component or system over its intended life. Additional benefits include:

- Reduction in maintenance costs and unplanned downtime
- Improved equipment lifespan and safety
- Access to the system from anywhere, if it is Web-based

4.2.2 Development Process

The development of a PMDT is one of the most complete uses of DT technology. As the case is evaluated, it will become evident why PMDTs can provide significant ROI. The purpose of this development process is not to discuss the design of a PdM program, but rather how a designed program can be connected to the physical representation of a system.

Figure 4-2 shows the development process of a PMDT following the framework defined in Section 2.3. For illustration purposes, the following sections will describe PMDT development for BOP systems. Mechanical and electrical BOP elements—such as the measurement of temperature differentials upstream and downstream of a heat exchanger or infrared thermal imagery of an electrical component to detect degradation or potential malfunction—are considered.

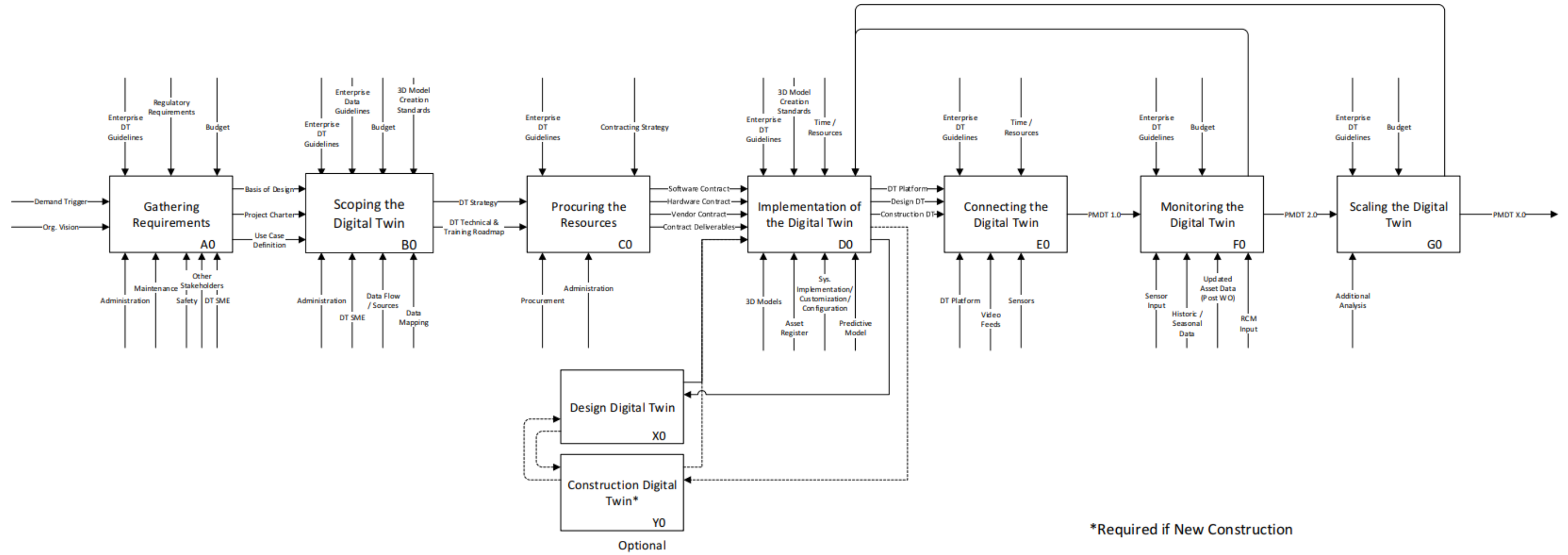


Figure 4-2
Use Case 5.5: development of a PMDT

4.2.2.1 A0: Gathering Requirements

Initially, when identifying the need for any type of DT or technology that augments traditional systems, it is reasonable to identify the needs of the parties who will use the technology. Inquiries should be posed to any personnel who might use the information developed by the DT. Common themes to identify when determining the requirements of a PMDT include the reduction of effort and cost in the O&M of the plant.

- Constraints/requirements
 - Enterprise DT guidelines: Organizational standards for definition, integration, and data ontologies.
 - Regulatory requirements: Federal, state, and local regulations governing the safety, security, and standardization of ARs.
 - Budget: Defines the resources available for DT development and identifies any economic/business constraints that will define success of the PMDT (such as a minimum annual net cost savings).
- Resources
 - Administration: Necessary to compile the design basis, project charter, and use case definitions.
 - Maintenance: Required for input regarding the key functional and nonfunctional requirements of the maintenance system.
 - Safety: Necessary to integrate the maintenance management platform with the safety and security processes and tools.
 - DT SME: Provide insight into the feasibility of the proposed solutions.

4.2.2.2 B0: Scoping the DT

The definition of the PMDT begins with the identification of the critical assets that must be managed in the PMDT. Not all equipment assets should be included in the monitoring because the physical hardware and virtual software overhead could become prohibitively expensive. Initially, consider elements with high replacement/repair/downtime costs that are mission-critical.

- Constraints/requirements:
 - Enterprise DT guidelines: Organizational standards for definition, integration, and data ontologies.
 - Enterprise data guidelines: A hierarchical classification of the BOP systems and elements, their installation and maintenance standards, guidelines for documentation and disposition of anomalous equipment performance, safety risks, and so on.
 - Budget: Provides a cap on the allowable duration and cost of defining the DT.
 - 3D model creation standards: Provide the necessary requirements for model development and management.

- Resources:
 - Administration: Develops the DT strategy, technical, and training roadmaps aligned with the overall vision and use cases for the DT.
 - DT SME: Provide insight into the feasibility of the proposed solutions.
 - Data flow/sources: Data sources should be documented and managed in accordance with the data standard. For instance, sources could include the 3D model, sensor telemetry, and the historian server.
 - Data mapping: Also known as the *normalization* of telemetry data. Telemetry data have many different protocols to which the information can be encoded; for this reason, there is sometimes a need to preprocess the data prior to analysis and storage by the system.

4.2.2.3 C0: Procuring the Resources

Procuring the necessary components for the implementation of a PMDT will vary based on the existing maintenance systems that are currently in use. Not all maintenance systems have modules to perform PdM, especially the older systems. In this situation, there are two options. One is to replace the entire maintenance system with one that is condition-based; the other option is to locate a maintenance system that can perform PdM and integrate it into the existing system. Although the latter option might be less expensive in the short term, it can become more expensive in the long run. Having to update the data integrations and having multiple sets of data and/or different user interactions will all accumulate to cost more in the long run. Additional components that must be procured include the sensors or cameras, hubs, and other human-machine interface elements. Often, these complex implementations will require the procurement of specialized services to assist in the development and integration of the technology.

- Constraints/requirements:
 - Enterprise DT guidelines: Organizational standards for definition, integration, and data ontologies.
 - Contracting strategy: Provided by the procurement management. This is inclusive of the procurement process, security reviews, and other necessary contracting methods.
- Resources:
 - Procurement: Personnel responsible for the contract review, negotiation, and execution of the software, hardware, and any other vendors.
 - Administration: Consults with procurement to align the contracts and deliverables with the overall goal of the PMDT.

4.2.2.4 D0: Implementation of the DT

After identifying the PdM managed assets and procuring the necessary systems, the CMMS can be implemented and/or configured to perform PdM. A database of information surrounding the assets will then be developed. These data should include data central to historic usage (if an existing element), any hard copy files converted to digital, and maintenance or commissioning records. The data are necessary to give the algorithm sufficient information to develop actionable insight. Also, when implementing a PMDT, it is important to identify failure modes with a

failure mode and effects analysis and develop predictive models. The predictive models must not be developed in isolation but rather with sensor measurements and other baseline information available from the manufacturer.

- Constraints/requirements:
 - Enterprise DT guidelines: Organizational standards for definition, integration, and data ontologies.
 - 3D model creation standards: Provide the necessary requirements for model development and management. These standards must be verified and validated during the implementation of the PMDT.
 - Time/resources: A limiting factor in the development of any DT or associated platform.
- Resources:
 - 3D models: The 3D models are not required for all PMDT use cases; however, design models are generally a starting point for early schedule decision-making. The 3D construction models are most important for PMDTs that will benefit from a higher level of geometric fidelity.
 - Asset register: A complete asset database inclusive of the design, construction, commissioning, and manufacturer information.
 - Predictive model: An algorithm curated from the fault tolerances.
 - System implementation/customization/configuration: The implementation, customization (development), and/or configuration (setup) of the maintenance management system.

4.2.2.5 E0: Connecting the DT

When first deploying PdM, it is recommended to deploy the system to a subset of the equipment identified. This provides the predictive algorithms to be tested and validated by using only a pilot set of equipment. For instance, vibration sensing telemetry is only collected and fed to the algorithms from one centrifugal pump. Training is also going to be performed during this stage.

- Constraints/requirements:
 - Enterprise DT guidelines: Organizational standards for definition, integration, and data ontologies
 - Time/resources: A limiting factor in the development of any DT
- Resources:
 - DT platform: The compiled maintenance management system
 - Video feeds: The video system that provides the DT platform with the real-time streaming visuals
 - Sensors: The IoT sensing systems that provide the DT platform with the real-time telemetry data

4.2.2.6 F0: Monitoring the DT

Upon connecting the PdM elements, the remainder of the elements can be operationalized. PdM should be assessed often because if the algorithms are inconsistent, the overall program will deviate quickly.

- Constraints/requirements:
 - Enterprise DT guidelines: Organizational standards for definition, integration, and data ontologies
 - Budget: The ongoing maintenance of a PMDT is constrained by the budget of monitoring the DT
- Resources:
 - Sensor input: Real-time data streams
 - Historical/seasonal data: Data that have been gathered at previous time-series intervals.
 - Updated asset data (post-work order): As maintenance is performed, the algorithm might have a deterioration function such that after a number of completed work orders, the equipment might trigger a complete shutdown or replacement.
 - Reliability-centered maintenance input: Input from time-based maintenance programs.

4.2.2.7 G0: Scaling the DT

Extending the PdM to secondary or tertiary systems and equipment is simplified because the initial system implementation and configuration has occurred. To add elements to the PdM module, the sensing capabilities would need to be installed and connected. It should still be noted that not all scenarios require predictive analysis.

- Constraints/requirements:
 - Enterprise DT guidelines: Organizational standards for definition, integration, and data ontologies.
 - Budget: The budget during the monitoring period might be more restrictive than other stages, but when considering the potential scalability of the PMDT, the benefits of nth-of-a-kind deployments should be considered to ensure that budgets are commensurate with potential value.
- Resources:
 - Additional analysis: Includes additional simulation capabilities that could be developed with the PMDT.

4.2.3 Use Case Definition

Table 4-2 maps the specific use case elements. It was developed following the use case prioritization process to display the architecture of the use case. Table 4-2 should be used as a supplemental document when developing the design basis and project charter during Stage A0: Gathering Requirements.

Table 4-2
Use Case 5.5 definition—PdM

Characteristic	Description
Use case identification	5.5
Use case name	Predictive Maintenance
End objectives	<ul style="list-style-type: none"> • Combine operating experience data (such as from the PMBD [44]), real-time instrumentation data, mechanics-based modeling, and ML/AI algorithms to assess current health and predict remaining life. • Used to inform and optimize maintenance activities, encouraging condition-based maintenance in favor of time-based maintenance. <p>Specific Applications</p> <ul style="list-style-type: none"> • Irradiation-assisted stress corrosion cracking (IASCC) of highly irradiated elements of primary system. Predict IASCC crack initiation and propagation and remaining time to significant degradation based on real-time measured data on flux rate, vibrations, temperature, and so on. • Condition assessment of electrical cables based on physics-based DT and operational history of the cables. • Main turbine bearings. Monitor parameters such as number of operational cycles, bearing temperatures and loads, vibration, and rpm. Determine grease degradation using ML/AI framework trained on photographs taken during visual inspections, reducing and eventually eliminating dependence on costly laboratory testing. • Emergency power lead-acid batteries (and/or other electrical equipment). Integrate loading histories captured over the service life with performance and aging models. Monitor cell chemistry, battery temperatures, cell voltage, power cycles, power quality, response to loading and charging, and so on.
User/actor	Utility engineers, maintenance personnel, administration personnel, information technology
DT summary	<p>The PMDT is a digital representation of the physical, operational, and performance characteristics of systems that require ongoing maintenance. The PMDT is updated at a frequency determined by use case with:</p> <ul style="list-style-type: none"> • Sensor telemetry data – sensors will vary by use case • Equipment performance data • Historical performance data • Ongoing O&M records <p>Real-time sensor and performance data are initially captured, stored, and analyzed to provide a baseline for operational performance. Based on historical performance data and O&M records, “rules” are developed to define desired states and states that might indicate anomalies. Based on these rules and the specific use case, predefined actions, such as alert notifications or work order generation, can be performed. This information can also be captured and added to the historical dataset.</p>

Table 4-2 (continued)
Use Case 5.5 definition—PdM

Characteristic	Description
DT inputs	<ul style="list-style-type: none"> • DDT – A DT representing the physical and functional characteristics of the real-world entities that comprise the design of the project. • CDT – A representation of the physical and functional characteristics of the virtualized construction process. Specifically, these DTs are leveraged for simulating constructability (clash detection, digital layout, sequencing, and so on). • O&M considerations during design and modularized approach results in more efficient operations. • Other preconditions of the PMDTs can include fully coordinated BIM, WBS, time-based maintenance schedules, equipment operating tolerances, and O&M, testing, and licensing documentation.
DT outputs	<ul style="list-style-type: none"> • Consolidated work order management system. • Operations dashboards with analytics consisting of: <ul style="list-style-type: none"> ○ Active systems performance ○ Open and pending work orders ○ System components that are within a 5% threshold of failure • Provides the foundation for DT use cases for the modular systems including maintenance training, replace/repair, system. • AuR-enabled work order execution.
Systems used	<p>BIM (such as Autodesk Revit), CAD (such as Plant 3D), common data environment (CDE; such as Bentley iTwin, Autodesk BIM 360, Procore), unified asset management database, IWMS (such as Maximo, Planon), CMMS (such as Archibus).</p>
Development steps	<ul style="list-style-type: none"> • Development/collection of DDT(s) and/or CDT(s). • Development/incorporation of work breakdown identifier into DDT and CDT based on required managed asset objectives. • Development of a federated geometric model (FGM) of the facility, system, and components based on the composite of the DDT and CDT. • Aggregation of managed asset metadata, checklists, time-based maintenance schedules, spare information, input/output checkout, systems engineering data, commissioning data, IoT network provisioning, and documentation. <ul style="list-style-type: none"> ○ Note that the managed asset information must be linked to the primary asset identifier (work breakdown identifier). ○ This data collection is typically achieved in a simple spreadsheet, but it would happen throughout the design, construction, and commissioning phases in the CDE. • Implementation, configuration, and customization of PdM IWMS platform/module. This would include training of the predictive algorithm. • QA/QC and importation of FGM and managed asset data to staging. • Managed asset data sensor connection integration. • V&V that IoT data is moving into the system and the managed assets are all classified with their available data. • System training. • Transition of information from staging to production. • Roll-out.

Table 4-2 (continued)
Use Case 5.5 definition—PdM

Characteristic	Description
Usage/ maintenance— basic flow	<p>Usage</p> <ul style="list-style-type: none"> • Outcomes of simulation via dashboard(s). Simulations can typically be viewed on computers, monitors, and VR headsets if exported in the proper format. • Automated work order generation. • Work order progress management. • Input of regulatory monitoring. • Managed asset and system information retrieval from a single digital source. <p>Maintenance</p> <ul style="list-style-type: none"> • As necessary, the FGM should be updated to match the modified or added systems of the facility. • Real-time telemetry linkages should be reviewed and refreshed on a quarterly basis. • PdM platform maintenance, such as upgrades, will be necessary from time to time. It is recommended to perform these modifications in a staging environment with automated system testing prior to performing the upgrade on the production server and data.
Benefits (business impact)	<ul style="list-style-type: none"> • Reduction in operating costs by detecting, preventing, predicting, and optimizing the systems. • Reduced asset and process related incidents. • Increased reliability of equipment performance. • Enhanced safety by minimizing avoidable/noncritical maintenance activities. • Reduction in asset maintenance frequency and costs.
Cost analysis	<p>Software: \$\$\$\$ out of \$\$\$\$\$*</p> <p>Typical IWMS platforms and implementation, starting at \$1 million.</p> <p>Labor: \$\$\$ out of \$\$\$\$\$*</p> <p>Includes AE/GC, Integrator, Operations inputs and effort.</p> <p>Infrastructure: \$\$\$ out of \$\$\$\$\$*</p> <p>\$ if cloud-based option is used.</p> <p>\$\$\$\$ if hosted option is used.</p> <p>Overall use case up-front costs: \$\$\$\$ out of \$\$\$\$\$*</p> <p>Cost savings metrics:</p> <p>Approximately 40% reduction in break-fix incidents 93–99.49% Increased reliability reduction of fixed O&M costs to ~\$2/MWh.</p>

* Representative values from heavy-construction applications.

4.2.4 Observations

PdM provides a real-time overview of the current conditions of the managed assets. This optimizes the time necessary for maintenance work and ensures minimal disruptions to productivity. Predictive operations require certain types of specialized equipment and an atypically large upfront implementation cost. This should not deter the implementation of this type of DT. It is a long-term solution that provides a significant benefit through improved performance and cost savings.

4.2.5 Best Practices and Recommendations

There are many criteria to consider when identifying and implementing a PdM solution. PdM technology features do not always consider *ad hoc* or corrective maintenance, and this is an area for improvement. Developers will need to spend substantial planning effort on various technical issues, including initial data migration or population of the new system, supplementary data inputs from field operations, IoT systems, security systems, and so on.

Other key points to consider are:

- Ease of use should be a main consideration; many platforms are overly complicated and have a user experience that few truly understand.
- Platform security to ensure reliability and unauthorized access.
- Interoperability and integration of the specific technology platforms used during the AR lifecycle.

5

CONCLUSIONS

5.1 Research Summary

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 that is the subject of this report is 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 digitalization of workflows.

To investigate the preceding issues and develop insights, the project consisted of the following main 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?

Conclusions

- 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 section summarizes key insights, best practices, and areas of future research identified as part of this project.

5.2 Key Insights

Key insights from this study are summarized in Table 5-1.

Table 5-1
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 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 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.

Table 5-1 (continued)
Key insights

Issue	Insights and Contributions
AR industry perspective	<p>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 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.</p> <p>The main DT implementation challenges identified during this research are covered in Section 2.5.3. 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. This report provides some tools and resources to make progress in this regard. Other key challenges are described in Section 5.4 along with future research opportunities to address them.</p>
DT technology readiness	<p>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. This effort provides insights into DT underlying technologies and offers a discussion on technology readiness and outlook of future technology development.</p>
DT costs and potential benefits	<p>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 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.</p>
DT use cases for ARs	<p>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.</p> <p>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) offer a set of considerations and issues that readers can use to assess their own potential use cases.</p>
DT development examples	<p>Using the conceptual DT development framework proposed in this study (Section 2.3), 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.</p>

5.3 Best Practices

Table 5-2 describes the best practices that are recommended for AR stakeholders planning to develop DTs for their assets and processes.

**Table 5-2
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 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-safety-related 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 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.	<p>A few key use-case-specific best practices are summarized here from Section 4.1.5:</p> <ul style="list-style-type: none"> • 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.

Table 5-2 (continued)
Best practices

Topic	Recommendation
PdM	<p>A few key use-case-specific best practices are summarized here from Section 4.2.5:</p> <ul style="list-style-type: none"> • 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.

5.4 Areas of Future Research

The research team found that DT technology is mature enough to transition from theory to practical applications for selected use cases. Several enabling technologies and use cases are vetted and viable; however, there are several areas where further research and development are needed to ensure full implementation and adoption. Only through advancements in the definition, implementation, monitoring, maintenance, and scaling of DTs will it be possible to provide additional insights and accelerate widespread adoption in the nuclear industry. Based on the literature review, conceptual framework development, use case evaluation, and DT development framework examples performed in this study, Sections 5.4.1–5.4.5 suggest several areas in which future research should be prioritized.

5.4.1 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). Results from this project and other industry efforts (for example, EPRI 3002015935 [14], GEMINA [13]) 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.

5.4.2 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.

5.4.3 Technology Readiness

This study investigated the state of technologies enabling DT applications (see Section 2.6). 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.

5.4.4 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.

5.4.5 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.

6

REFERENCES

1. E. Glaessgen and D. Stargel, *The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles*. 2012. <https://ntrs.nasa.gov/citations/20120008178>
2. F. Biesinger and W. Weyrich, *The Facets of Digital Twins in Production and the Automotive Industry*. 2019. <https://ieeexplore.ieee.org/document/8932101>
3. D. Gunasegaram, A. Murphy, M. Matthews, and T. DebRoy, *The Case for Digital Twins in Metal Additive Manufacturing*. 2021. <https://iopscience.iop.org/article/10.1088/2515-7639/ac09fb/pdf>
4. B. Gerlach, S. Zarnitz, B. Nitsche, and F. Straube, *Digital Supply Chain Twins—Conceptual Clarification, Use Cases and Benefits*. 2021. https://mdpi-res.com/d_attachment/logistics/logistics-05-00086/article_deploy/logistics-05-00086.pdf?version=1638801109
5. X. Sun, *Digitalization in the port industry from the perspectives of bibliometric analysis*, 2021. https://commons.wmu.se/cgi/viewcontent.cgi?article=2621&context=all_dissertations
6. R. Xie, M. Chen, W. Liu, W. Jian, and Y. Shi, *Digital Twin Technologies for Turbomachinery in a Life Cycle Perspective: A Review*. 2021. https://mdpi-res.com/d_attachment/sustainability/sustainability-13-02495/article_deploy/sustainability-13-02495-v2.pdf
7. J. Kooning, K. Stockman, J. De Maeyer, A. Jarquin-Laguna, and L. Vandeveldel, *Digital Twins for Wind Energy Conversion Systems: A Literature Review of Potential Modelling Techniques Focused on Model Fidelity and Computational Load*. 2021. https://mdpi-res.com/d_attachment/processes/processes-09-02224/article_deploy/processes-09-02224-v3.pdf?version=1639376710
8. G. Mylonas et al., *Digital Twins From Smart Manufacturing to Smart Cities: A Survey*. 2021. <https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9576739>
9. *Proceedings of the Workshop on Digital Twin Applications for Advanced Nuclear Technologies*. U.S. Nuclear Regulatory Commission, Washington, D.C.: December 2020. <https://www.nrc.gov/docs/ML2108/ML21083A132.pdf>
10. *The State of Technology of Application of Digital Twins*. U.S. Nuclear Regulatory Commission, Washington, D.C.: June 2021. <https://www.nrc.gov/docs/ML2116/ML21160A074.pdf>
11. *Proceedings of the Workshop Enabling Technologies for Digital Twin Applications for Advanced Reactors and Plant Modernization*. U.S. Nuclear Regulatory Commission, Washington, D.C.: September 2021. <https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML21348A020>

References

12. *Technical Challenges and Gaps in Digital-Twin-Enabling Technologies*. U.S. Nuclear Regulatory Commission, Washington, D.C.: December 2021. <https://www.nrc.gov/docs/ML2136/ML21361A261.pdf>
13. *Generating Electricity Managed by Intelligent Nuclear Assets*. GEMINA. U.S. DOE ARPA-E, October 2019. <https://arpa-e.energy.gov/technologies/programs/gemina>
14. *Advanced Nuclear Technology: Economic-Based Research and Development Roadmap for Nuclear Power Plant Construction*. EPRI, Palo Alto, CA: 2019. 3002015935. <https://www.epri.com/research/products/000000003002015935>
15. *Quick Insight Brief: Digital Twin Activities at EPRI*. EPRI, Palo Alto, CA: 2020. 3002020014. <https://www.epri.com/research/products/000000003002020014>
16. S. Boschert and R. Rosen, “Digital Twin—The Simulation Aspect,” *Mechatronic Futures*, P. Hehenberger and D. Bradley, Eds. https://doi.org/10.1007/978-3-319-32156-1_5; Springer, Cham, 2016. https://doi.org/10.1007/978-3-319-32156-1_5
17. M. Grieves, *Origins of the Digital Twin Concept*. August 2016. https://www.researchgate.net/publication/307509727_Origins_of_the_Digital_Twin_Concept
18. M. Grieves, “Digital Twin: Manufacturing Excellence through Virtual Factory Replication,” March 2015.
19. P. Wang et al., “Sensor Control in Anti-Submarine Warfare—A Digital Twin and Random Finite Sets Based Approach,” *Entropy*, vol. 21, no. 767, August 2019. <https://doi.org/10.3390/e21080767>
20. *The Definition of a Digital Twin*. Digital Twin Consortium, July 2021. <https://www.digitaltwinconsortium.org/hot-topics/the-definition-of-a-digital-twin.htm>
21. E. Patterson, R. Taylor, and M. Bankhead, “A Framework for an Integrated Nuclear Digital Environment,” *Progress in Nuclear Energy*, vol. 87, pp. 97–103, March 2016. https://www.researchgate.net/publication/286480447_A_framework_for_an_integrated_nuclear_digital_environment
22. M. Grieves and J. Vickers, *Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems*. 2016. https://link.springer.com/chapter/10.1007/978-3-319-38756-7_4
23. A. Kuhn et al., *Analytics Canvas—A Framework for the Design and Specification of Data Analytics Projects*. 2018. <https://www.sciencedirect.com/science/article/pii/S2212827118301549>
24. *Quick Insight Brief: Elements of Digital Twins and Projects Updates*. EPRI, Palo Alto, CA: 2021. 3002022555. <https://www.epri.com/research/products/000000003002022555>
25. Defense Acquisition University Press. *Systems Engineering Fundamentals*. January 2001. ocw.mit.edu. https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2005/6128a102c1a9b6dbd30f2fb18c12aa64_sefguide_01_01.pdf

26. *Glossary of Digital Twins | Digital Thread*. Digital Twin Consortium. July 2021. <https://www.digitaltwinconsortium.org/glossary/index.htm#digital-thread>
27. *U.S. Nuclear Plant Shutdowns, State Interventions, and Policy Concerns*. Congressional Research Services: 2021. <https://crsreports.congress.gov/product/pdf/R/R46820/3>
28. *Level of Detail*. U.S. General Service Administration: 2019. <https://www.gsa.gov/real-estate/design-and-construction/3d4d-building-information-modeling/bim-software-guidelines/document-guides/level-of-detail>
29. *Advanced Nuclear Technology: Data-Centric Configuration Management for Efficiency and Cost Reduction: An Economic Basis for Implementation*. EPRI, Palo Alto, CA: 2014. 3002003126. <https://www.epri.com/research/products/000000003002003126>
30. *Digital Systems Engineering: Configuration Management Guideline*. EPRI, Palo Alto, CA: 2020. <https://www.epri.com/research/products/000000003002015755>
31. *Advanced Nuclear Technology: Quality Assurance Inspections for Embedded Items in Concrete Members using Alternative Techniques*. EPRI: Palo Alto, CA: 2022. 3002023902. <https://www.epri.com/research/products/000000003002023902>
32. X. Qi and J. Ebert, “A Computer Vision-Based Method for Fire Detection in Color Videos.” 2009. <https://www.usu.edu/cs/people/XiaoJunQi/Promotion/IJI.FireDetection.09.pdf>
33. *Digital Twin Implementation: Applications for Fleet Tracking and Increased Virtual Sensing*. EPRI, Palo Alto, CA: 2020. 3002018031. <https://www.epri.com/research/products/000000003002018031>
34. *Predictive Maintenance Primer: Revision to NP-7205*. EPRI, Palo Alto, CA: 2003. 1007350. <https://www.epri.com/research/products/000000000001007350>
35. *Developing a Technical Basis for Using On-Line Equipment Condition Monitoring to Reduce Time-Based Preventive and Predictive Maintenance Instrumentation and Control Program*. EPRI, Palo Alto, CA: 2018. 3002012784. <https://www.epri.com/research/products/000000003002012784>
36. R. Ayo-Imoru and A. Cilliers, *A Survey of the State of Condition-Based Maintenance (CBM) in the Nuclear Power Industry*. 2018. <https://www.sciencedirect.com/science/article/pii/S0306454917303365?via%3Dihub>
37. P. Higg et al., *A survey on condition monitoring systems in industry*. 2004. <http://www.plant-maintenance.com/articles/CBM-Survey-results.pdf>
38. *VVUQ 70 Verification, Validation, and Uncertainty Quantification of Machine Learning*. American Society of Mechanical Engineers, New York, NY. https://cstools.asme.org/csconnect/CommitteePages.cfm?Committee=103099834&_ga=2.210044053.1484375034.1659976193-1283103775.1654546811
39. *Appendix B to Part 50—Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants*. U.S. Nuclear Regulatory Commission, Washington, D.C. Page last reviewed/updated Monday, June 14, 2021. <https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-appb.html>

40. *Sensor*. Wikipedia. Retrieved January 2022. <https://en.wikipedia.org/wiki/Sensor>
41. O. Hamdi, *Advanced Work Packaging from Project Definition through Site Execution: Driving Successful Implementation of WorkFace Planning*. Masters thesis, The University of Texas, Austin, 2013. <http://hdl.handle.net/2152/21384>
42. T. Hurst, “Tow Nuclear Power I&C Out of the 'Digital Ditch.’” *Power*, January 2007. <https://www.powermag.com/tow-nuclear-power-ic-out-of-the-digital-ditch/>
43. H. Hashemian, “Nuclear Power Plant Instrumentation and Control.” *Nuclear Power—Control, Reliability and Human Factors*, Pavel Tsvetkov, Ed. IntechOpen, 2011, pp. 56–58. <https://www.intechopen.com/chapters/21051>
44. *EPRI Preventive Maintenance Basis Database (PMBD) v6.0*. EPRI, Palo Alto, CA: 2015. 3002005428. <https://www.epri.com/research/products/000000003002005428>
45. F. Flager, B. Welle, and J. Haymaker, *Multidisciplinary Process Integration and Design Optimization of a Classroom*. 2009. <https://www.itcon.org/paper/2009/38>
46. J. Martins and A. Lambe, *Multidisciplinary Design Optimization: A Survey of Architectures*. 2013. <https://arc.aiaa.org/doi/10.2514/1.J051895>
47. H. Peng, X. Wang, T. Wang, Y. Liu, and J. Wang, *A Multi-Criteria Decision Support Framework for Inland Nuclear Power Plant Site Selection under Z-information: A Case Study in Hunan Province of China*. 2020. <https://www.mdpi.com/2227-7390/8/2/252>
48. S. Kabadayl, A. Pridgen, and C. Julien. *Virtual Sensors: Abstracting Data from Physical Sensors*. 2006. <https://ieeexplore.ieee.org/document/1648519>
49. S. Mohanty, “On-line AI/ML and Computational Mechanics-Based Predictive Tools for a Digital-Twin Framework,” *Proceedings of the Workshop on Digital Twin Applications for Advanced Nuclear Technologies*, pp. 442–449. December 2020. <https://www.nrc.gov/docs/ML2108/ML21083A132.pdf>
50. *Azure Digital Twins*. Microsoft Corporation, 2022. <https://docs.microsoft.com/en-us/azure/digital-twins/overview>
51. N. Barroca et al., *Wireless Sensor Networks for Temperature and Humidity Monitoring within Concrete Structures*. 2013. <https://www.sciencedirect.com/science/article/abs/pii/S0950061812009233>
52. Y. Lim, K. Kwong, W. Liew, and C. Soh, *Practical Issues Related to the Application of Piezoelectric-Based Wave Propagation Technique in Monitoring of Concrete Curing*. 2017. <https://www.sciencedirect.com/science/article/abs/pii/S095006181731303X>
53. R. Navon, *Automated Project Performance Control of Construction Projects*. 2005. <https://www.sciencedirect.com/science/article/abs/pii/S0926580504001232>
54. J. Park, K. Kim, and Y. Cho, *Framework of Automated Construction—Safety Monitoring Using Cloud-Enabled BIM and BLE Mobile Tracking Sensors*. 2017. <https://ascelibrary.org/doi/10.1061/%28ASCE%29CO.1943-7862.0001223>

55. B. Akinici et al., *A Formalism for Utilization of Sensor Systems and Integrated Project Models for Active Construction Quality Control*. 2006.
<https://www.sciencedirect.com/science/article/abs/pii/S092658050500052X>
56. Q. Wang, J. Cheng, and H. Sohn, *Automated Estimation of Reinforced Precast Concrete Rebar Positions Using Colored Laser Scan Data*. 2017.
<https://onlinelibrary.wiley.com/doi/10.1111/mice.12293>
57. T. Hong, Z. Wang, X. Luo, and W. Zhang, *State-of-the-art on research and applications of machine learning in the building life cycle*. 2020. <https://escholarship.org/uc/item/5zt6c00q>
58. *Smart Torque System*. Cumulus, 2019. <https://www.youtube.com/watch?v=zFjeJqCXPzE> and https://cumulusds.com/wp-content/uploads/2020/06/cumulus_data_sheet_5-6-2020-Final.pdf
59. M. LeVasseur and R. Kitchen, *Digital Twin for the Manufacture and Qualification of Additively Manufactured Nuclear Components*. p. 316/784. 2020.
<https://www.nrc.gov/docs/ML2108/ML21083A132.pdf>
60. *Use of Control Room Simulators for Training of Nuclear Power Plant Personnel*. International Atomic Energy Agency, 2004. IAEA-TECDOC-1411. https://www-pub.iaea.org/MTCD/Publications/PDF/te_1411_web.pdf
61. P. Hoffmann, R. Schumann, T. Maksoud, and G. Premier, *Virtual Commissioning of Manufacturing Systems: A Review and New Approaches for Simplification*. 2010.
<https://www.scs-europe.net/dlib/2010/2010-0175.htm>
62. C. Lee and S. Park, *Survey on the Virtual Commissioning of Manufacturing Systems*. 2014.
<https://www.sciencedirect.com/science/article/pii/S2288430014500292>
63. A. Cilliers, *A Deterministic Approach for Establishing a Narrow Band Dynamic Operating Envelope to Detect and Locate Hardware Deterioration in Nuclear Power Plants*. 2013.
https://repository.nwu.ac.za/bitstream/handle/10394/9001/Cilliers_A.pdf?sequence=1
64. W. Leech and T. Dean, *Automated rule based process control method with feedback and apparatus therefor*. 1988.
<https://pdfpiw.uspto.gov/.piw?PageNum=0&docid=04754410&IDKey=B62E3DB9FB10%0D%0A&HomeUrl=http%3A%2F%2Fpatft.uspto.gov%2Fnetacgi%2Fnph-Parser%3FSect1%3DPTO2%2526Sect2%3DHITOFF%2526u%3D%25252Fnethtml%25252FPTO%25252Fsearch-adv.htm%2526r%3D128%2526f%3DG%2526>
65. B. Golchert and G. Banyay, *Nuclear Regulatory Commission*. p. 301/784. 2020.
<https://www.nrc.gov/docs/ML2108/ML21083A132.pdf>
66. P. Langley and H. Simon, *Applications of Machine Learning and Rule Induction*. 1995.
<http://www.isle.org/~langley/papers/mlapps.cacm95.pdf>
67. R. Busquim e Silva, “Asherah NPP Simulator Cybersecurity in a Digital Closed-Loop Environment.” *Proceedings of the Workshop on Digital Twin Applications for Advanced Nuclear Technologies*, pp. 574–587. December 2020.
<https://www.nrc.gov/docs/ML2108/ML21083A132.pdf>

References

68. A. Cilliers, *Kairos Power ARPA-E Gemina Projects*. p. 590/784. 2020.
<https://www.nrc.gov/docs/ML2108/ML21083A132.pdf>
69. P. Ramuhalli, “Digital Twins for Prognostic Health Management (PHM) in Nuclear Energy: Opportunities and Challenges.” *Proceedings of the Workshop on Digital Twin Applications for Advanced Nuclear Technologies*, p. 714–735. 2020.
<https://www.nrc.gov/docs/ML2108/ML21083A132.pdf>
70. J. Barlett, *The Changing Costs and Values of Electricity Generation Technologies: Measuring Profitability and Evaluating Options for Integrating Renewables*. June 2019.
https://media.rff.org/documents/RFF-IB-19-04_4.pdf
71. V. Nguyen, *Ontologies and Information Systems: A Literature Study*. Australian Government Department of Defense: 2020. <https://apps.dtic.mil/sti/pdfs/ADA546186.pdf>
72. “Difference Between Descriptive Analysis and Comparisons.” *Difference Between Taxonomy and Ontology*. DifferenceBetween.info. 2022.
<http://www.differencebetween.info/difference-between-taxonomy-and-ontology>

A

USE CASE TABLE

**Table A-1
Use cases**

	Use Case	Application Area	Target Benefits	Requirements
1 – Design				
1.1	<p><u>Automated Design Updates via Integrated Design Platform</u></p> <ul style="list-style-type: none"> • Building information modeling (BIM) model integrating 3D geometry; bill-of-materials parametric design calculations, models, and analyses; hierarchical design requirements database; probabilistic risk assessment (PRA); cost model; schedule; etc., to enable automated design updates across interdependent components and systems. • Enables rapid iterative design process/virtual prototyping. • Can provide design update impacts on safety margin, risk insights, clash detection, cost, schedule, etc. • Analogous to multidisciplinary design optimization (MDO) as described in Flager et al. [45] and Martins and Lambe [46]. 	<ul style="list-style-type: none"> • Design Optimization 	<ul style="list-style-type: none"> • Mitigates cost of design updates, accelerating iterative design process. • Enables optimization across design alternatives for various design outcomes (safety/risk, cost, schedule, etc.). 	<ul style="list-style-type: none"> • Development and integration of parametric models for various elements of design information (e.g., parametric geometry models, analysis models, cost estimates, schedules, etc.). • Development of optimization algorithms. • Reliable material and labor rate data for local markets.
1.2	<p><u>Construction Sequence Simulation</u></p> <ul style="list-style-type: none"> • BIM model integrating 3D geometry, construction sequencing information, cost model, schedule, etc., to visualize and simulate detailed work sequencing. • Enables 4D (spatiotemporal) virtual constructability, inspectability, and maintainability reviews in parallel with design development process. When coupled with Use Case 1.1, design changes stemming from these reviews can be rapidly incorporated in an iterative fashion. • Assists in ensuring completeness of design information prior to construction to minimize requests for information (RFIs) and preclude construction-stage design changes, requalification engineering assessments, extended regulatory inspections, and associated cost and schedule impacts. • Incorporate uncertainty into model input parameters to enable probabilistic simulations of construction sequence. Identify most likely scenarios with least desirable outcomes and adjust the construction plan to mitigate them. For example, simulate various potential as-built placement/geometries to identify high-risk elements of design most adversely affected by out-of-tolerance/nonconforming construction. 	<ul style="list-style-type: none"> • Design Optimization • Configuration Management 	<ul style="list-style-type: none"> • Minimize ambiguity in design to preclude construction delays and costly design changes during construction. • Improves fidelity of construction cost estimates and schedules. • When integrated with cost model and schedule, alternative construction sequences / processes can be analyzed and optimized. 	<ul style="list-style-type: none"> • Development of construction sequence models. • Design tools with construction sequence modeling capability, and integration with other elements of design information. • Early engagement of construction SMEs in design phase.
1.3	<p><u>Site Selection Optimization</u></p> <ul style="list-style-type: none"> • Automate site selection for a standard design, which in turn can also be used to automate generation of regulatory submittals (environmental impact studies, site licensing submittals). • Optimize site selection across multiple factors, such as location-specific construction cost variance, resource availability and transportation, public safety and natural hazards, socioeconomic impacts, ecological and environmental impacts, geographic features, security, technological feasibility, and factors affecting economics of operation, such as transmission losses and ambient temperatures of heat sinks. See Peng et al. [47] for an example of a potential optimization framework for NPP siting. • Coupling with integrated design platform described in Use Case 1.1 could enable two-way optimization of both site selection and plant design. 	<ul style="list-style-type: none"> • Design Optimization 	<ul style="list-style-type: none"> • Assist in identifying sites most likely to be economically viable and successfully licensed. Directs focus of development efforts toward markets/regions for which advanced reactors (ARs) provide maximal value. • Shortened schedules for site selection, feasibility studies, and site licensing process for different site alternatives. • Potential to inform plant design based on site selection optimization by integrating with integrated design platform described in Use Case 1.1. 	<ul style="list-style-type: none"> • Geographic information system (GIS)-based framework for the region(s) under consideration, including data on factors affecting optimal site selection. • Development of optimization algorithms.
1.4	<p><u>Sensor Layout Optimization</u></p> <ul style="list-style-type: none"> • Employ a data-driven or physics-based model of a physical asset to create “virtual sensors” that replace and/or augment physical sensors (Kabadayi et al. [48]). • Virtual sensors enable reduction of the number of real sensors deployed on the asset and/or provide additional information about the asset that is not feasible to collect using physical sensors (Mohanty [49]). • Perform optimization analysis to identify minimal set of physical sensors that, when integrated with digital model to create virtual sensors, provide the required descriptive data for the physical asset. 	<ul style="list-style-type: none"> • Health Monitoring 	<ul style="list-style-type: none"> • Cost savings by reducing number of physical sensors installed and maintained. • Increased fidelity and completeness of descriptive data about the asset enables improved diagnostic, predictive, and prescriptive analytics. 	<ul style="list-style-type: none"> • Data-driven or physics-based model of asset. • Sensor placement optimization algorithms.

Table A-1 (continued)
Use cases

	Use Case	Application Area	Target Benefits	Requirements
2 – Construction				
2.1	<p><u>Supply Chain Modeling, Simulation, and Tracking</u></p> <ul style="list-style-type: none"> Digital model for visualizing, simulating, and tracking delivery of critical elements of supply chain for construction (Microsoft Corporation [50]), e.g., concrete batch plants, structural steel suppliers, structure module manufacturers, and primary loop component manufacturers. Prior to construction, can be used to run simulations to determine high-risk elements of supply chain and develop mitigation strategies. During construction phase, vendors, suppliers, and manufacturers provide live data feeds from their facilities/processes (e.g., facility production rates, qualification/inspection status, status and location of shipping vehicles, live camera feed), which are integrated into the central digital twin (DT) platform for real-time tracking, control, and issue mitigation. Could be integrated with Use Cases 1.2 and 2.2 to further improve the fidelity of construction sequence simulations. 	<ul style="list-style-type: none"> Configuration Management Informed Decisions 	<ul style="list-style-type: none"> Identification of high-risk elements of supply chain to enable early adoption of mitigation strategies. Minimizes cost and schedule disruptions. Rapid identification of suboptimal supply chain links during construction. Enables quick implementation of mitigation measures to minimize schedule delays and associated costs. 	<ul style="list-style-type: none"> Identification of critical elements of supply chain and monitoring parameters important to production and delivery. Data on historical and current trends for reliability of supply chain elements that enables predictive modeling using DT.
2.2	<p><u>Real-Time Construction Sequence Optimization and Front-Running Simulations</u></p> <ul style="list-style-type: none"> During construction phase, use DT similar to Use Case 1.2 to perform real-time optimization and front-running simulations informed by monitoring of schedule- and cost-critical parameters (e.g., concrete curing (Barroca et al. [51]; Lim et al. [52]); health, efficiency, and productivity of construction equipment (Navon [53]); quantities of materials delivered and installed; current weather and forecast; environmental/health hazards (Park et al. [54]); number, geolocation, and biometrics of personnel; status of work products and inspections; supply chain data and predictions from Use Case 2.1; billings from suppliers). Real-time tracking of critical parameters enables identification and mitigation of suboptimal construction operations. Front-running simulations provide real-time analysis of the likely consequences/outcomes of construction project events and deviations from plan. Provides construction management with high-fidelity information to support optimal responses to construction deviations. 	<ul style="list-style-type: none"> Health Monitoring Configuration Management Informed Decisions 	<ul style="list-style-type: none"> Improved efficiency of construction operations Optimized costs and schedule. Early warning of personnel health hazards during construction for improved safety. Informed <i>ad hoc</i> decision-making based on knowledge of likely consequences of unplanned events that occur during construction and potential outcomes of mitigating actions. 	<ul style="list-style-type: none"> Integrated construction sequence simulation DT similar to Use Case 1.2. Sensor network/infrastructure to monitor critical parameters during construction. Supply chain modeling DT similar to Use Case 2.1. Development of optimization algorithms.
2.3	<p><u>Automated Construction Quality Assurance</u></p> <ul style="list-style-type: none"> Capture and document as-built configuration using real-time sensing data, such as light detection and ranging (LiDAR), computer vision, photogrammetry, instrumented tools. Integrate sensor data (e.g., point clouds, torque measurements on pipe flange bolts) with 3D BIM to automate and/or facilitate QA of as-built configuration (e.g., rebar size and spacing, concrete finished surface dimensions) and identify deviations/nonconformance (Akinici et al. [55]; Wang et al. [56]; Hong et al. [57]; Cumulus [58]). Couple with automated/integrated design calculations, such as in Use Case 1.1 to enable rapid evaluation and requalification of as-built configuration. Can extend into maintenance and operations phases to automate tracking and QA as-operated plant configuration. 	<ul style="list-style-type: none"> Configuration Management 	<ul style="list-style-type: none"> Improved quality control. Reduced cost and schedule impacts from manual inspections. Automated generation of as-built documentation and plant maintenance records. 	<ul style="list-style-type: none"> Portable and durable sensor equipment capable of deployment at construction sites for generation of high-resolution point-cloud data. Artificial intelligence/machine learning (AI/ML) algorithms for integrating point-cloud data with 3D geometry models, classifying objects, detecting deviations, etc.

Table A-1 (continued)
Use cases

	Use Case	Application Area	Target Benefits	Requirements
2.4	<p><u>Prefabrication</u></p> <ul style="list-style-type: none"> • Portions of the facility and/or systems that are manufactured off-site in sections to enable rapid assembly on-site. • Industrialized construction promotes the advancement of construction processes by employing mechanization and automation. • Industrialization provides reapplication of design to multiple projects, reducing time in planning, procurement, manufacturing, and assembly. • Inclusive of two stages—manufacturing of assemblies then erection of assemblies. • Presents high quality for repetitive assemblies. <p><i>Specific Applications</i></p> <p><u>Quality Control and Qualification of Off-Site Manufactured Components</u></p> <ul style="list-style-type: none"> • Off-site manufactured components (such as ASME-qualified vessels, structure modules) are delivered with an accompanying DT designed to assist in demonstrating compliance with design requirements/ qualification. • DT consists of a full characterization of design requirements, corresponding as-built measurements and parameters, and a comparison to validate that the as-built configuration meets all specified requirements. • For example, the DT could include a 3D geometric design model of a structural module, LiDAR scan of the as-built module, and an analysis demonstrating that the as-built geometry is within the specified geometric tolerances required in the design. • Data gathered during manufacturing is integrated with DT to aid in defect detection, quality control, and design optimization (e.g., LeVasseur and Kitchen [59]). 	<ul style="list-style-type: none"> • Configuration Management 	<ul style="list-style-type: none"> • Maximize design efforts. • Minimize schedule delays and associated costs resulting from rejection of nonconforming work products delivered to construction site. • Automate and expedite validation of as-built conformance to design requirements. • Can reduce costs associated with destructive testing and design iteration for manufactured components (LeVasseur and Kitchen, 2020). 	<ul style="list-style-type: none"> • Upfront design/construction considerations for prefabrication/ industrialized manufacturing of systems. • Specification of requirements for DTs, parameters to be modeled and measured, and validation tests to be conducted and integrated with DT upon product delivery. • Development of methods for comparing measured data to design requirements (e.g., point cloud data vs. 3D model geometry).
3 – Commissioning				
3.1	<p><u>Virtual Plant Simulator for Operations Training and Optimization</u></p> <ul style="list-style-type: none"> • Augment traditional concept of nuclear plant control room simulators (IAEA [60]) with 3D model of control room and/or plant environment integrated with process models for simulating plant behavior. • Train personnel in simulated environments via virtual reality (VR)/augmented reality (AuR) without entering the physical plant or physical simulator. Simulate procedures involving activities both inside and outside of control room with 3D visualization and real-time simulated plant response. • Supplement traditional written procedures with guided walkthroughs using AuR. • Integrate other elements of personnel training (e.g., classroom instruction, visualization of thermodynamic processes inside equipment) with virtual simulator environment to provide more immersive and interactive training. • Full-plant simulator can be used to augment training programs for other plant personnel besides control room operators, e.g., managers, maintenance personnel, outage crews, health physics personnel (IAEA [60]). • Run simulations on scenarios most likely to induce human error, and then design the system to mitigate those scenarios, errors, and consequences (Grieves and Vickers [22]). 	<ul style="list-style-type: none"> • Design Optimization 	<ul style="list-style-type: none"> • More flexible scheduling and reduced cost for personnel training in virtual vs. physical environment. Decentralizes training facility to anywhere that could support VR/AuR. • Data collected from simulations can be used to evaluate training effectiveness and optimize control system, procedures, and human error models. • Improved training for personnel other than control room operators. • Enables feedback from training and human interaction simulations to inform designs. 	<ul style="list-style-type: none"> • 3D model of the environment (e.g., main control room, whole plant, safety systems) being simulated. • Plant controls logic/process model integrated with virtual environment.
3.2	<p><u>Virtual Commissioning</u></p> <ul style="list-style-type: none"> • Virtual plant simulating physical sensors, actuators, and plant physics/behavior are integrated with physical or virtual control system to test, troubleshoot, and optimize plant systems and controls. • Can be extended to Use Case 3.1. • Analogous to virtual commissioning concepts described for manufacturing systems (Hoffmann et al. [61]; Lee and Park [62]). 	<ul style="list-style-type: none"> • Configuration Management 	<ul style="list-style-type: none"> • Reduced overall commissioning time and rate of control system errors requiring troubleshooting during commissioning stage. • Identification of design flaws and potential operational faults before construction mitigates costly corrective actions that would otherwise be required during commissioning. • Enables feedback from commissioning process into design of physical plant systems, procedures, and I&C systems. 	<ul style="list-style-type: none"> • Virtual plant model described at the level of sensors, actuators, and plant behavior. • Physical digital control system or virtual representation of control system logic integrated with virtual plant model.

Table A-1 (continued)
Use cases

	Use Case	Application Area	Target Benefits	Requirements
4 – Operations				
4.1	<p><u>3D mapping and AuR Visualization of Ambient Radiation Levels</u></p> <ul style="list-style-type: none"> Integrate radiation monitoring sensor data with 3D building models to provide real-time <i>in situ</i> mapping of ambient radiation levels throughout the plant. Equip plant personnel with mobile AuR equipment integrated with the ambient radiation maps and personnel location tracking to enable real-time visualization of radiation levels in the field, e.g., safety glasses with projected images indicating radioactive “hot spots” to improve implementation of “as low as reasonably achievable” (ALARA) dose management principles. Use pathfinding algorithms to guide personnel through optimal routes to their destination to minimize personnel dose exposure. Compare real-time measurements from distributed sensors in plant and dosimeters worn by plant personnel with historical data to provide event-driven alarms and notifications of unexpected and new hotspots, which could be indicative of system faults, leaks, or malfunctions. Couple personnel location tracking with contamination monitors to facilitate tracking, tracing, and cleanup of contamination sources. 	<ul style="list-style-type: none"> Optimized Operations Configuration Management 	<ul style="list-style-type: none"> Enhanced personnel safety, reduced dosage. Decreased personnel effort for performing radiation surveys manually. 	<ul style="list-style-type: none"> A DT of the facility capturing spatial and component layout information, and historical radiation levels in different parts of the facility. Network of radiation sensors (e.g., permanently installed, worn by plant personnel), integrated with DT. VR/AR software and devices. Algorithms for analyzing new vs. historical data to identify and classify anomalies.
4.2	<p><u>Smart Chemistry Monitoring and Control</u></p> <ul style="list-style-type: none"> Integrate plant-specific heat balance/physical water chemistry models for secondary systems with SMART Plants Works, a tool that enables importing of near-real-time chemistry data from plant systems, and includes a primary-to-secondary leak rate calculator, trend analyzer, and other modules to evaluate plant chemistry (EPRI 3002020014 [15]). Provide plant staff with robust description of current water (or other working fluid) chemistry conditions. Enable analytics to optimize chemistry controls and identify, classify, and mitigate adverse trends and anomalies. Possible extension to other plant areas, including heat exchangers and flow-accelerated corrosion modeling, to predict and represent transients. 	<ul style="list-style-type: none"> Informed Decisions Health Monitoring 	<ul style="list-style-type: none"> Optimized chemistry controls. Increased reliability via early identification and mitigation of adverse trends. 	<ul style="list-style-type: none"> Improved PCS module to represent plant-specific heat balance/ physical models. Integration of data feeds from SMART Plants Works into improved PCS.
4.3	<p><u>Smoke and Fire Detection and Response System</u></p> <ul style="list-style-type: none"> Integrate 3D building model with live data feeds from smoke detectors, temperature sensors, and video cameras. Use camera feeds for computer vision fire detection (Qi and Ebert [32]). Integrate data feeds and building model with fire propagation models and computational fluid dynamics (CFD). Perform front-running simulations (Grieves and Vickers [22]) to predict propagation scenarios and assess efficacy of alternative mitigation measures to inform crisis management decisions in real time. 	<ul style="list-style-type: none"> Informed Decisions Design Optimization 	<ul style="list-style-type: none"> Enhanced safety. 	<ul style="list-style-type: none"> Physics-based DT of the facility that predicts smoke and fire propagation. Network of high-quality cameras, smoke detectors, and temperature sensors.
4.4	<p><u>Narrow-Band Dynamic Operating Envelope</u></p> <ul style="list-style-type: none"> A model of the plant at the level of sensors, actuators, and plant behavior runs real-time simulations to predict the plant state corresponding to the actual control operations (Cilliers [63]). Deviations between the simulated state and the measured state indicated by instrumentation signal plant faults, which would normally otherwise be imperceptible and/or masked by automated control system compensation. The DT also simulates the control system response to faults, which is used to classify faults and inform operator response decisions. 	<ul style="list-style-type: none"> Informed Decisions Health Monitoring 	<ul style="list-style-type: none"> Enhanced safety via increased sensitivity to faults that could otherwise be imperceptible. Early identification of faults before they result in conditions that trigger safety system response. Improved efficiency and efficacy of maintenance and troubleshooting operations by providing additional context to operators to aid in fault classification and root-cause analysis. 	<ul style="list-style-type: none"> Network of sensors and actuators. Development and training of anomaly detection and classification algorithms. DT platform for integrating facility models, sensor data, data processing algorithms, and user interface.
4.5	<p><u>Personnel Tracking and Authorized Access Enforcement</u></p> <ul style="list-style-type: none"> Use data from motion, infrared, light, and security access sensors with wearable personal location device and the as-built facility DT to provide visibility into occupancy and movement of personnel throughout plant. The personal location devices could include features such as push-button emergency alert for accidents, biometric sensors to detect dangerous vital conditions, and automated detection of slips-trips-falls. 	<ul style="list-style-type: none"> Informed Decisions Configuration Management 	<ul style="list-style-type: none"> Enhanced security through improved visualization of real-time personnel location. Enhanced personnel safety via monitoring and tracking biometric responses to plant environments and tasks. 	<ul style="list-style-type: none"> A DT of the facility capturing spatial and component layout information. Network of motion, infrared, light, and security access sensors integrated with data from personal location and health-monitoring wearable devices.

Table A-1 (continued)
Use cases

	Use Case	Application Area	Target Benefits	Requirements
4.6	<p><u>Automated Quality Control and Yield Optimization of TRISO Pebble Production</u></p> <ul style="list-style-type: none"> Collect data feed from various parameters potentially affecting tristructural isotropic (TRISO) fuel pebble quality (e.g., chemical composition, temperature, pressure at various production stages). Integrate with data on quality of end-state product. Leverage ML/AI algorithms to implement a smart process control system to maximize yield and quality of TRISO pebbles for pebble-based ARs. Analogous to Westinghouse approach for nuclear fuel pellet manufacturing [64], with reported savings in excess of \$1 million per year (Golchert and Banyay [65]) and increased business of \$10 million per year (Langley and Simon [66]). 	<ul style="list-style-type: none"> Informed Decisions 	<ul style="list-style-type: none"> Cost savings and increased yield of usable product by minimizing process waste, rejected product, and destructive testing. 	<ul style="list-style-type: none"> Network of sensors to detect the yield of the manufacturing process. A network of actuators that can alter the parameters of the manufacturing process to maximize yield.
4.7	<p><u>Fleet-Level Performance Optimization</u></p> <ul style="list-style-type: none"> Use an integrated system of individual plant-level DTs to rapidly optimize fleet output and operational costs. Integrate data feeds and predictive models for grid demands, individual plant performance, maintenance schedules, environmental factors affecting efficiency (such as ambient temperatures) into optimization algorithms to provide prescriptive guidance on individual plant operation that optimizes overall plant performance. Applicable to nearly identical components, systems, or plants in a fleet, such that data collected from one plant may be used to inform decisions pertaining to other plants. Analyze feeds of operational parameters across the fleet to automatically identify patterns, outliers, inefficiencies, “best practices,” etc., which can inform operational decisions. Particularly relevant for ARs because many designs are anticipated to be deployed with multiple units at a single site and/or across multiple sites, that is, deployed as a fleet of nearly identical plants. Monitoring fleet performance enables identification of opportunities for enhancements and improved design features into next-generation designs. 	<ul style="list-style-type: none"> Informed Decisions 	<ul style="list-style-type: none"> Improved operational efficiency and safety by facilitating sharing of lessons, trends, and data across plants in a fleet. Real-time monitoring of fleet performance. 	<ul style="list-style-type: none"> DTs for corresponding components, systems, or entire plants, integrated across multiple plants within a fleet. Development of fleetwide optimization algorithms. Deployment of optimized procedures.
4.8	<p><u>Mobile Access to Digital Configuration Management Information</u></p> <ul style="list-style-type: none"> Allow real-time access and viewing of current and historical documents (e.g., drawings, P&IDs, design-basis documents, procedures) by pointing a mobile device’s camera at a component of interest, scanning a QR code with a mobile device’s camera, or selecting from a list of nearby components based on the mobile device’s current location in the plant. 	<ul style="list-style-type: none"> Configuration Management 	<ul style="list-style-type: none"> Cost savings from increased efficiency during operations, maintenance, inspection, and walkdown activities. Improved human performance and error reduction by providing high-quality information to support decision-making in the field. 	<ul style="list-style-type: none"> Data-centric CMIS (EPRI 3002003126 [29]) A DT of the facility capturing as-built spatial and component layout information (End State 5 – 2D/3D Model Integration per EPRI 3002003126 [29]). Development and validation of ML/AI algorithms that can identify components from mobile camera feeds; or installation of scannable QR codes on each component; or technology capable of listing nearby components based on mobile device location.
4.9	<p><u>Monitoring and Active Management of Thermal Stresses in High-Temperature Coolant Lines</u></p> <ul style="list-style-type: none"> Use active control to manage large thermal movements and stresses in AR high-temperature coolant lines via DT with predictive stress models. Perform analysis of real-time sensor data (e.g., temperatures, displacements, strains, and forces in pipes and supports) in integrated physics-based (FEM) and/or data-driven (AI/ML) predictive models to determine full-field characterization of displacement response, stresses, and strains. Leverage the analytical results to optimize actuator response to accommodate thermal movements of the connected equipment and mitigate stresses. Can be extended to lateral supports of the reactor vessel as well. 	<ul style="list-style-type: none"> Health Monitoring Informed Decisions 	<ul style="list-style-type: none"> Active control using DTs has the potential to significantly simplify the high-temp piping design and construction of ARs, a key cost target of AR developers. 	<ul style="list-style-type: none"> Sensor network providing real-time inputs to predictive models. Integrated physics-based and/or data-driven predictive models for piping, equipment, supports, and potentially structure. Capability to adapt predictive models based on actual response from actuator inputs to system. Actuator hardware, engineering, and maintenance.

Table A-1 (continued)
Use cases

	Use Case	Application Area	Target Benefits	Requirements
4.10	<p><u>Digital Twin Application for Earthquake Early-Warning Scram System</u></p> <ul style="list-style-type: none"> • Use a DT of the site geodynamics coupled with spatially distributed accelerometer network to proactively scram a reactor before the arrival of damaging seismic waves from a distant seismic event. • Can potentially allow for relaxation of seismic design criteria for various SSCs, such as those affecting safety only during reactor operation (i.e., not required to function following reactor scram). 	<ul style="list-style-type: none"> • Informed Decisions • Health Monitoring 	<ul style="list-style-type: none"> • Increased safety by early initiation of reactor scram. • Cost reduction via enabling relaxed seismic design criteria for SSCs. 	<ul style="list-style-type: none"> • DT integrating seismological activity monitoring with wave-field prediction models. • Demonstration of efficacy and reliability of predictive capability with sufficient warning time for scram. • Framework for justifying relaxation of seismic design criteria based on crediting early scram.
4.11	<p><u>Simulated Stress Testing of NPP’s Cyber Security Framework</u></p> <ul style="list-style-type: none"> • Employ a DT of the plant primary system that simulates the operations of the primary components, the reaction control systems, the main control room supervisory control and data acquisition (SCADA) systems, the logic controllers that manipulate the reactor operating parameters, and the plant’s cyber-security systems (e.g., firewalls) to create a testbed for simulation of various cyber-attacks, test the facility’s cybersecurity systems, and assess vulnerabilities. • Attack vectors are simulated to breach the cyber-security systems modelled in the DT testbed and gain access to the virtual plant controllers and SCADA systems to acquire control of the virtual reactor. • Can be used to assess the impact of a particular system being compromised. • The concept has been demonstrated through IAEA-sponsored (Coordinated Research Project #J02008) Asherah Nuclear Power Plant Simulator deployed in a closed-loop DT testbed (Silva [67]). 	<ul style="list-style-type: none"> • Health Monitoring 	<ul style="list-style-type: none"> • Extensive testing of the facility’s cyber-security strategies in a cost-effective manner, resulting in better coverage of potential vulnerabilities, which can be addressed to develop more robust cyber-security systems. 	<ul style="list-style-type: none"> • A simulator of the facility’s primary system, critical control systems, and cyber-security systems.
5 – Maintenance				
5.1	<p><u>Robotic Maintenance</u></p> <ul style="list-style-type: none"> • Training, rehearsals, and commissioning of autonomous robots performing maintenance activities in digitally simulated environments. • DT can integrate various combinations of virtual and physical plant systems, components, and environment; robot controller and control program; and robot itself. • DT of robot enables optimization, health monitoring, performance enhancement, qualification, etc., for the robot and the services it provides. Enables digital engineering of robot design and de-risking of robot operations prior to initial deployments. • DT of robot and environment, integrated with actual robot controller enables virtual commissioning of robot controllers (e.g., programmable logic controllers, control programs and algorithms) analogous to Use Case 3.2. 	<ul style="list-style-type: none"> • Health Monitoring • Design Optimization • Configuration Management 	<ul style="list-style-type: none"> • Cost savings. • Enhanced safety and reduced dosage via unmanned maintenance. • Enabling technology for AR designs with highly irradiated local environments. 	<ul style="list-style-type: none"> • A DT of the plant environment being simulated. • Integration of plant environment DT and robot DT or the environment DT and the physical robot and its controls/sensing systems.
5.2	<p><u>Virtual Walkdown and Inspection</u></p> <ul style="list-style-type: none"> • VR with a 3D BIM model integrated with live-feed video or periodically updated photographic surveys (undertaken manually or automatically using high-end cameras mounted on autonomous vehicles). • Virtual access (VR/AuR) for maintenance/outage planning and strategizing in highly irradiated and contaminated areas. • Perform pre-job briefs and even rehearse outage activities on a virtual plant before the actual outage to help coordinate, plan, and optimize activities. • Limits physical plant access improving worker safety (minimizes radiation dose and other workplace hazards), schedule, and associated costs. 	<ul style="list-style-type: none"> • Health Monitoring 	<ul style="list-style-type: none"> • Increased efficiency in activities requiring eyes-on access to plant, and corresponding reductions in costs and schedules. • Enhanced safety, dosage reduction from reduced congestion in plant. 	<ul style="list-style-type: none"> • A DT of the facility capturing spatial and component layout information. • VR/AuR development software and devices. • Dedicated VR/AuR facility.

Table A-1 (continued)
Use cases

	Use Case	Application Area	Target Benefits	Requirements
5.3	<p><u>Integrated Dynamic Probabilistic Risk Assessments</u></p> <ul style="list-style-type: none"> Integrate systems logic model with data-centric configuration management information system (CMIS; EPRI 3002003126 [29]) to keep model current with as-operated plant configuration. Parameterize failure probability calculations (e.g., fragility calculations for seismic and high-wind PRAs) by SSC parameters that can be measured and updated automatically. Measure/monitor risk-dominant parameters as determined by PRA and underlying analyses, e.g., median water level in storage tanks, common-cause failure data, SSC availability. Integrate real-time data feeds with failure probability calculations to enable real-time dynamic PRA. Run “front-running” simulations of accident progressions in real time to assist operators with sensemaking during complex situations and crisis management (Grieves and Vickers [22]). 	<ul style="list-style-type: none"> Health Monitoring 	<ul style="list-style-type: none"> Shorter cost and duration for ongoing maintenance of PRA. Reduced risk/enhanced safety. Increased opportunity for incorporation of risk-informed insights into licensing applications. 	<ul style="list-style-type: none"> PRA integrated with data-centric CMIS, real-time sensor data for risk-important parameters, and parametric failure probability calculations. Electronic failure probability calculations using software where calculation inputs can be parameterized. Efficient solver/algorithm for quantifying PRA model to enable real-time updates.
5.4	<p><u>Sensor Fault-Detection</u></p> <ul style="list-style-type: none"> Use a physics-based DT coupled with ML/AI algorithms to determine whether a deviation between the DT and sensor readings is due to faulty sensor readings or anomalous component operation. Effectively, use virtual sensing (Use Case 1.4) to monitor the health of physical sensors (Cilliers [68]; Ramuhalli et al. [69]). Can determine whether the sensor needs to be inspected, recalibrated, repaired, replaced, etc. 	<ul style="list-style-type: none"> Health Monitoring 	<ul style="list-style-type: none"> Increased reliability. Improved safety, e.g., assist operators in sensemaking during crisis situations/accident scenarios by identifying sensor readings that may be unreliable/faulty. 	<ul style="list-style-type: none"> Physics-based DT of the component of interest. Development of training data for the ML/AI algorithms. Validation of ML/AI algorithms.
5.5	<p><u>Predictive Maintenance</u></p> <ul style="list-style-type: none"> Combine operating experience data (e.g., PMBD, EPRI 3002005428 [44]), real-time instrumentation data, mechanics-based modeling, and ML/AI algorithms to assess current health and predict remaining life. Used to inform and optimize maintenance activities, encouraging condition-based maintenance in favor of time-based maintenance. <p><i>Specific Applications</i></p> <ul style="list-style-type: none"> Irradiation-assisted stress corrosion cracking (IASCC) of highly irradiated elements of primary system. Predict IASCC crack initiation and propagation, and remaining time to significant degradation based on real-time measured data on flux rate, vibrations, temperature, etc. Condition assessment of electrical cables based on physics-based DT and operational history of the cables. Main turbine bearings. Monitor parameters such as number of operational cycles, bearing temperatures and loads, rpm, etc. Determine grease degradation using ML/AI framework trained on photographs taken during visual inspections, reducing and eventually eliminating dependence on costly laboratory testing. Emergency power lead-acid batteries (and/or other electrical equipment). Integrate loading histories captured over the service life with performance and aging models. Monitor cell chemistry, battery temperatures, cell voltage, power cycles, power quality, response to loading and charging, etc. 	<ul style="list-style-type: none"> Health Monitoring 	<ul style="list-style-type: none"> Cost savings. Reduced maintenance. Increased reliability of equipment performance. Enhanced safety by minimizing avoidable/noncritical maintenance activities. 	<ul style="list-style-type: none"> Hybrid physics-based, data-driven DT of the subject component or system. Historical operating experience empirical data. Development of training data for the ML/AI algorithms. Validation of ML/AI algorithms.

Table A-1 (continued)
Use cases

	Use Case	Application Area	Target Benefits	Requirements
5.6	<p><u>Structural Health Monitoring (SHM)</u></p> <ul style="list-style-type: none"> Employ a system of embedded or surface-mounted strain gauges and load transducers capturing real-time data integrated with physics-based structural models to detect structural degradation and/or anomalous load conditions. Implement ML/AI-enabled drone-based inspections to detect concrete cracking and estimate the severity of cracking condition with regard to structural performance for design-basis loads. <p><i>Specific Applications</i></p> <ul style="list-style-type: none"> SHM for below-grade structural wall water intrusion and degradation. Enables vertical cut excavations for embedded AR cavity construction to reduce costs, which otherwise pose QA and regulatory challenges with regard to below-grade waterproofing systems. The DT-based SHM system can monitor moisture penetration to identify and predict significant structural element degradation and its impact on the credited safety functions for operability. SHM for vibration-based damage and degradation. Modal behavior analysis can help verify that the <i>in situ</i> behavior conforms to the design intent and reveal structural deficiencies induced by unforeseen conditions. Examples include load amplifications and stress concentrations due to SSCs double-resonance or flexible structure response. SHM for inelastic deformations and crack detection through acoustic emission monitoring. Applications include structural elements made of reinforced concrete, steel, or composites. Acoustic wave analysis can identify defect formation and failures, such as those resulting from creep, thermal stresses, cooldown cracking, fiber breakage, debonding, and leakage. SHM in extreme environments, such as highly radioactive or electromagnetic spaces, through optical fiber Bragg grating (FBG) sensors. FBG sensors measure strains and temperature changes by measuring propagation of particular wavelengths through the fibers. FBG sensors' distinctive advantages (compactness, lightweight, linearity, embedding capability, immunity to electromagnetic interference and corrosion, high signal-to-noise ratio) make them attractive for a variety of monitoring applications, including thermal gradients during concrete curing, crack propagation, and multi-axial strain and tilt information. 	<ul style="list-style-type: none"> Health Monitoring 	<ul style="list-style-type: none"> Increased reliability Reduced maintenance 	<ul style="list-style-type: none"> Physics-based structural models. Network of strain gauges and load transducers. Development of training data for the ML/AI algorithms. Validation of ML/AI algorithms.
6 – Decommissioning				
6.1	<p><u>Deconstruction Sequence Simulation</u></p> <ul style="list-style-type: none"> Similar to Use Case 1.2, enables simulation of the planned deconstruction sequence to identify feasibility and challenges that could surface during execution. Allows simulation of various deconstruction strategies and a more realistic evaluation of alternative strategies. Enables evaluation of impact of various uncertainties that could result in undesirable outcomes, to better optimize the deconstruction plan. 	<ul style="list-style-type: none"> Configuration Management Design Optimization 	<ul style="list-style-type: none"> Improved fidelity of decommissioning cost and schedule estimates. 	<ul style="list-style-type: none"> Development of deconstruction sequence models.
6.2	<p><u>Chain of Custody Management for Irradiated Waste</u></p> <ul style="list-style-type: none"> Digital model for visualizing and tracking handling and movement of irradiated waste at and away from site during decommissioning/deconstruction. Can be used to run simulations to determine high-risk elements of moving irradiated waste and develop mitigation strategies. 	<ul style="list-style-type: none"> Configuration Management Informed Decisions 	<ul style="list-style-type: none"> Identification of high-risk elements of handling and moving irradiated waste to enable early adoption of mitigation strategies. Improves safety. 	<ul style="list-style-type: none"> Identification of critical elements and monitoring parameters important to safety of moving irradiated waste.

B

QUESTIONNAIRE ON USE CASES FOR DTS

Questionnaire on Use Cases for Digital Twin (DT) Applications for Advanced Reactors (ARs)
for the
Advanced Reactors Technical Advisory Group (TAG)

1. Based on the initial screening of the twenty-nine use cases, please pick your top five use cases, and rank them in each category per the table below:

Use Case Number	Rank (1 = Best, 5 = Worst)							Comments
	Technology Readiness / Feasibility	Cost	Utility / Value	Scalability	Regulatory Challenges	AR Applicability	Overall	

2. Which considerations (technology readiness, cost, utility/value, scalability, regulatory challenges, AR applicability) were most important to you when screening the use cases, and why?
3. Please advise on any additional aspects, qualities, or characteristics of use cases that should be considered in prioritizing and down-selecting going forward.
4. Please identify any specific systems or features that are unique to ARs and/or to your particular AR technology (e.g., molten salt pumps, pebble-bed reactor) that could potentially benefit from a DT application but was not mentioned in the use case list.
5. Are there any use cases you envision for your AR technology that we missed and which you would have ranked the same or higher than the above five use cases? If so, please describe.
6. What are the most significant challenges you see to implementing DTs for ARs?



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