Program on Technology Innovation: Using Digital Engineering Tools and Methods for New Nuclear Projects

A Review of the State of the Art

2022 TECHNICAL REPORT

Program on Program on Technology Innovation: Using Digital Engineering Tools and Methods for New Nuclear Projects

A Review of the State of the Art

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ABSTRACT

Digital engineering (DE) is an integrated digital approach that uses system models and data from a single source of truth across multiple platforms and stakeholders using a digital thread to support the entire plant lifecycle. DE is an example of digital transformation applied to the engineering, procurement, construction, commissioning, operations, maintenance, modification, and decommissioning of facilities. Recently, technology developments have been accelerating at unprecedented speeds, which is creating new opportunities to improve the execution of new nuclear projects.

This report defines key use cases that represent the state of the art in DE. The benefits and selection considerations for each use case are summarized. Also, because interoperability of software packages is critical for the success of DE, several methods for providing connectivity have been defined. Lastly, approaches to implementing DE have been provided. This information will be of value to Electric Power Research Institute members looking to select and implement the latest technologies in DE to improve the project management, engineering, procurement, construction, and commissioning of new nuclear projects.

Keywords
Common information model
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Digital thread
Digital transformation
Digital twin
Project life-cycle management

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PRIMARY AUDIENCE: Architect/engineering/construction (AEC) firms and reactor original equipment manufacturers engaged in new nuclear plant projects

SECONDARY AUDIENCE: Owner-operators engaged in new nuclear plant projects

KEY RESEARCH QUESTION

Digital engineering (DE) is an integrated digital approach that uses system models and data from a single source of truth across multiple platforms and stakeholders using a digital thread to support the entire plant lifecycle. DE holds the potential to reduce the cost, schedule, and risk in the design and construction of advanced reactor plants. The key research questions are as follows:

- What is the state of the art of DE in industry?
- How could this be of benefit to the development of new nuclear plant projects?

RESEARCH OVERVIEW

The research consisted of performing a survey of industry tools used for project management, engineering, procurement, construction, and startup. Based on that survey, generic use cases were selected for being new (that is, state of the art). For the purposes of this report, *state of the art* is loosely defined as a capability that has become available and mature in the past five years.

KEY FINDINGS

- There are many use cases of DE that currently have the capability to improve various aspects of new nuclear plant projects, including project management, engineering, procurement, construction, and commissioning.
- The specific end user needs should be carefully considered when selecting a software package to implement a use case defined herein.
- There are several methods of connecting various software platforms to enable integrated DE environments.
- Processes and standards for implementation of DE are new and evolving.

WHY THIS MATTERS

This research provides the end user information regarding the state of the art of DE and information to support implementation, including interoperability considerations. Ultimately, DE has the potential to improve quality and to reduce the schedule and cost of new nuclear projects.

HOW TO APPLY RESULTS

End users can apply the results of this project when setting up a DE infrastructure for a new nuclear plant project.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Related Electric Power Research Institute (EPRI) work includes the following:
  - *Digital Twin Applications for Advanced Reactors* (3002023904, 2022)
  - *Common Information Model Primer: Seventh Edition* (3002021840, 2021)
  - *Application Integration Using Standards-Based Messaging: Implementation of Energy Supply Common Information Model (ES-CIM) Interfaces* (3002020923, 2021)
- Organizations involved in the design and construction of new nuclear power plants
- Please note – if you are interested in the design of digital control and monitoring systems, see the *Digital Engineering Guide* (3002011816, 2021).

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Background

The development and execution of new nuclear projects are often challenged with long schedules and high costs. Digital engineering (DE) is one tool that has the potential to reduce the schedule and costs of these significant capital projects.

DE has been used in many industries in many different forms since computers were first able to perform basic tasks, such as computerized schedule management or computer-aided design (CAD) in the 1960s. Since then, DE has evolved to include tools such as three-dimensional (3-D) models, engineering databases, and computerized work packages.

In recent years, there has been an acceleration of DE technology development related to the engineering and construction of complicated facilities and systems. As a result, there are many options that can be used to help to improve the performance of new nuclear projects. This report highlights the state of the art of DE for use by those involved in new nuclear projects.

Objectives

The objectives of the project that is the subject of this report are as follows:

- Research the state of the art for DE methods.
- Research standards used for DE.
- Identify potential areas of benefit for the new nuclear plant projects.

Approach

This project began with a brief literature review and DE tool market survey to determine state-of-the-art DE practices. This research and use case development considers a wide variety of commercial and heavy industrial industries application of DE technology. For each use case, a brief description is provided, along with an enumeration of the benefits, as well as selections for consideration.

Next, results are presented from a survey that was conducted to develop an aggregated list of integration methods and common standards. Finally, a discussion of the future areas of research and current technological challenges provides context of which standards and guidance should be considered when applying DE methodologies to new reactor projects.

2
STATE OF THE ART OF DIGITAL ENGINEERING

The purpose of this section is to identify and describe the use cases related to DE for new nuclear plant projects. This report is focused only on *state-of-the-art use cases*, defined as having evolved to maturity in the past five years.

The use cases are categorized with respect to one of five project elements that are shown in Figure 2-1. Project management is shown as an overarching element that follows the entire project. The rest of the use cases are categorized within engineering, procurement, construction, and commissioning.

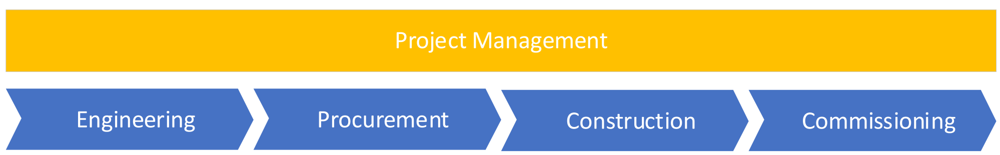

Figure 2-1
Project elements

Project Management

Project management is an overarching element that spans the entire project. The identified use cases in this section focus on the ability to manage cost and schedule. These items are often the most difficult to manage and control during a project's life cycle. Considering the state of the art in project management, most of the technology development has been focused on being able to plan and manage the construction process, including procurement, whereas the design process is not always included in this planning and management. Although legacy scheduling and costing tools are available and flexible to include all stages of a project's life cycle, the management of this information is done in a very manual process.

The following use cases are related to project management.

Automated Schedule Management

Description

Automated schedule management (ASM) is the use of technology to automatically develop and manage critical path scheduling to reduce the schedule and minimize risk. Traditional approaches to determine the schedule and critical path of tasks can be a manual and time-consuming process and prone to errors. By leveraging technology to provide scenario-based options, ASM provides users of the tool a way to explore multiple schedule options and improve the accuracy of the result.

Artificial intelligence- (AI-) based project management applications that used construction methodologies have shown the ability to locate the critical path and interrogate what-if alternatives while visually displaying actuals versus scheduled to confirm schedule and budget adherence. These what-if scenarios can also be applied to the supply chain in the delivery of materials and premanufactured components to the site.

Typical inputs for ASM include a 3-D model, of either the entire facility or a portion of it. Construction methodology instructions are needed to inform the systems how the components of the facility are intended to be installed. These instructions can be referred to as *recipes*. A base schedule is an optional component.

In addition to initial schedule development, a site video capture system can be integrated to automatically update the statuses of the completed segments of construction—meaning that, as the formwork for a concrete wall is erected, the status of that task could automatically be changed from *not started* to *in progress* and finally to *complete* when the pour begins.

Outputs from the analyses involve elements such as Portable Document Format (PDF) reports, 4-D animation videos, or e-mail notifications. E-mail notifications can include dependency changes, weather-related delays, and/or status updates. Certain platforms have indicated that they are working toward the ability to add, update, or delete tasking and issues directly from an e-mail client that would be fed back into the system and recalculated.

Although the primary focus of ASM is the construction process, other portions of the project can use ASM as well. Some tools can also be applied to submit bids in the project acquisition and planning phases. During the bid process, these platforms can be implemented to perform multivariant analyses of the build sequence. Outputs from this type of simulation offer the most cost-effective sequence and the number of crews and additional resources that are necessary to meet stringent milestones. These tools have also begun to expand their functionality to connect to common data environments (CDEs) and general insight into labor and equipment cost utilization.

Benefits

Benefits are as follows:

- By providing the input of construction progress, the schedule can be updated in real time to reflect current construction progress to optimize the path forward.
- Removing the manual component of managing schedules reduces the effort of the construction project managers. This enables them to better focus on the bigger picture.
- By having a better understanding of the critical path, the project cost and schedule can be reduced.
- The scope and planned work sequence can be accurately communicated to stakeholders.
- On-site resource needs for personnel and/or equipment are precise.

Selection Considerations

Selection considerations are as follows:

- Platform interoperability with legacy and future schedule formats
- Simplistic user interface and functionality
- Interoperability with desired interfacing technologies, including the following:
  - 3-D model authoring platforms
  - Site video capture
  - Data repositories
  - E-mail clients
- The ability to select automatic or manual updates of the schedule
- The type of machine learning (ML) and/or AI assist algorithms that are used
- A mobile or web-based application to view the real-time schedule while out of the office

Advanced Estimating and Cost Controls

Description

Advanced estimating and cost controls (AECC). AECC is the process of grouping and categorizing data within 3-D models to develop work packages of systems and assemblies. Based off these assemblies, estimates, costs, and packaging can be tracked on a project. Tracking can start at engineering and flow through procurement and construction. It is optimal when AECC is used early in the design for developing budget programs. During the preconstruction and construction stages, AECC is used to evaluate value engineering scenarios. The approach that AECC uses is known as *bottom-up estimating*, which is considered component-based estimating as opposed to generalized, top-down estimating. Again, AECC uses a cost database and a loaded schedule to develop cost estimates and cost controls.

Benefits

Benefits are as follows:

- Cost estimates can be done early in the design process, driving changes in programming.
- Changes in the models can be updated quickly for real-time cost updates.
- The ability to perform cost analysis and projections is improved.
- The ability to perform bottom-up estimation techniques.

Selection Considerations

Selection considerations are as follows:

- Ability to interface with 2-D and 3-D models for take-offs
- Capability to assess the impacts on a project to include items such as weather, labor and skill set availability, material availability, and economic conditions
- Estimation of items considered temporary—for example, construction trailers, scaffolding, cranes, and fencing

Engineering

Prior to the start of a project, it is critical to select various engineering tools and integrate them to support the desired engineering process and deliverables to be produced to support procurement, construction, and commissioning efficiently and effectively. For example, 3-D modeling provides engineers with the ability to build virtual models of the systems prior to mockup or construction. These models foster the use of advanced simulation techniques. Further acceleration of model creation and standardization has been found by using a kit of parts, otherwise known as *reusable 3-D components*. These libraries can contain generic and vendor-specific equipment. Further advances in DE are beginning to allow the systems engineering models to be integrated with the 3-D models for systems analysis. This integration has been shown to be most beneficial when model-based systems engineering (MBSE) is being implemented by an organization. Additionally, several technologies allow the 3-D model to test-fit options in multiple scenarios using generative design (GD). When the 3-D model has progressed to a point that finer details and layouts are completed, technologies such as virtual reality (VR) can be used to allow stakeholders a real-world glimpse of the finished product. Comments and areas of concern identified from stakeholders during VR reviews can be folded into the final design for construction.

CDE for Document Control

Description

The CDE for document control is a collaboration platform for hosting and sharing documents, models, and data. These data can include 2-D models, 3-D models, drawings, asset information, and schedules. The CDE is a centralized repository for the data storage and project team of collaboration and future project stakeholders. Despite the CDE consisting of many different file types from disparate creators, file storage, viewing, and data dashboards can be developed within the environment.

The purpose of the CDE is to provide the design, construction, regulatory, and operations teams quick access to all facility information. CDEs encompass a graphic user interface that provides users specific facilities data, dashboarding, and communication tools. After documents are available, automated workflows make information available for review, acceptance, and long-term digital storage for future use or processes in the workflow. Future use can include routing to content management or enterprise resource platform (ERP) systems.

Benefits

Benefits are as follows:

- The CDE is unified for the owner; existing and future project stakeholders can contribute data into the CDE. Owners are not left to look for information in multiple locations. These data can be leveraged as well for downstream uses in operations and maintenance.
- From the view of the operating organization, the implementation of a CDE enhances transparency and control functions to reduce costs, increasing quality and moderate time delays. Data are centralized by definition and accessible by multiple stakeholders, each with various project roles, permissions, and responsibilities to the data.
- The CDE is the single source of truth for data.
- The CDE will mature to include not only graphic and geometric information but also information related to technical documents, specifications, and maintenance manuals.
- Data on total cost of ownership, maintenance and repairs, and environmental compliance, as well as installation, warranty, and any other information pertinent to the selection of a product, can be stored on the CDE.
- After documents are loaded on to the CDE, they are available for review, acceptance, and storage or for further processes in the workflow, including routing to content management or ERP systems.
- The CDE eliminates duplication of documents, while tracking revisions.

Selection Considerations

Selection considerations are as follows:

- The CDE should be easy to use and intuitive with minimal training. The user experience is a vital component of the CDE.
- It is recommended to use a cloud-based CDE that is accessible from anywhere, for any stakeholder on the team.
- CDE should be interoperable with other project and operational systems and processes.
- The CDE should allow for standardization regarding document naming, workflows, and data collection.
- To maintain data integrity, the CDE should be secured with user access control. Often, CDE systems are connected to a company's active directory to prove ownership of the account.

Virtual Reality for Collaboration

Description

Virtual reality for collaboration (VRFC) is the use of a computer headset and 3-D building models to create an immersive environment, a virtual experience within a 3-D model. VRFC provides one-to-one visualization of the 3-D model to convey the proposed design by the AEC team. VRFC is not for developing the 3-D model; rather, it is used to visualize the 3-D model. VRFC allows the user to provide feedback into the model for the design team to refine the design using other software.

Recent progress in the development of VRFC has displayed the ability to integrate not only the native authored 3-D models but also to perform physics and other simulations. VRFC meeting-based applications are available to provide a virtual multiscreen presentation environment. These programs do not require navigating through a representative model but inspect images of a model, white-boarding features, and other virtual communications options.

Although VRFC technology has been around since the early 1990s, it was expensive, tethered to a computer, and limited by file sizes—all making it difficult to implement at scale. Today, the cost of entry has dropped significantly. Most of the hardware today is largely untethered (wireless).

Benefits

Benefits are as follows:

- Can reveal constructability, operability, or maintainability issues early in the design, eliminating or mitigating rework and change orders.
- This gives users an ability to explore multiple variations of a layout, to review materials, and to test-fit components and find issues early.
- Users can collectively explore, make comments, and initiate changes to improve the final design and verify layout of key reactor components, control rooms, and pipe routing.
- Issues regarding the maintenance of equipment.
- Ability to review detailed control room layout and control placement, and ergonomics.
- Environmental and safety checks for compliance to standards and regulations. Ongoing safety and security training.
- New employee orientation and personnel in operations and maintenance roles can simulate work on the equipment.

Selection Considerations

Selection considerations are as follows:

- User interface and access to current model data (ease of use).
- Markup and interaction features for developing and tracking issues through the CDE and back to stakeholders.

- The ease to which the headset fits and is comfortable; the layout of controls buttons.
- Software and 3-D model compatibility with models, and CDE.

Project Centric Data Management

Description

The project centric data management (PCDM) approach is based on the organization and classification of project data around the project. Project data are organized, tagged, and cataloged within the project's CDE. However, these data can be extended across design and construction and into operations. Because of the wide domain of data collected and presented in the PCDM, the system requires data that are standardized and categorized for efficient search and dashboarding into the relevant project. An example of this can be collecting data for an upcoming project to replace pumps. Questions the field personnel could ask include: *When was the pump installed, who was the manufacturer, what associated power systems will need to be de-energized*?

Benefits

Benefits are as follows:

- A process using an organized management system will efficiently aid in the maintenance and operation of a facility and its assets.
- The assets can include 3-D model(s) and consist of physical buildings, systems, the adjoining environment, and equipment. These elements must be maintained, upgraded, and operated at an efficiency that will satisfy the operating and governing bodies at a minimal cost.
- It assists in financial decision making, as well as short-term and long-term planning.
- Simulate impact scenarios using models and real-world system datasets.

Selection Considerations

Selection considerations are as follows:

- A PCDM must work with current systems and processes. The goal is to break down silos and increase collaboration overall.
- A PCDM should allow one to standardize workflows and processes across projects.
- The PCDM platform must be secure, to ensure data integrity and provide controlled access.
- A cloud-based PCDM is accessible from anywhere, for anyone on the team who needs access to the information.
- The user experience is an essential component of the CDE. To be most effective, the PCDM needs to be easy to use and intuitive with minimal training to get teams working.

Generative Design

Description

GD is a process by which computers calculate all of the unique design scenarios that are possible based on user criteria. These criteria can consist of physical constraints such as fittings, critical components, specific manufacturing processes, material requirements, loads, and other spatial limitations. This process then creates multiple 3-D models by leveraging ML algorithms and the user's inputs in the form of constraints. The computer then generates 3-D models and other information, such as 2-D drawings and parts lists that are needed for manufacturing, and visually displays the multitude of results into multiple options for the users to explore and to make additional refinements while discarding others. GD provides the means to quickly develop a design and explore multiple variations of a building, system, or layout prior to final design [1].

Benefits

Benefits are as follows:

- Multiple design ideas are generated. The time to develop a design decreases.
- Ensures that all design parameters and constraints are considered.
- GD integration into existing workflows during the preliminary stages of design development.
- Offers multiple choices for design development. Design options allow the user to then explore all options and discard others while continuing to refine the design.

Selection Considerations

Selections are as follows:

- Multiple design outputs are dependent on user constraint inputs, as well as the applications' capabilities in terms of evaluating material and production methods.
- The variety and complexity of software including the user interface differs from platform to platform. The ability to quickly learn a software, as well as effort to train the users on the software, should be a consideration when selecting a solution.
- Manufacturing methods, such as additive, subtractive, and casting, require different equipment to manufacture. Consideration for final manufacture should be considered.
- User interfaces vary in the way they visualize complex shapes or are dependent on other applications to work.

Automated Site Layout

Description

Automated site layout (ASL) is a process in which a computer automatically develops a site plan. The ASL enables the use of a standard design, which, in turn, can also be used for factoring regulatory guidelines. This approach leverages program goals, local building codes, and site constraints to present multiple options for building layout. ASL allows users to model, analyze, and visualize design concepts within a real-world context of the built and natural environment, improving decision making and project outcomes. The user can refine plans based on selecting different options and feedback to the system. ASL enables multiple sites to be considered.

Benefits

Benefits are as follows:

- Multiple building and positions scenarios can be developed and optimized to the site.
- Building setbacks, entitlements, local and regional land use codes, and height considerations (for example, environmental impact studies).
- Proximity to utility locations and proximity to power, water, and telecommunications are analyzed.
- For a prototypical design, which, in turn can also be used to automate required regulatory documentation.
- Grading restrictions to minimize cut and fill of soils and shoring.

Selection Considerations

Selection considerations are as follows:

- Applications vary in sophistication, automation, and user interface. Consider platforms that align to user capabilities.
- ASL applications include varying feature sets. These features depend on goals and objectives. For instance, ASL for parking lot layout could focus on parking space layout to building and utility layout, which could focus on building space and density layout. Applications can include features such as connectivity to satellite imagery and geographic information system (GIS) integrations for geospatial layout.
- Outputs to move data from one workflow to another (for example, conceptual to site development). The ability to import civil models, drone data, and survey data.

Procurement

Procurement is the identification and acquisition of the equipment, materials, and labor necessary to construct a facility. During this stage the AEC will perform various analyses from the traditionally 2-D documentation, systems diagrams, and other supporting documentation to obtain an accurate count of equipment and understanding of systems. With this comprehension of the design, the AEC will then solicit costs from various equipment manufacturers and specialty trade contractors. Sophisticated AECs will provide a valid cost database of equipment and labor rates to the engineering teams to be integrated as early into the project as possible for the use in project controls processes. The wide adoption of ML to procurement technologies has displayed increased efficiencies not seen since migrating from a paper-based system to a spreadsheet-based system.

Vendor Document Review and Archival with Natural Language Processing

Description

Large datasets containing vendor document review data can be difficult to sort and analyze. Natural language processing (NLP) uses ML to scan, analyze, sort through exceptionally large datasets. The output is verbalized in speech or visualized through a dashboard. As stated in *Encyclopedia of Library and Information Science*:

> NLP notes the contents of the documents that are being searched will be represented at all their levels of meaning so that a true match between need and response can be found, no matter how either are expressed in their surface form [2].

NLP allows one to find answers to critical questions quickly and eliminates the need to sift through millions of documents. Moreover, all documents can be located so that an audit trail of documents can be established and analyzed.

Organizations collect massive amounts of data that outstrip a person's ability to locate, analyze, and share data. As a result, key documents are missed or left unfound. A key benefit of NLP is to reduce the effort to locate and find relevant information contained within a document.

Benefits

Benefits are as follows:

- Ability to locate multiple documents with document index review controls and routing steps
- Ability to locate proper documentation of required design
- Assurance of being able to locate critical safety documents
- Fast access to critical operating documents, requirements, and specifications
- A scalable knowledge base that can sift through millions of documents in seconds
- Ability to find answers to critical questions quickly, monitor updates in real time, and automatically generate easy-to-read reports.

Selection Considerations

Selection considerations are as follows:

- The use of NLP is dependent on training the application to optimize searches specific to the nuclear industry, to improve the results of relevant information in documents that are being found.
- NLP, AI, and ML technologies vary in capabilities and optimization in learning and in their search functions. The use of universal models can aid in improving results.

- The size of dataset that is required to be processed should be considered during selection.

Automated Quantity Take-Off

Description

Automated quantity take-off (AQTO) is a process that uses a 3-D model at various stages of development to produce accurate quantity and material take-offs. First, 3-D model data must be properly formatted for use as input to AQTO. AQTOs query the 3-D model(s) data to determine project costs. AQTOs contain detailed measurement of components, materials, and labor required to complete a construction project. AQTO is typically timed to be generated at regular intervals and major milestones by the AEC teams; this can extend to include subcontractors and import external data of nonmodeled items during the construction phase of the project.

Benefits are as follows:

- There is consistency in counting of items and material areas.
- 3-D model updates and changes are automatic with AQTO.
- Rapidly try different scenarios and layouts, and calculate costs.

Selection Considerations

Selection considerations are as follows:

- AQTO requires normalized data. Alignment and format of data early in the project is key. Some features can help to automate that process.
- Ability to use specific industry classification of systems such as UniFormat[1] or Master Specification should be determined before selection of an application.
- Ability to integrate nonmodeled activities and resources. Resources such as temporary work, formwork, trenching, fencing, and cranes have costs during construction.
- Quality assurance/quality control process should eliminate duplicate elements that are commonly found in shared models—that is, plumbing fixtures modeled in the architectural and plumbing models.
- Categorization and grouping of data elements vary from AEC to AEC and from trade to trade; the tool should align these variations.

[1] *UniFormat* is a registered trademark of the Construction Specifications Institute, Inc.

Construction

Once the design is sufficiently complete, the project moves into the construction phase. It is at this point when 3-D models delivered by the engineering teams are used to develop construction plans, with work delineated between on-site and off-site fabrication. Construction sequence simulation (CSS or 4-D simulation) will be used to illustrate the system construction and resource logistics sequencing using a 3-D model that is integrated to one or more schedules. As the project begins, construction data from site cameras can be used to monitor changes and ML employed for conformance to safety plans. Laser scanning affords opportunities for validating installed components and intermediate progress validation for use later in operations and maintenance.

Construction Sequence Simulation (4-D)

Description

CSS, also known as *4-D*, is the process in which 3-D model elements are connected to a schedule. The schedule data in the form of task ID, task name, dates, effort, and other resources found in scheduling software are imported into the 4-D application and then linked to corresponding model elements. The 4-D software develops an animation to depict the sequencing construction activities. The 4-D animation typically displays a timeline of the schedule as the building elements appear on the screen. Elements can also have color coding to indicate demolition, installation, and completion. More sophisticated 4-D simulations will include labor tracking and associated costs. The CSS will be used to inform users and illustrate building erection and crane sequencing and to demonstrate safety zones, muster points, and site/facility orientation of new workers.

Benefits

Benefits are as follows:

- The CSS process is a powerful way for analyzing the proposed building sequencing and installation. CSS surfaces issues in the construction sequence clearly—for example, installation of equipment before the concrete pad is poured.
- CSS can serve to inform new workers how the building will be constructed, illustrating crane picks, ingress and egress, laydown, and delivery areas.
- For all site workers to understand where fall hazards, pedestrian paths, restricted areas, muster points, and first aid stations exist on site.
- CSS can serve to inform the sequencing of building construction, site access points, and closures of roads and utilities at specific times so that coordination with state and local officials can occur.
- CSS serves to visualize crane locations, trailer locations, laydown areas for trades, site access, and movement of materials.

Selection Considerations

Selection considerations are as follows:

- Software should be compatible with popular scheduling software and 3-D models software. The ability to update (re-import) native data to CSS software should be considered.
- In addition to the 3-D model, there are temporary 3-D model components (construction equipment such as trailers, cranes, and fencing). These components are necessary to properly illustrate construction activities. Efforts to develop these libraries can be significant if they are not part of the software package.
- Less sophisticated schedules typically do not have resource loading data. Special consideration of the features and subsequent training is required.
- CSS model quality and model rendering vary from game-like interfaces to rudimentary; however, the final output of CSS is a computer amination file. There is additional post-processing of the animation for final output. The post-processing includes images, labeling of activities, audio, and transitions. This post-processing software is a separate software package.

Artificial Intelligence-Enhanced Site Safety

Description

Enhanced site safety through AI makes the jobsite safer and reduces hazards, injuries, and insurance costs. Artificial intelligence-enhanced site safety (AIESS) uses video and photo images to analyze computer images to identify and flag unsafe practices and conditions. Using image recognition and classification, algorithms mine image data collected from construction cameras, drones, and jobsite photos to identify potentially unsafe worker practices. These unsafe practices range from not wearing personal protection equipment (PPE), such as hard hats, gloves, and safety vests, to larger issues, such as improperly stored materials. Flagged items can then be mitigated in the field through training or requests for change.

AIESS can also encompass smart wearables. Wearables are represented in the form of a smart badge or device attached to a hard hat. Sensors detect when a worker passes by a device reader or triggers an internal sensor (such as a fall).

AIESS helps to adhere to Occupational Safety and Health Administration (OSHA) requirements for worker health and safety.

Benefits

Benefits are as follows:

- Automatic and push-button emergency alerts for accidents (slips and falls); biometric sensors to detect dangerous conditions and a worker traveling into restricted areas.
- Automated daily logs, timekeeping verification, evacuation verification, authorization tracking.
- Enhanced compliance to applicable site and federal training (OSHA).
- Restricted access alerts or areas for qualified workers.
- Social distancing compliance, confined spaces.

Selection Considerations

Selection considerations are as follows:

- AIESS platform features to consider include capabilities to leverage camera data real time, AI, and ML to automatically identify hazards. Reporting and communication of potential hazards to team.
- Data integration into a CDE platform to automate daily logs into the CDE.
- Camera resolution and AI enabled for object and thermal recognition.
- Methods of interconnect system components.
- Goals for monitoring unauthorized personnel, unsafe practices, improper equipment, and materials.

Augmented Reality for Infrastructure Enablement

Description

Augmented reality for infrastructure enablement (ARIE) is an exciting and rapidly evolving technology tool for construction and operations. ARIE uses devices such as tablets or headsets to superimpose 3-D models onto the environment. Using sensors and spatial anchors, the device displays the 3-D model locked into the environment, and, as the user moves through the space, the 3-D model remains placed. The user sees the 3-D model full scale and as if it were real and in context of the surroundings. The users can interrogate the model for information and create field notes for additional uses in the workflow.

Benefits

Benefits are as follows:

- Site utilities underground, built, and unbuilt, in context of the site surroundings.
- Users can quickly find, confirm, and determine whether there is a difference between the existing conditions and the 3-D model(s).
- Reduce time for workers to familiarize to the project. Quickly visualize complex pipe routing, ceilings, and foundation details on the headset rather than interpreting 2-D drawings.

Selection Considerations:

Selection considerations are as follows:

- Platforms vary in their ability to display large file sets. Users must have a sufficient level of development in the model to make informed decisions. Careful consideration of hardware (memory and refresh rates) must be considered.
- Global positioning system integration with hard hats to allow for rapid determination of site personnel location during emergency situations. The solution must conform to meet applicable PPE requirements; often, special hard hats or clips are required to be compliant.

- Drift is the viewed difference between the physical plant and the overlayed VR. Consider spatial anchoring to help to mitigate drift by re-anchoring models' common digital and physical locations.
- In bright outdoor conditions, 3-D models tend to dim on the headset; consider headsets that mitigate dimming.
- Access to the internet in the field can be a challenge, making it difficult to load 3-D models, initiate headset commands/features, or log issues back to the cloud. Consideration for dedicated hotspot connection to enable connectivity might be necessary.
- Hardware and software costs prohibit mass adoption; consider device sharing and cleaning protocols for units between users.

Construction Verification with Laser Scanning Comparisons

Description

Construction verification with laser scanning comparison (CVLSC) is the process of using laser scanners to create electronic 3-D point cloud files. The 3-D point cloud consists of multiple individual laser scan files that are then merged into one point cloud file. CVLSC is based on using the point cloud file to compare against other point cloud files captured. Both are of the same location but captured at different times. The point clouds can also be compared to the 3-D model(s) of the same area. The CVLSC uses software to compare the point clouds and 3-D model(s) to develop a report that indicates deviations between the files. CVLSC is applicable in construction to detect deviations from project progress base-lined 3-D models or adherence of the installed systems. CVLSC can be used for progress tracking. CVLSC can inform teams of changes in design and changing conditions through updated point cloud files. The output highlights deviations to tell the user if significant issues are occurring.

Benefits

Benefits are as follows:

- CVLSC provides validation of equipment and systems that are installed according to design and validated to coordinated locations.
- Enables software to perform comparisons and identify gaps between the 3-D model and existing conditions.
- The software also can create sharable 3-D views for distribution amongst stakeholders that visually communicate an issue or discrepancy.
- Mitigate costly rework and additional time on the schedule by catching issues early.
- Captures and validates all elements on-site once and serves as the basis of existing conditions for future designs and modifications.
- Bridges gaps missing in the final record 3-D model that typically are not required to be in the model.

Selection Considerations

Selection considerations are as follows:

- The technology around CVLSC is evolving rapidly. Hardware and software that are adaptable to different delivery methods (robots, drones, and wearables) can further reduce time or automate the capture process.
- The most sophisticated CVLSC applications are cloud-based. More traditional solutions are add-ons to popular clash detection software. Careful planning and alignment of objectives is necessary.
- Reality capture specialists require extensive hands-on training and have specific working knowledge of hardware and software. Time and effort for training personnel should be considered in selection.

Commissioning

Commissioning consists of starting up the various systems in the plant and validation of their performance to the design. By using the DE methodology, commissioning can be brought into the fold of using the authoritative source of truth. DE technology can deliver the value to aid the need to have distinct key stakeholders interact with the processes, procedures, and generating documentation all in a collaborative way. These advantages can be realized with the use of mobile, virtual, and real-time collaborative tools.

Mobile Connected Commissioning

Description

Web-based enterprise commissioning management systems are not a novel concept; however, technology platforms have been able to develop their commissioning features in a nimbler way. This agile development has enabled delivering purpose-built commissioning solutions that are designed from the ground up. *Mobile-connected commissioning* (MCC) is the implementation and management of the pre-commissioning, commissioning, fuel loading, and startup with a mobile platform. These MCC platforms are agile in the sense that they are modular and can be configured in ad hoc ways. Additionally, MCC has been shown to limit the amount of paper waste generated through the course of commissioning. This assists the commissioning and operating organizations to commission a new plant cooperatively, responsibly, sustainably, and safely.

To begin using MCC systems, it is necessary, as in all projects, to develop the key requirements and criteria. MCCs offer form-driven tools to aggregate the requirements; these requirements are then used to automatically generate the testing, evaluation, and validation checklists and surveys. Moreover, these interactive documents can be created manually or uploaded to the system. The technical requirements can be connected to systems engineering requirements and other procedures as they are defined. It should be noted that there is considerable upfront work necessary for technology-based commissioning. Commissioning in general should not be an afterthought of the team.

During the construction or installation of components, MCC systems that are connected to a live scheduling and progress tracking tool present the commissioning agent a view into the handover on a subsystem and potentially component level. To further assist the commissioning agents' organization, MCC use state-of-the-art technology to identify elements on the component level. ML object recognition and computer vision are used on photos taken with the system to extract name plate data, which are then used to populate reports and create connections to the designed asset.

Benefits

Benefits are as follows:

- MCCs allow the creation and collection of digital reports and documents that integrate equipment, systems, and subsystems into the commissioning progression.
- MCC increases communication and effortlessly share information with the necessary team members.
- MCC allocates online and/or offline testing and operating procedures, inspection results, and quality assurance of manufacturer or installation to key stakeholders through user access control.
- MCC delivers a lone source full life-cycle solution that takes the project from design through plant handover with embedded operations readiness and safety.
- MCC initiates automated packing of commissioning phases and systems by leveraging pre-defined business prerequisites.
- Automatic formation of close-out and delivery packages. Rather than delivering reems of paper and binders full of process documentation, MCC can supply fully electronic packages. Because of the interoperable nature of MCC connectivity to the operating organization's electronic document, licensing, and operations management systems can be established.

Selection Considerations

Selection considerations are as follows:

- The availability of the technology on all major mobile operating systems
- The interoperability and/or integration with design, construction, and document management systems for the linkage to documentation created by other team members
- The capacity to curate custom workflows and stage-gate or phased checklists, surveys, and tasks
- The ability to automatically develop, sign, and share reports in real time or at scheduled intervals to provide project summaries
- Security of the platform with respect to where the data are hosted, how they are accessed, how to control access, and other mobile technology security risks
- Activity and insight dashboards to provide a project activity news feed and track the performance of the project

Virtual Commissioning

Description

A virtual plant simulating physical sensors, actuators, and plant physics/behavior that is integrated with either physical or virtual control system to troubleshoot, test, and optimize a plants systems and controls is known as *virtual commissioning* (VC). VC is also known as *remote commissioning*. VC evaluates physical performance, configuration options, and human operator interactions prior to construction of the systems to conduct the commissioning reviews.

VC of a system and procedure dynamics consists of three pieces, a controller that governs the motion and responds to sensor responses, an accurate 2- or 3-D digital model, and an environment that connects and simulates both. These systems initiate with the digital model connection to a process logic controller (PLC), human-machine interface (HMI), and/or supervisory control and data acquisition (SCADA) streams. For instance, when the pressure of a pipe exceeds a certain pressure, a set of valves must open to bleed this excess pressure away from the main line. In VC, this can be simulated to identify potential upstream root causes and how the system must perform to efficiently reduce the pressure after a sensor is triggered. Consequently, this simulation can be used to develop standard operating procedures for all levels of critical scenarios.

The use of VR can be integrated with VC. VR can connect remote participants in a shared virtual environment to experience the machine commissioning process and systematically evaluate each system control component virtually. Observations from the virtual environment can summarize system behaviors, and effects are recorded in the session. After they are recorded, the results are available for export. These exports are used to perform pre-job briefs and even rehearse outage activities on a virtual plant before the actual outage to help coordinate, plan, and optimize activities. Digitizing workforces affords field personnel the ability to efficiently validate engineering information while inspecting, testing, and repairing equipment.

Benefits

Benefits are as follows:

- Ability to validate commissioning procedures before going to the field.
- Virtual prototypes execute the verification and validation to produce higher quality environments.
- There is reduction of safety and risk related to errors that are often found later during the commissioning process.
- Provides the potential to reduce the time needed for pre-commissioning, commissioning, fuel loading, and startup.
- Operations training and orientation is early and sufficient.

Selection Considerations

Selection considerations are as follows:

- Bidirectional interoperability with native application authoring platforms (that is, CAD/building information modeling [BIM] platforms), as well as PLC, HMI, and SCADA technologies
- Strong discrete event simulation capabilities
- Digital twin visualization requirements
- Real-life signal-based simulation

3
DIGITAL ENGINEERING INTEROPERABILTY METHODS

Interoperability allows the connection and transfer of data to support the various project life-cycle elements. Interoperability, according to Shepard and Scherb, is "a common practice in private industry that involves the creation and storage of a system's lifecycle artifacts, in digital form, and which can be modified as a system evolves throughout its lifecycle" [3]. For interoperability to be as congruous as possible, common vocabulary and ontologies should be used. Additionally, the DE life cycle encompasses different domain expertise and audiences. As such, interoperability is a key enabler of the use cases defined previously.

Many technology vendors claim to be interoperable with other processes and technologies; however, it is crucial to comprehend that there are distinct types and levels of integration. A significant point of clarification when speaking with a technology vendor is to recognize the difference between configuration and customization. In short, *configuration* refers to changing or defining settings within the core platform or module. *Customization* is the additional development of the core platform or module(s) to achieve a business goal. This leads to the differences between integration and interoperability.

The intention of interoperability is to not develop a monolithic technology, nor is the intention to develop a monolithic microservice technology stack. Standards set out by standards development organizations will aim to limit the siloed data by defining recommended functional and/or nonfunctional requirements. Regardless of the outcomes, a common vision, agreements, and general process concepts should be implemented within the digital thread.

The following are various approaches used to provide for interoperability.

Interoperability Framework

In a white paper released by the Digital Twin Consortium titled "Digital Twin System Interoperability Framework" [4], the authors provide seven key concepts for interoperability of digital twins. The paper goes on to note that the aggregation of the concepts brings together the digital thread, or as noted in the Background section of this report, DE. These seven concepts are noted in Table 3-1.

Table 3-1
Seven interoperable concepts [4]

Term	Definition
System-centric design	Enables collaboration across and within disciplines—mechanical, electronic, and software—creating systems of systems within a domain and across multiple domains.
Model-based approach	With millions and billions of interconnections implemented daily, designers can codify, standardize, identify, and reuse models in various use cases in the field.
Holistic information flow	Facilitates an understanding of the real world for optimal decision-making, where the world can be a building, utility, city, country, or other dynamic environment.
State-based interactions	The state of an entity (system) encompasses all of the entity's static and dynamic attribute values at a point in time.
Federated repositories	Optimal decision-making requires accessing and correlating distributed, heterogeneous information across multiple dimensions of a digital twin, spanning time and life cycle.
Actionable information	Ensures that information exchanged between constituent systems enables effective action.
Scalable mechanisms	Ensures that interoperability mechanism(s) are inherently scalable from the simplest interoperation of two systems to the interoperability of a dynamic coalition of distributed, autonomous, and heterogeneous systems within a complex and global ecosystem.

The interoperability framework considers these concepts disparate but associated. These concepts can be used as a core framework for various web applications. Quintessentially, a takeaway from the paper is that, to scale systems, simplicity will be an important success criterion.

The seven concepts in Table 3-1 and the work of the interoperability paper are invariably linked to the work that has been delivered from the International Organization for Standardization Technical Committee (ISO/TC) 184 Ad Hoc Group on Digital Twins [5]. This group has been formed to validate what a digital twin is, evaluate the current applicable standards within ISO, and propose the subsequent data architecture. The group notes that it is premature to assign a specific framework across all types of digital twins; however, the group has provided insight into their directionality by describing a landscape framework. This landscape framework provides a higher-level perspective of the data structure and flows.

The interoperability framework points out that there are two main types of connection. As visualized in Figure 3-1, a grid structure is one where there is not a centralized point of connection; conversely, a hub and spoke model provides a single authoritative source of connection. It is widely regarded to leverage the hub and spoke model to minimize the number of managed connections between edge nodes. However, a hub and spoke model requires a common data model and standards to be used between the nodes. This could be accomplished by using an adapter between the data link and the subsequent data node.

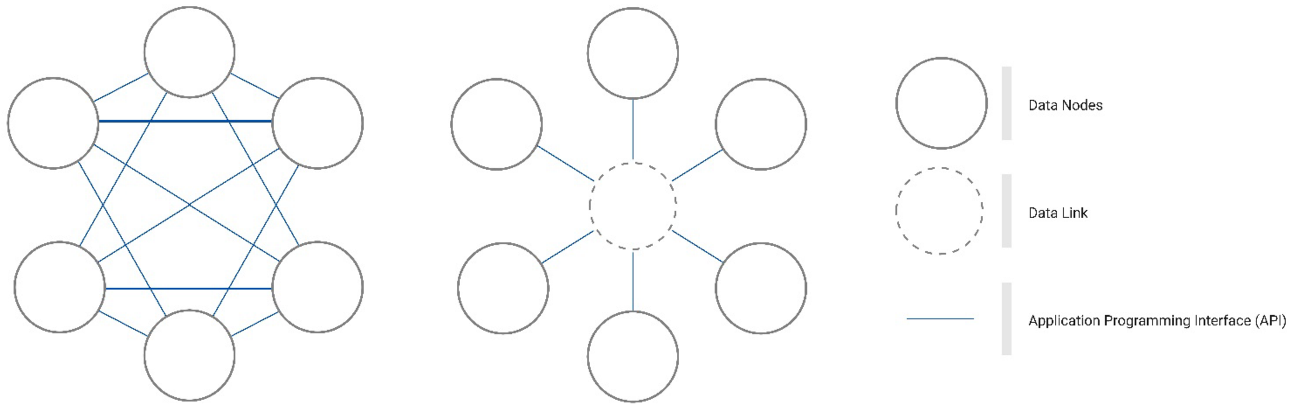

Figure 3-1
Comparison of grid structure and hub and spoke data integration methods

The authors of the paper, in fact, identify the possibility of using the grid model as a more efficient method of managing data. The grid model can be sectioned off to represent different models, as illustrated in Figure 3-2. This infers that each of the models could contain its own data model and the only time that standards would be required is at the point of data exchange. There is the possibility of generating a hybrid data structure of the grid and hub and spoke; this would provide a centralized data structure standard but afford flexibility within the outer nodes, as noted in Figure 3-2.

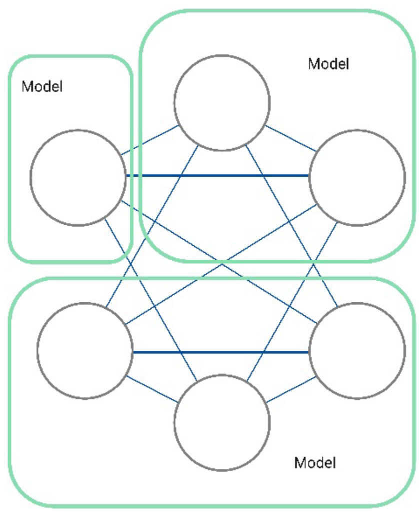

Figure 3-2
Grid data structure divided into models

Common Information Model

For a novel perspective of interoperability, the Electric Power Research Institute (EPRI) has taken the common information model (CIM) [6] and developed an Energy Supply Common Information Model (ES-CIM).

In a recent paper, titled "Application Integration Using Standards-Based Messaging: Implementation of Energy Supply Common Information Model Interfaces," [7] the authors expound on the use of the EPRI CIM framework to provide a more specific model for electrical supply assets. Strategies identified to provide interoperability include vendor consolidation, messaging solutions between technology platforms, and data layer connection by means of common database connections. To accomplish interoperability of any system, there are characteristically various methods that are used. Interoperability methods are classified as direct, indirect, or hybrid. Direct methods include web services or database connections. Indirect methods include file exchanges with static data. Finally, hybrid methods are a compilation of direct and indirect methods.

The authors of ES-CIM have also taken steps to extend the CIM framework to use more nimble messaging protocols. Specifically, the CIM was historically built upon Simple Object Access Protocol (SOAP), which typically has large payloads for both the request and response. By extending the CIM with the use of Representational State Transfer (REST) and JavaScript Object Notation (JSON), the request can be sent in the header and the response is provided in a semi-human readable format. Cloud technologies that employ REST protocols, hosted externally or on-premises, are developed in a microservice architecture for flexibility during development and future system support.

DeepLynx

DeepLynx is a tool that has been developed by the Idaho National Laboratory to aid in the interoperability of enterprise platforms. According to the tool's documentation:

> DeepLynx is an open-source data warehouse focused on enabling complex projects to embrace DE. It accomplishes bringing the digital thread and digital twins to these projects with integrations to a diverse collection of software systems across a projects lifecycle [8].

As has been noted in both the ISO paper and the ES-CIM paper, there is a need for extract-transform-load processes and adapters to normalize the information flow prior to it bi-directionally moving between systems and/or storage.

DeepLynx provides adapters to many common engineering tools, including building information management, requirements management, and MBSE, in addition to multiphysics and facility data acquisition software. This tool is in use in many nuclear projects today at Idaho National Laboratory.

4

DIGITAL ENGINEERING IMPLEMENTATION CONSIDERATIONS

Governing Standards

The implementation of DE should be performed in accordance with standards; unfortunately, standards of practice specifically geared toward DE have been slow to be developed. The general subset of considerations can be divided into requirements management, process management, data management, geometric (model) interoperability, and/or deliverable standardization. Usual challenges relating to the implementation of standards stem from organizational culture, performance, domain specificity, as well as competition from the various standards development organizations.

Several governing bodies have undertaken the definition and application of the complete DE framework. For example, the transportation division of the New South Wales government has defined its DE framework up to the operational stage. These standards look to be inclusive to ensure compatibility, safety, interoperability, and cyber security.

Standards organizations such as ISO, International Council on Systems Engineering, buildingSMART[2] International, American Society of Mechanical Engineers (ASME), and Institute of Electrical and Electronics Engineers have all defined DE practices, drawing standardization, and information management definitions. Currently, many of the previously mentioned organizations are collaborating to provide the engineering markets an aligned set of DE life-cycle standards.

Requirements and Process Standardization

To begin the development of complex systems, the scope, requirements, and end states must be comprehended and documented. These requirements must be developed in such a way that they are stringent but flexible enough to capture future evolutions of technology and process developments. Of course, these requirements must be developed in conjunction with the licensing, testing, and operational requirements set forth by the regulating bodies. There have been several different standards and frameworks established and implemented for requirement and process management. These include the following:

- American National Standards Institute/Electronic Industries Association Standard 632-2003 [9] Processes for Engineering a System, defines the fundamental processes for executing a system engineering program.

[2] *buildingSMART* is a registered brand of buildingSMART International.

- ISO Standards 29148 [10] and 15288 [11] provide system engineering requirement definition and system life-cycle processes, respectively. Though these previously established guidelines are specific to areas of expertise such as systems engineering, they can be applied to a DE life-cycle process although they might be limiting in their overall applicability for new nuclear plant projects.
- Although not a standard, the Department of Defense has issued the Digital Engineering Strategy [12]. This strategy discusses approaches to developing and using models across the enterprise, providing a single source of truth, incorporating technological innovation, establishing infrastructure and environments, and workforce transformation.

Requirements for a DE process include the following:

- **Structure**. What is the general operating structure to achieve organizational, regulatory, asset management, simulation, safety, and testing activities?
- **Collaboration**. What principles and activities must be adhered to during the DE life cycle to advance communications and processes for removing animosity or conflicts?
- **Data**. Which data schemas and ontologies of data and information are to be implemented and exchanged? This is to include structured, unstructured, and documentation.
- **Modeling**. How will various models (2-D, 3-D, process, and so forth) be executed, linked, and published throughout the DE life cycle?
- **Security**. What measures must be taken to maintain transparency but restrict unfettered access to sensitive information?
- **Culture**. What are the organization's norms and behaviors that will allow for the adoption of DE?

For DE to work effectively, there must be an integrated, collaborative approach across all stakeholders on the project. Shared values of the teams are to be guided by an overall vision and goal or goals set by the owner-operator.

Data and Information Management

Data consist of raw facts, whereas information is data within a specified context providing a meaning. Uniqueness can be likened to data being equivalent to unstructured or unorganized, whereas information is structured or organized. It is imperative that data and information are managed during the DE life-cycle process. Assembling data and information in an intelligent way leads to greater knowledge or cognition and familiarity with the facility. The nuclear industry is one that is based upon dependable, quality, and accurate information. Data and information management (DIM) is an approach to improve predictability around simulation and risk mitigation, support strategic decision making, and enrich operational conclusions.

Reducing the silos in the design, procurement, and construction segments of the life cycle alone produces a historic record of decisions. Additionally, it provides a significant reduction in project rework, locating required documentation, and the synchronization of analysis completed by multiple subject matter experts. Further, the connection and/or exchange of DIM to the operations and eventually decommissioning phases should be overseen with strategic care. Many projects can consolidate and collaborate on a sole source of truth through the various project stages; however, the information then is delivered in a disjoined way to the operator.

ISO has developed a set of standards to negate this breakdown of data and information. The ISO 19650 [13] set of standards is an evolution from British Standards and Publicly Available Specifications standards to delineate data management standards through the entire life cycle of a facility. This standard is specific to the utilization of BIM; nevertheless, the concepts can be applied to all data-driven applications.

ISO 19650 has been separated into five parts to delimit core concepts, the delivery of assets, operation of assets, and information exchanges, as well as security considerations. At the time of this report, versions of all of the standard sections have been published apart from the information exchanges. The core standard specifies several different document types to manage information throughout a life cycle. The leading document that controls all others is titled the Organizational Information Requirements (OIR). This document provides the interested parties a high-level scope of how the contracts should be structured and the organizational business model. The OIR is intended to be a prominent level and not specific to any given project. The OIR subsequently influences the Asset Information Requirements (AIR) and the Exchange Information Requirements (EIR). Both documents are considered to contain detailed information, where the AIR is not project-specific; however, the EIR is project specific. The AIR provides the necessary requirements for data to be tracked and managed according to each of the identified assets and systems. Additionally, the EIR specifically notes how the employer would like the asset information and other documentation to be created and managed during a project life cycle. ISO 19650 also defines a CDE and how it should be used in conjunction with the information requirements that have been noted previously. The standard notes four structured sections of information: work in progress, shared, published, and archived. It is recommended that all required documents generated in a project move through these four sections.

The Department of Defense Architecture Framework (DoDAF) is an additional architectural framework that can be considered when implementing and using DE. The DoDAF provides the ability to define, monitor, and control complex information systems that require multifaceted integrations through numerous viewpoints or groupings of activities. Specifically, DoDAF 2.0 and onward include a project viewpoint that communicates the correlations between operational and capability requirements of a project.

Documentation Standardization

Standards are a means by which to provide a framework to implement project solutions. As most deliverables are still plotted out, a commonality of symbology, line styles, typography, and unit tolerance must be maintained to display design and/or manufacturer intent. These commonalities should bridge the 3-D isometric layouts, 2-D floor plan layouts, and the piping and instrumentation drawings, and they should be generated directly from optimized CAD models to provide a direct correlation of graphic information. Maintaining these links and using standards, the documentation will be universally interpreted based upon the specific industry requirements.

As noted in the section introduction, several of the standards-defining organizations have curated their industry and/or applicable vision of what documentation should look like and how it should perform. Some standards have gone as far as to note how documentation should be created. In the case where the *how* is defined, this will typically be linked to a set of requirements according to the authority having jurisdiction.

A common standard that is used by the U.S. Department of Defense is the ASME Y14 [14] standards. The ASME Y14 standards provide a set of geometric dimensioning, tolerances, and symbols within the 17 standards. These standards cover documentation from drawing sheet conventions to drawing practices and through symbols and abbreviations. The Y14 standards are specific to the United States market to foster performance-driven results from concept to delivery. Alternative standards have been developed for geometric product specification (GPS) by ISO. The ISO GPS standards are inclusive of specifying and verifying the geometry of a part and the measurement of part geometry. The GPS family of standards consist of 100 standards, each with a limited focus.

The number of documents and organization of the sets of standards might be different, but there is a great deal of overlap between the Y14 and GPS standards. ASME Y14.47 and the GPS standards both define a model organization. These model organizations are specific to model-based engineering. These definitions maximize the reuse and repurposing of model elements. It is only when necessary that one-off parts are developed.

Caution should be exercised when consuming standards from different governing bodies that have not coordinated their efforts. For example, a certain standard could explain the required equipment tagging methodology to include a location in the equipment naming; however, another standard could contradict this equipment naming with its own work breakdown structure methodology.

Engineering and construction industry professionals are quickly moving toward providing and leveraging only virtual deliverables. It will be no less important to maintain the same standards as noted previously. In fact, this evolution will include the addition of standards from the previous section about data management and the subsequent section about integrated viewing.

Integrated Viewer Standards

Standardization considerations should also be extended not only to how the information and geometry is created but also how it is consumed and viewed, as an extension of the deliverable standardization. When building or selecting a DE platform, one should consider the native platforms that are generating the views and how the final platform will aggregate them together.

There is no shortage of geometric viewers that are available for desktop, mobile, and/or web computing. Many of the available viewers leverage a myriad of file formats; however, the digestible formats are often not the same as what is generated from the native model authoring platforms. For this reason, direct integration is performed by transforming the native authoring views to compressed versions of the original. For example, the reactor vessel could have been modeled in one process-centric software and the overall containment structure might be modeled in another platform. To see the combined geometry, a common or interoperable file format is used to link them together. The most common interchange file formats for desktop computing today are Drawing (DWG), Standard for the Exchange of Product Data (STEP), Stereolithography (STL), and Initial Graphics Exchange Specification (IGES). There are certainly others available that will be necessary depending on the use case. It is important to keep in mind that these file formats often only contain the geometric representation and some metadata, but not all, of the modeled elements and do not include the parametric data that are driving them.

To evolve from strictly desktop computing to web and mobile computing, the needed formats are evolving from static geometric formats to structured data-rich formats. These structured formats have the possibility to include not only 2- and 3-D representations but also attribute data. File formats that have gained popularity for web applications are Scaled Vector Graphics (SVG), Serial Vector Format (SVF), Industry Foundation Class (IFC), Wavefront Object Format (OBJ), Virtual Reality Modeling Language (VRML), and GLTransmission Format (glTF). The IFC has been developed by the buildingSMART Alliance and has shown to be the most flexible when connecting to data sources. The IFC files are based upon a basic Extensible Markup Language (XML) structure to have the geometric, facility, and entity data separated. A current restriction of the IFC files is their file size, because they can get quite large, often magnitudes larger than that native file format.

Of additional consideration when using several different platforms are the units and coordinate systems from the base files. Most authoring tools treat the units and coordinates in unique ways. For example, one software might use Cartesian coordinates whereas another software might use Euclidean coordinates, and even a third software could use the true GIS coordinates.

5
CONCLUSIONS

Summary

DE use cases have been identified that support various aspects of new nuclear power plant projects, including project management, engineering, procurement, construction, and commissioning. Although these are not inclusive of all possible scenarios, these represent the state of the art in the industry today. Methods of interoperability of digital engineering tools to support these use cases was discussed. It was found that governing standards by which the digital representations of new nuclear power plants are early in development.

With the identification of DE use cases, there is no shortage of technology being adopted to meet the project management, engineering, procurement, construction, and commissioning of nuclear facilities. These topics are innovative, and many of the technologies available today have not caught up with the needs of the defined processes. Figure 6-1 has been developed to illuminate how DE (digital thread), the purple ring, encompasses a system of systems or many digital twins. The diagram illustrates that the twins are linked together by their data sources that are hosted into an authoritative source of truth, the CDE.

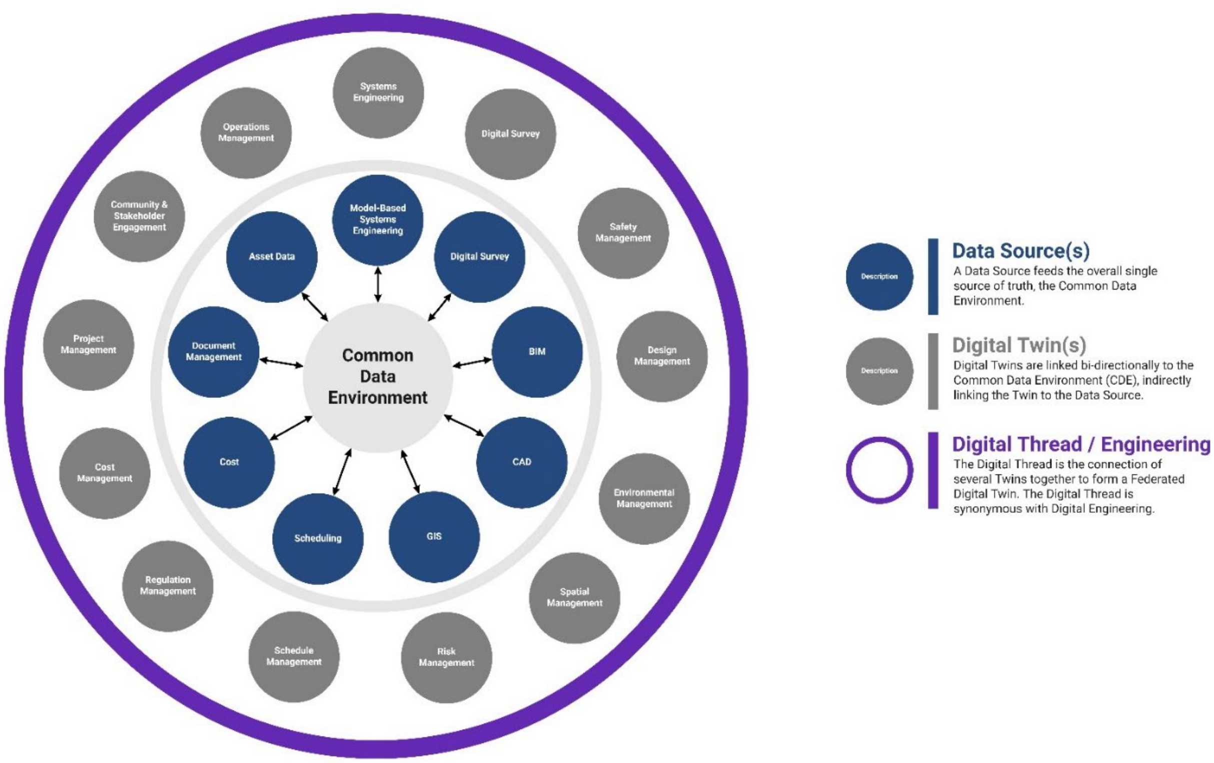

Figure 5-1
DE connectivity

DE is not a static process, and neither is the technology that enables the life cycle. The collective elements between the DE technologies that continuously surfaced have been similar to the technologies that have permeated general knowledge. Specifically, all of the technologies covered in this report use algorithm-derived data-backed solutions. AI, and its subcategory of ML, are dissected into numerous areas of study ranging from supervised learning for object recognition, to transductive learning for statistical purposes to hybrid options. These algorithmic terms have often been overused and misrepresented in marketing literature. Nonetheless, these computational approaches are paramount to the dissection, interpretation, and analysis of data and information generated by the DE life cycle.

The promise of DE is not only to curate a fully integrated life-cycle process but it has also been displayed to reduce project schedule, cost, and waste and to improve quality. These promises have yet to be fully realized in the application of traditional reactors; however, the implementation of DE on new nuclear power plants provides the flexibility to fully take advantage of the cutting-edge technology and process.

Insights

Several years ago, Industry 4.0 was promoted in many industries regarding how to collect sensing data, store them in a database, and perform semi-automated analytics to result prescriptive insights. DE is about to begin an evolution unlike any other seen to date. This evolution is referring to the transition between Web 2.0, reactive web applications, to Web3 (W3) immersive applications. These new web technologies propose to be trustless, secure, and based upon blockchain. A strategic value of W3 is the idea of composability. *Composability* is using a trusted underpinning to develop higher level computational platforms. A potential example of composability is implementing a user authentication module that has already been developed so that the developers would be able to focus on the development of a physics engine.

A key challenge that remains is integration of different systems and data connectivity. These new technologies will pave the way for truly trackable methods of changes and transactions. W3 technologies will impact the nuclear industry by providing private chains of data hosted on high performance private clouds.

Recommendations

Future Research Opportunities

From the research surrounding the state of the art for DE, there were several use cases identified for future research opportunities. For example, the use cases are only theoretical and/or the use cases were only in a proof-of-concept stage of development. These research opportunities are as follows:

Project Management

- **Probablistic risk management**. Leveraging probabilistic methods and AI to manage risk could provide potentially numerous avenues by which to reduce overall project risk by instilling new processes and technology.

Engineering

- **Automated code compliance**. Determining code requirements by generating a list of applicability based upon a few data inputs about the project.
- **Programmed site analysis**. A process in which 3-D/GIS tools are used to evaluate properties in each area to determine the most optimal site location for a future project.
- **Automated scan to model**. The utilization of computer calculation and machine vision to develop a 3-D model out of a laser scan or photogrammetric input.
- **Non-fungible token signatory of models and plans**. A process by which an authorized signatory can provide validation and certification that a plan and/or model was created, modified, and so forth by a certain organization and meets the requirements of the contract.
- **GD for overall systems and facilities design**. Current GD tools focus on the architecture and the more simplistic elements of a facility. On the horizon, GD is beginning to be able to aggregate the various design inputs and iterate to locate the optimal system design.

Procurement

- **Product life-cycle barcoding**. The process will provide information to the recipient so that the object can be tracked throughout its manufacturer, fabrication and shipping, and installation, also known as the *complete supply chain*.
- **Vendor submittal validation and verification with a blockchain key**. A potential use for blockchain technology is to validate that the latest product information is being used on a project. Dated keys might be able to be applied to the document and information to have a traceable link back to it origination.

Construction

- **Industrialized construction work package development**. Autogenerate work packages for engineering, construction, procurement, and installation work.
- **Automated construction work status management**. AIESS could be a possibility to identify emergency and/or life-threatening situations early.

Commissioning

- **Model-dependent input/output checkout process and procedures**. In the near term, it will be possible to commission and test the wiring of a control system with the use of a DE model.

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