Informing Standards: Evolving the Business Case for Maintaining Complex Process Facility Digital Twins

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An industry standards organization sponsors a project to design a standard and document a means to assess the practical and economic benefits of 3D model maintenance throughout the complex process facility lifecycle. This article chronicles the elaborated action design research (eADR) approach used to evaluate the design and implementation stages of this project, reflecting on this ongoing effort to deploy a standard for management of 3D models. These 3D design models are a foundational element of the virtual representation or 'digital twin' of physical assets. The researcher evaluates the project artifacts created to date, focusing on the business case for the standard with various use cases where value can be derived from investment in maintaining the model beyond the design stage of capital facility development and its impact on total cost of ownership. Included in the analysis is an outline of key artifacts created as part of the researcher's intervention and how they were created as well as a summary of the project's artifacts and the use cases they support. Initial results of the project team's analysis reveal how firms can reduce total cost of ownership while improving the performance and reliability of complex process facilities by maintaining the 3D design models and using them throughout the facility lifecycle.

> A team of process industry experts unveil value pockets for full lifecycle management of 3D design models and how to use them to reduce the total cost of ownership for complex process facilities.

Anders, the chairman of USPI-NL, had more questions than answers. He knew that to create and evolve digital twins to higher levels of maturity for his industry, it must start somewhere; 3D models seemed like a logical choice. But, he asked himself, "How much value could a 3D model bring to an operational asset? What are the extra costs incurred when organizations fail to make use of the 3D model created when projects handover to operations? What are the use cases for extracting value out of an accurate 3D model throughout the lifecycle of a complex process facility?"

This article explores the problem of practice faced by Anders and stakeholders of USPI-NL, the process industry standards organization that launched the Facility Lifecycle 3D Model Standards (FL3DMS) project in 2020. USPI-NL's break out business case development working group of volunteers began by brainstorming potential 'value pockets' then mapping them back to various use cases in the process industry. The task of bringing together all the findings into a single deliverable seemed overwhelming. Anders knew he could not do it by himself, particularly if his goal was to develop a solution that would accommodate his stakeholders' use cases. By evaluating where they had come from, reflecting on what they had accomplished so far, and learning from other perspectives, the researcher could help the FL3DMS project team develop a tactical plan to create a practical business case for 3D model lifecycle management, the primary objective of this research-based intervention.

According to Gartner research, a major challenge for designers of digital twins is the production of several items identified by Lheureux et al (2020), including "entity metadata" (p. 7), such as a 3D model, at the level of detail that excludes "superfluous information" (p. 7) yet still includes "information we need" (p. 7). They also highlight another challenge associated with these 3D design models, "To avoid data becoming obsolete, policies will be needed to ensure that digital twin metadata is updated when changes occur (e.g., when the model or make of equipment, or a change to a process, changes)" (Lheureux et al., 2020, p. 7). The operating cost associated with maintaining these models (typically created on large capital projects) is not well understood. As large firms prepare for Industry 4.0, digital transformation initiatives are an opportunity to alter paradigms that have previously constrained operational efficiency (McNair, 2021a). Organizational structures are being reimagined; also, traditional information silos are breaking down in favor of enterprise level data management and information sharing while technological innovations are being enabled through digital platforms. Firms that undergo this transformation will be better equipped to apply valuable

lessons learned from experiences elsewhere (Kohli & Johnson, 2011).

This article documents a scientifically based action design research (ADR) approach to understand, document, and mitigate a challenge oil and gas (O&G) facilities information managers have faced since the advent of the network connected personal computer: Facilities engineering information management systems and processes in this sector were typically architected to support 2-Dimensional (2D) unstructured electronic content (McNair, 2021a). As the technologies and planning involved in managing operational requirements for process facilities have become more complex, there is an ever-increasing demand for comprehensive 3D visualizations of these facilities linked to data from component systems. The effort to manage and maintain 3D content as a continuously accurate representation of the corresponding physical assets is difficult and commands a higher level of organizational capability and engineering rigor than required by siloed 2D-based content management processes. The many competing software tools to create, edit, update, visualize, and share this content require consistent standards guidance for data governance (Cameron et al., 2018).

Research Roadmap

As variation from one organization to the next creates a barrier inhibiting sharing and integration across silos of data and information repositories, a few standards organizations are attempting to address that challenge. To that end, the International Standards Organization (ISO) has recently updated ISO 10303-1:1994, the legacy international standard for industrial automation systems and integration for product data representation and exchange. The new standard, ISO 10303-1:2021, states that it seeks to provide the ability to describe a product throughout its lifecycle. The standard applies to file exchange, database sharing, and content archiving. The content about a product is used for many purposes at each lifecycle stage. Its usage may connect multiple computer systems across various locations. To accommodate these use cases, information must be represented in a common format to ensure consistency and completeness when data exchange occurs between different computer systems (International Standards Organization [ISO], 2021a).

The Facility Lifecycle 3D Model Standards (FL3DMS) project is an example of an industry endeavor to support that objective. This project is a collaborative international effort sponsored by USPI-NL (also known as Uitgebried Samenwerkingsverband Procesindustrie-Nederland), a process industry standards consortium based in the Netherlands that has brought together owner/operators (OOs) of large capital facilities (primarily in the O&G sector), Engineering/Procurement/Construc-
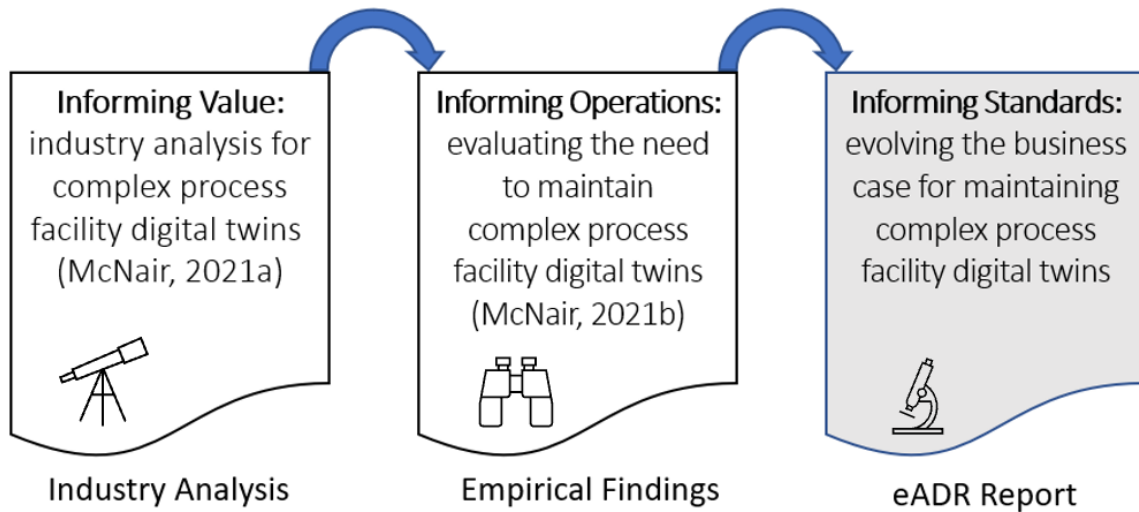
Figure 1. Roadmap of Research into Digital Twins as Valuable Asset

tion contractors (EPCs), 3D modeling software firms, and other stakeholder members of the Capital Facilities Information Handover Standard (JIP36/CFIHOS) community. The FL3DMS project team recently drafted an industry standard for 3D model content while simultaneously working on developing use cases for implementation of the standard in various stakeholder organizations, particularly OOs and EPCs (Uitgebried Samenwerkingsverband Procesindustrie-Nederland [USPI-NL], 2020).

As shown in Figure 1, an industry analysis completed earlier this year highlights the problem of practice faced by O&G firms in the petrochemical process industry resulting from lagging adoption of digital twin technology. It reviews the research literature and identifies limitations imposed by the economic, political, environmental, process safety, and societal constraints the O&G sector has encountered over the past decade. As many firms in this sector have begun to consider information a valuable business asset, they are also facing financial pressure to extract more value out of existing physical assets. The convergence of digital innovations in data visualization, integration, and analysis requires firms to invest in smarter technologies in the future as they pivot to prepare for Industry 4.0 (McNair, 2021a). An empirical study completed in January 2021 determined that firms in the O&G sector must also proactively work to build the organization capability to leverage the value derived from these innovations (McNair, 2021b).

Figure 2 is a Digital Twin Maturity Model adapted for this trilogy of research articles from similar models used to illustrate the incrementally more complex stages a digital twin must pass through as it evolves to higher levels of maturity (DNV-GL, 2020; Evans et al., 2019). The FL3DMS project is focused on establishing foundational (level 1) digital twins in the

form of basic 3D models. The project's key assumption is that to evolve to higher levels, the model used to visualize, design, and build the complex process facility must be trustworthy and complete throughout the facility lifecycle. Software agnostic standard data schematics and model element nomenclature ensure that stakeholders can expect uniform consistency of key data across complex process facilities resulting in greater insights from data aggregation, providing optimized integration opportunities as other smart systems and data are connected to the 3D model to adapt into a higher-level digital twin.

Beginning in 2020, the FL3DMS project team built a prototype use case value pocket assessment tool to help calculate the cost, benefits, and return on greater investment in maintenance of the 3D model for the full facility lifecycle. This third article in the series documents actions taken to improve project deliverables. The researcher joined the FL3DMS project team in early 2021 to assist with refining the business case for adopting both new standard and its recommended 3D model lifecycle management strategy. After analyzing their project archives, the researcher introduced an ADR methodology (Sein et al., 2011) that was enhanced by Mullarkey and Hevner (2019) to allow evaluation and evolution of a project already underway. Next, the researcher shared resulting findings with the project team and documented the lessons learned as they continued to iterate on their deliverables based on observations, interventions, and design recommendations.

Background/Context

Global adoption of the standards for 3D model implementation will foster greater informing efficiency throughout the value chain, resulting in reduced waste, increased productivity, and better alignment with Industry 4.0 capabilities associated with the

Level

5						Autonomous Operations & Maintenance
4					Two-way interactive data	remote control
3				Enriched with real time sensor data	operational efficiency & situational awareness	
2			Model links to static docs/data	process simulation, asset management		
1		Basic 3D Model	design, optimize asset performance & coordination			
0	Capture Reality	facility as-built survey (e.g., point cloud, photogrammetry)				

Maturity Progression   typical usage

Figure 2. Digital Twin Maturity Model (Adapted from Evans et al., 2019)

on-going digital transformation in the O&G sector (Kohli & Johnson, 2011). Initial findings show that firms in the process industry have increasing interest in coalescing around a standard, particularly as the current low commodity price environment has tightened capital budgets (Mohaddes & Pesaran, 2017) and increased pressure on firms in this sector to glean latent value from data assets (Wanasinghe et al., 2020).

The current trend favoring digital twin adoption in the O&G sector (McNair, 2021a) supports a better understanding of digital twin value, costs, and benefits for OOs of complex process facilities. Preceding this trend, firms in the O&G sector have rarely invested scarce operating expense resources on the maintenance of 3D models of complex facilities after custody transferred from the capital project implementation team to the operations organization following start up. This research evaluates the business case for various use cases for maintaining the 3D model. It starts by assessing the potential adoption of a detailed cost/benefit tool developed for sharing with members of the process industry standards organization. The researcher then recommends improvements to their tool based on the application of academic research rigor following a scientific process. One research objective is to help the project team develop and deploy a tool to help decision ex-

ecutives, operations managers, and engineering data managers make better decisions about the need to maintain 3D models for the full facility lifecycle and highlight the opportunity costs lost if the model is not updated and maintained after the design phase of a complex facility development project.

This research is important because there is widespread recognition within the O&G sector that 3D models (that take the form of a digital twin of a complex facility) have value (Wanasinghe et al., 2020); the FL3DMS project seeks to show managers how to assess that value and enable their organizations to capture that value through investment in maintaining the 3D models throughout the asset lifecycle (McNair, 2021b). This practitioner-scholar engagement offers the researcher direct access to the diverse perspectives of thought leaders within the global USPI-NL community. The researcher's interventions on the project provide a framework to improve the artifacts to ensure that the project objectives are realized while informing the researcher with greater empirical insight into the financial and technical drivers supporting adoption of this technology across the process industry supply chain.

Although value is derived in all phases of the lifecycle, the FL3DMS project effort is focused on exposing underappreciated value pockets after the design phase, beginning with execution, start up, and com-

missioning phase of capital projects, and continuing through operations and maintenance (O&M) phase as well as management of change events, including facility turnarounds, brownfield projects, facility decommissioning, and/or asset retirement. Particular interest is in the O&M phase as that is where the best use case for lower total cost of ownership is predicted to exist based on input from OOs and EPCs. This premise is supported in "International Energy Agency - Energy Technology Perspectives 2020"

Methods

The research began by reflecting upon "observational case studies" and considering the results of a "confirmatory focus group" study (Hevner & Chatterjee, 2010, p. 119) conducted on the FL3DMS kick off session in August of 2020. Coding done on the transcript of that session using Saldaña's (2016) methodology externally validated the empirical observations from an O&G firm's exploratory case study conducted in 2019 (McNair, 2021b).

The Design Science Research (DSR) methodology known as eADR (elaborated Action Design Research) was employed to evaluate the artifacts created from project inception through each iteration leading to global deployment. Through evaluation, the research designer analyzes the prior efforts and suggests improvements for the planning stage of their next iteration. This active role in the artifact creation process allows for a practical engagement; without this direct involvement, "designers can never know which techniques or methods are effective, or why certain approaches fail" (Hevner & Chatterjee, p. 111). The researcher intervention entry points in the eADR process (outlined in Figure 3) allow the researcher direct participation in the instantiation of a solution to the problem of practice being investigated (Mullarkey & Hevner, 2015).

Qualitative analysis on these observations based on Saldaña's (2016) textual coding methodology was conducted on transcripts of working group sessions, periodic project iteration deliverables, and several use case narratives. Themes manually derived from these artifacts provided the researcher with a holistic understanding of the project team's desired outcomes, their progress to date, and their plans for future development to instantiate a solution. By comparing their stated objectives against the actual results of their efforts, the researcher was able to identify gaps and provide meaningful feedback to help the project team forge a plan to mitigate the gaps. Figure 4 depicts the roadmap the researcher used to conduct this intervention based on the core eADR process illustrated in Figure 3.

that listed "digital twin O&M" as an example of an innovative "sustainable development scenario" that "replaces hardware or labour with digital solutions" (International Energy Agency, 2021, p. 337).

*Research Question/Research objectives*

What factors influence the rationale for maintaining complex process facility digital twins? The researcher evaluated an in-flight project to assess ways to support the need to instantiate solutions to the problem of practice that stems from foundational (level 1) digital twins (specifically, 3D design models) rarely being maintained as accurate representations of the current state in the operational context of complex facilities in the process industry (McNair, 2021a).

The primary objective for the researcher is to inform the business case for maintaining digital twins at complex process facilities through a systems management process as proposed in the empirical findings article noted in Figure 1. Next, as recommended by Maxwell (2013), building upon those findings in a use case provides a means for triangulation to reduce "the risk of chance associations and systematic biases due to a specific method" (p. 128) while improving the researcher's ability to assess the generalizability of the findings, specifically, those associated with building a foundation use case for developing digital twins in the O&G sector (McNair, 2021b).

The secondary objective of this DSR project is to leverage the opportunity to apply academic rigor to the analysis of a global cross-functional design team's iterative process to develop a business case and assist with the evaluation of its applicability outside of the organization upon which it was based. The desired results of this research underscore the method the project team used to show how organizations that invest in maintaining digital twins can be cost efficient, productive, and resilient amidst uncertainty, particularly during periods of low commodity price pressure on profitability. This research also highlights expected personnel and process safety benefits as industry 4.0 innovations foster the emergence of adaptive cyber-physical systems (McNair, 2021a).

Design Science Research Review

Design Science Research (DSR) is an approach for systematically exploring and solving the world's wicked problems using scientific rigor to better understand the way things are through development of innovative DSR artifacts. The researcher uses these artifacts to reveal new knowledge about the way things could be (Hevner & Chatterjee, 2010). Sein et al. (2011) offer a methodology known as Action Design Research (ADR) that facilitates development of a DSR artifact in designs, experiences, and assessment activities that directly involve building, intervention, and evaluation activities that occur during direct engagements with practitioners. The resulting
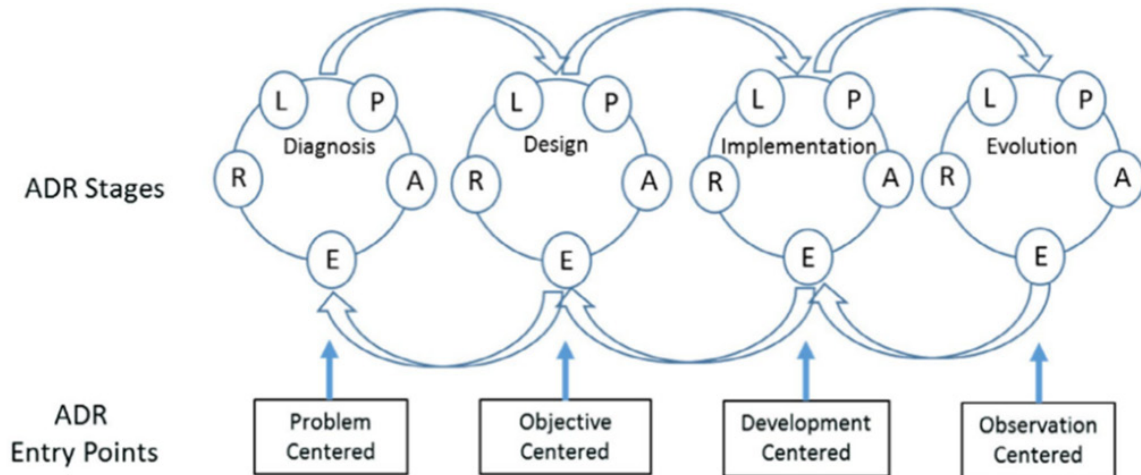
Figure 3. Nature of Interventions at each stage in the eADR method (Used with permission from Mullarkey & Hevner, 2019)

DSR artifact can be applied to practical requirements that are influenced by an iterative process based on sound theory. Elaborated Action Design Research (eADR) is an iterative approach within the DSR process to generate artifacts through diagnosis, design, implementation, and continuous improvement while investigating a given phenomenon or problem/solution domain (Mullarkey & Hevner, 2019).

The DSR artifacts for this research article leverage eADR methodology to evaluate development of an industry standard to manage 3D Models of selected complex facility assets. This process repeats until a viable solution artifact emerges that anchors the concept presented by addressing the research objectives and ultimately, resolving the problem of practice.

Adapted from Mullarkey and Hevner (2015), Figure 3 illustrates how each stage of the eADR process cycles through five steps. As each stage is informed by the preceding stage, the ADR cycles iterate until they achieve a state that contributes to one or more innovative artifacts. Note the steps in this illustration are abbreviated as follows: P = Problem Formulation/Planning; A = Artifact Creation; E = Evaluation; R = Reflection; L = Learning (Mullarkey & Hevner, 2019).

Though all four stages are potential entry points, according to Mullarkey and Hevner (2019), the third ADR stage (Development) supports the progression to final release of instantiated artifacts during the Implementation cycle. This stage allows the researcher to evaluate "the efficiency and effectiveness of the proposed design" (Mullarkey & Hevner, 2019, p. 10). The evaluated artifacts in this cycle include systems, tools, data repositories, and processes. Mullarkey and Hevner (2019) also recommend that this eADR process be expanded and adapted to demon-

strate its utility to practitioners in other application domains beyond IT projects. This recommendation aligns with the FL3DMS objective that involves corporations, consultants, vendors, suppliers, and public utility professionals. Thus, the researcher adapted Figure 3 into a graphical depiction of eADR interventions on the FL3DMS project as Figure 4.

Narrative of the intervention

For this research, since the FL3DMS project was already underway as the project team prepared to release its primary deliverable, the researcher started at the Development Centered entry point with the Evaluation step in the Implementation ADR stage of the eADR process (following the green arrows on Figure 4). The first direct action was to assess whether the FL3DMS project's principal artifact (a value pocket worksheet) satisfied the stated requirements of the project team, industry standards body, and its intended audience. The researcher did not publish this feedback as an artifact to the full project team at this stage but met personally with key members of the team to determine how decisions were made and how receptive they were to outside perspectives. Nearly all the researcher's interactions were conducted via formal Microsoft Teams® meetings or informal Teams® chat sessions without video in many cases, so the researcher found it difficult to assess body language and reactions to appraisal feedback without first establishing a foundation of trust, personal connection, and solidarity of purpose.

Building this foundation solidified mutual respect between the researcher and those who served on the business case working group. This mutual respect enabled the researcher to secure team member confidence then invite team members to Reflect upon prior iterations to identify how their principal
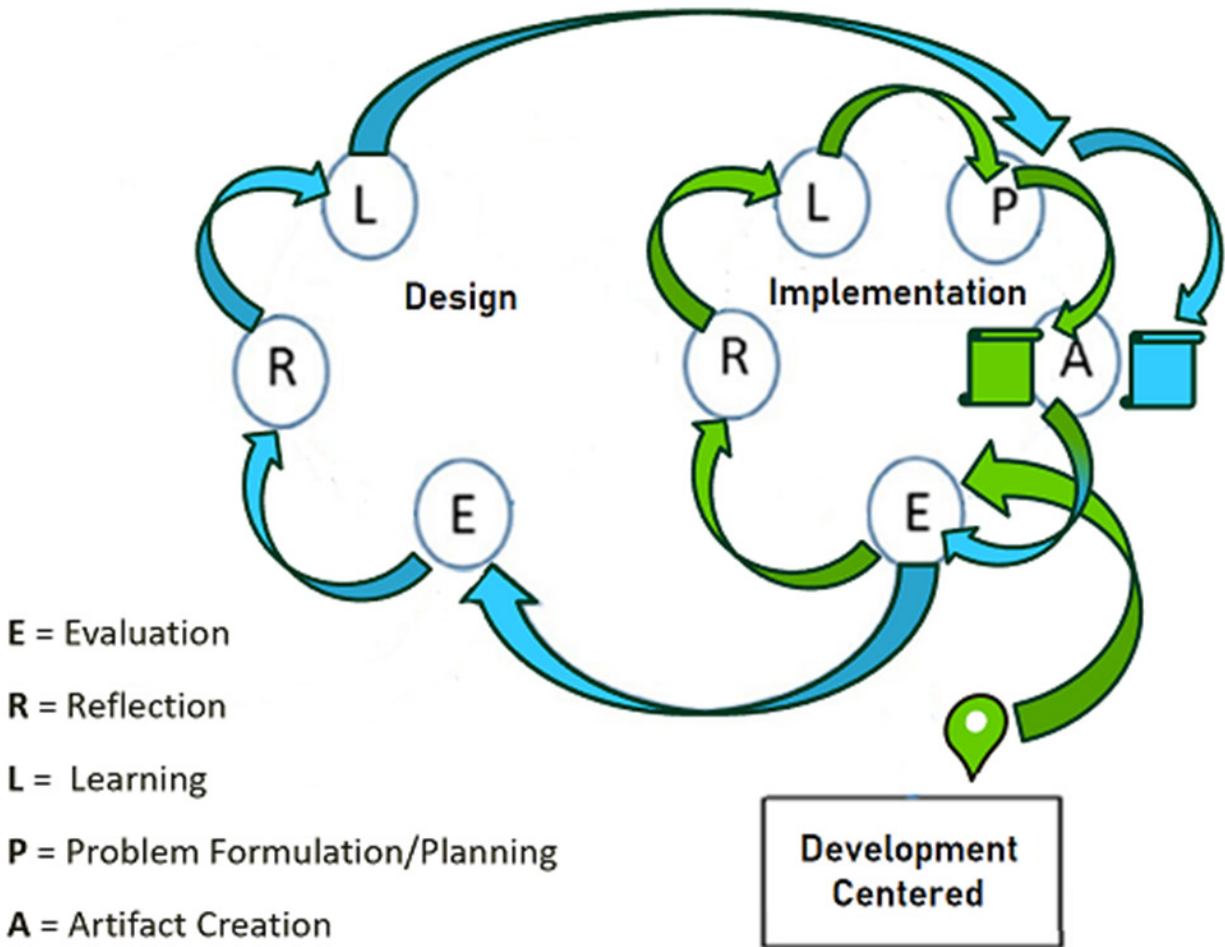
Figure 4. Flow of eADR interventions on FL3DMS project, Adapted from Mullarkey & Hevner, 2019

artifact was produced and prompt them regarding what could be done differently on future iterations to evolve the artifact to a final instantiation. As the eADR process was new to the team but not unlike "sprints" in the iterative Scrum® methodology (Sutherland & Schwaber, 2020, p. 7) that many research participants used in their workplace on product development projects, it only took a few weeks of direct engagements and non-verbal interactions to gather a representative set of data to generate useful research artifacts.

Next, best practices and lessons learned were shared with the researcher in the Learning step. These insights were coupled with the researcher's Teams® discussion thread postings of eADR artifacts provided in the general channel open to all FL3DMS project participants. This active engaged scholarship demonstrated the researcher's commitment to the project team's objectives. For example, one of the DSR artifacts posted was a mind map of relevant examples of value pockets from an external perspective based on the researcher's professional experience and extensive literature reviews conducted for

the Industry Analysis (McNair, 2021a) and Empirical Findings (McNair, 2021b) studies referenced in Figure 1. This mind map generated a lot of discussion, and at least two weekly progress meetings were dedicated to discussing any value pockets gaps that their initial prototype total cost of ownership model had not yet incorporated. In the project team's first stop at the Planning step, the researcher invited the team to ideate around recommended improvements to the principal artifact prior to release for use in practical situations. This Teams® discussion thread incorporated feedback from a broader audience of stakeholders and new members who had joined the project team in later iterations.

At the Implementation stage Artifact Creation step, several DSR artifacts were presented to the team (noted by the green document icon on Figure 4). Artifact 1 was posted via Teams® shortly after the researcher joined the project. It was an anonymized transcript of the kickoff meeting for the FL3DMS project dated August 2020. The artifact was generated from an audio recording featuring practitioners representing several O&G firms as well as other

interested parties (EPCs, Software Vendors, etc.) It highlighted the project team's initial objectives and included key stakeholders assembled by the project sponsor: USPI-NL, a process industry standards organization interested in 3D content management for the full asset lifecycle. Discussions focused on the need to coalesce around a standard for full lifecycle management of 3D Models and building a business case to implement that standard within the industry (McNair, 2021b).

Artifact 2 was an early draft of the digital twin maturity model (Figure 2) used to help the project team assess what level of evolution the 3D model needed to reach for various value pocket use cases before value realization could take place. Artifact 3 was the mind map of potential digital twin value pockets created independent of any FL3DMS content, later edited for clarity and supplemented as artifact 4 with narrative of digital twin value pockets at various asset lifecycle stages based on the researcher's professional experience. It was then integrated with the maturity levels in artifact 2 so the project team had a consistent reference point for assessment of owner/operator readiness to progress to higher level digital twin maturity. Appendix 1 is included as a reference table used to develop artifacts 3 and 4 when feedback from the project team indicated that a simple mind map needed further clarification to help project team members understand the digital twin lifecycle maturity context of each of the value pockets proposed. Appendix 2 includes both of these eADR research artifacts.

In the next step of the eADR process, the project team evaluated these new DSR artifacts by comparing them to the principle FL3DMS artifact (value pocket worksheet). This extra Evaluation step in the Implementation stage assessed any gaps not captured in earlier iterations prior to researcher participation. Following the blue arrows in Figure 4, results of the gap analysis were analyzed in subsequent sessions of the working group and the decision was made to revert to the Design stage to include the researcher's participation in subsequent weekly working group sessions. Informal interviews were conducted with members of the project team to ask them for Reflection upon the new DSR artifacts and how they may impact the final deliverable. The feedback from those engagements led to insights in the Learning step that resulted in a special planning meeting where project leadership opted to revise their deliverable plan in their second stop at the Planning step of the Implementation stage. They created a list of five new project deliverables (the blue document icon at the Artifact Creation step). This list included action items, due dates, and accountability assignments targeted to satisfy the new FL3DMS project objectives. From here, the project team will continue to iterate until they reach instantiation of a solution, as new deliverables are identified in the reflection step, learnings from that reflection are added to the backlog, and new deliverables are assigned a priority during the next stop in the planning step. The cycle continues to repeat; however, some deliverables are promoted off the action list into instantiation in the artifact creation step of the implementation stage.

The researcher's ongoing contribution to the revised project deliverable list includes update and delivery of the iteration-by-iteration critique of the value pocket spreadsheet deck (mentioned earlier) with recommendations for improvement observed sequentially, noting any improvement incorporated before the researcher joined the team (artifact 5). Because the eADR intervention identified material gaps in the project team's principal artifact's readiness for release through this process, the researcher discussed and documented the designers' experiences as they developed their new deliverables using Design Science Research (DSR) principles. DSR analysis of the design stage was contrasted with alternative approaches that had been used by these designers and developers in past iterations. Finally, the researcher concluded this stage of the intervention by identifying what the development group identified as 'best practices' over the course of their eADR experience and the potential impact it may have on a future instantiation of their desired solution to the original and revised problem of practice the FL3DMS project was created to address.

Discussion regarding implications of this research

The DSR process facilitates design improvements by providing a framework for collaboration, ideation, iteration, and instantiation of viable solutions to complex 'wicked' problems (Mullarkey & Hevner, 2019). Herbert Simon (1996) suggests that complex systems that lack discernable hierarchies "may to a considerable extent escape our observation and understanding" (p. 207). The complexity of facilities in the process industry tend to fit this description. From a systems management process perspective, during the early phases of a capital project to build a complex process facility, the facilities engineer may be able to track, categorize, and describe a system's component elements at the discipline, sub-system, or tag number level. However, to illustrate Simon's point, not long after that system is put into service, many untracked factors external to the hierarchies of a complex system have a potential impact on its remaining lifecycle.

For example, the protective coatings on a pressure vessel may be expected to last a given "average" duration based on the manufacturer's specifications, but those guidelines cannot fully account for the random actions of wildlife, extreme weather conditions, sun exposure, radiation from flare stacks, humidity,

algae growth, proximity to petrochemical solvents, acidic gases, and other by-products of O&G production. As a result, predictability regarding its potential future failure to preserve the integrity of the vessel is compromised. Something as simple as a bump or scrape from a passing hand truck could potentially compromise the coating's capacity to fulfil its designed purpose.

This unpredictability is compounded by variations that may not be physically apparent to a passing observer. A given pressure vessel's post oil/gas/water separator feedstock may have been expected to consist of natural gas hydrates at a specified acidity, so its expected useful life was predicated on consistency of the inputs over a projected time span. When this hypothetical production process was later modified to include reinjection of produced water into the reservoir to boost production pressure, the net effect was higher concentrations of hydrogen sulfide (H2S) in the pressure vessel. The design 3D model would have only accounted for the design criteria based on known conditions. Uncertainty is introduced unless that model evolves to a higher-level digital twin (e.g., connected to a sensor data system capable of tracking variations in the acidity or even accounting for predictable effects of higher injection rates in the reservoir). In this case, the original 3D model used for facility design would no longer reflect the current state of that vessel, thus compromising the "insight value" (McNair, 2021a) that informs the pressure vessel's preventative maintenance schedule, spare parts (e.g., seals, rings, instruments), inspections, and maximum pressure capacity.

A standard for 3D model digital interfaces and data storage requirements that might better inform decisions regarding equipment after it is put into service could reduce uncertainty, creating a more accurate visualization and service history of the asset over its lifecycle. The FL3DMS project seeks to provide the foundation for that standard (USPI-NL, 2020). Although their first published iteration may not be able to accommodate every use case, a disciplined scientific approach to developing the standard and improving its value proposition would benefit from actively managed feedback loops such as those provided by the researcher in this eADR project.

Discussion of research outcomes

This research effort asked the question, 'What factors influence the rationale for maintaining complex process facility digital twins?' Table 1 lists insights gained from analysis of each value pocket at various steps in the eADR process and how they may contribute to the business case for investment in lifecycle management of digital twins. According to the project team's analysis using information from EPCs, OOs, and Software Vendors, the estimated cost of maintaining a 3D CAD model is 2.85% of

Capital Expense (CapEx) or 0.5% of the Total Cost of Ownership (TCO) for a greenfield project. The cost of 3D model lifecycle management is mostly offset by an estimated net benefit over the lifecycle of the asset that ranges from 0.47% to 0.85%, assuming the original asset is never modified in the brownfield context. Since that use case is practically unheard of in the process industry, the TCO consideration must include costs and benefits in the operational context, allowing for an additional 0.46% TCO investment in brownfield model lifecycle management.

Based on the value pockets analysis conducted by the FL3DMS project, CapEx for a complex process facility project represents roughly 35% of the TCO. Assuming the asset undergoes at least one major brownfield capital modification, the total TCO % savings potential from 3D model management ranges from 1.31% minimum to 2.84% maximum. Thus, a typical $500 million would translate to a lifecycle TCO of $1.43 billion; 3D model management over that asset lifecycle would cost $13.72 million, and potential savings would range from $18.7 million to $40.6 million. Table 1 shows the eADR step where the influencing factor was identified, the factor that specifically contributes to the business case for lifecycle 3D model management, and a column listing selected benefits or cost savings within the activities associated with that value pocket factor. Table 1 only lists tangible cost savings and benefits associated with maintaining the 3D model. Intangible benefits, such as any resulting increase in decision quality, safety performance improvements, opportunity costs avoided, engineering and operations workforce retention, training quality enhancement, greater production throughput, and higher asset reliability, are extra benefits that contribute to the overall value proposition for 3D model management.

Interesting aspects of Design Science influence on outcomes

During the Implementation ADR stage, the use of the Digital Twins Maturity Model adapted from similar models proposed by DNV-GL (2020) and Evans et al. (2020) allowed the researcher to bring the perspectives of experts in digital innovation and best practice recommendations into the artifact design and development process. Specifically, understanding how 3D models evolve as digital twins at higher levels of maturity enabled the team to expose latent value pockets that might have otherwise been obscured as their focus was primarily on the benefits of maintaining a stand-alone 3D model.

Since the project team struggled to articulate their definition of 'done' prior to eADR influence, prior iterations had developed linearly in gradual increments. The introduction of an intentional feedback loop with learning and planning steps built in allowed the project team to collaborate around a solu-

Table 1. Factors Contributing to Business Case (derived from FL3DMS Project Business Case Spreadsheet – used by permission)

eADR step influencing factor analyzed	Factors contributing to business case	Benefits or Cost Savings within activity
Evaluation	Level of value realization from each cost category	FEED: 10 ~ 13% Design: 2.1 ~ 3.4% Maintenance: 3 ~ 7% Brownfield Eng: 3 ~ 10% Brownfield Const: 3 ~ 6% Decommissioning: 0.5 ~ 3%
Reflection	Value pockets expected to benefit from 3D model standardization (required or preferably)	84% (16 of 19) value pockets identified
Reflection	Safety improvement / project risk reduction	100% of cost categories
Reflection	'Hands on Tool Time' reduction	Pre-FEED: 2 ~ 4%
Reflection	Travel expense reduction, particularly at brownfield sites (post-pandemic logistics)	60% of cost categories
Learning	Effectiveness of management of change integration with 3D model maintenance	60% of cost categories
Learning	Relative improvement in decision quality support in each stage of asset lifecycle	1 ~ 3% savings in Brownfield engineering
Learning	Greater energy efficiency / sustainability	70% of cost categories
Planning	Organizational capability to maintain	40% of cost categories
Artifact Creation	Level of 3D model contribution to data as an enterprise asset (reuse, standardization)	FEED: 1 ~ 2% Detail Eng: 10 ~ 13% Execution: 0.4 ~ 7.5%
Artifact Creation	Training efficiency gains / employee retention	Operations: 2.5 ~ 5%
Artifact Creation	Level of 3D model integration with other data sources	Detail Design: 1 ~ 2% Repair/Maint: 2.5 ~ 5%
Artifact Creation	Level of complexity of systems / facilities	Brownfield Eng: 1 ~ 3%
Artifact Creation	Age of systems / facility assets	Repair/Maint: 3 ~ 7%
Artifact Creation	Geographic location of asset (on-shore/off-shore/remote/centralized/seasonal access)	Repair/Maint: 2.5 ~ 5%
Artifact Creation	Advanced Work Package (AWP) integration	Greenfield Const: 2 ~ 4% Brownfield Const: 1 ~ 2% Brownfield Design: 3 ~ 6%
Artifact Creation	Minimize rework	Detailed Design: 0.4 ~7%
Artifact Creation	Planning efficiency gains (beyond AWP)	Construction: 1 ~ 2% Brownfield Eng: 2 ~ 7% Decommissioning: 0.5 ~ 3%
Artifact Creation	Relative reduction in total cost of ownership (TCO) across all lifecycle stages	Net 1.31 ~ 2.84% < TCO

tion and maintain closer alignment on what they ultimately agreed would be their minimum viable product for their first release. The Design Science approach enabled the project team to focus on the key insights from their prototype value pocket analysis workbook. That effort resulted in a total cost of ownership model that highlights how each cost category contains value pockets that could contribute to savings derived from their proposed standard and on-going maintenance of 3D models at each stage of the complex facility lifecycle.

Implications for Design Science

The flexibility of the eADR process with multiple entry points, as illustrated with the diagram in Figure 4, allowed the researcher to focus on specific interventions within a defined research period with clearly understood objectives and expected outcomes. Action Design Research methodology foregrounds artifacts that are influenced by the values, assumptions, and interests of diverse communities of stakeholders, including developers, end users, and external contractors, "without letting go of the essence of design" as research (Sein et al., 2011, p. 38). This convergence of the internal and external enabled by eADR thought demonstrates how the methodology is capable of adaptation and evolution in accordance with the needs and dynamic circumstances of the specific design project context wherever its methodologies are applied. This work is empirical evidence that eADR can be adapted to projects that did not set out explicitly to create Information Systems (IS) artifacts as much as to develop standards and a business case for an IS related tool or systems management process.

Implications for Stakeholders

The active collaboration of the researcher with the project team to prepare its deliverables for release provided a fertile environment for expanding its influence beyond the participants' individual firms. As the regular interventions sparked side conversations with participants, the researcher's role as an engaged scholar vs. a positional peer or direct competitor fostered greater transparency and trust through mutual respect of the process used to help team members improve their desired outcomes from the project deliverables. Beyond the team, the findings benefit stakeholders in the broader community who represent constituent interests that may or may not align with the unique perspectives of the individual members of the project team. The intentional pursuit of generalizable value pockets in multiple use cases allows stakeholders to evaluate their unique situations against the project team's artifacts to make informed decisions based on data designed to account for variability in cost accounting procedures, contracting strategy, content hosting platforms, data owner-

ship, and diverse operational contexts.

The O&G sector may be late adopters of digital twin technology, but with a better understanding of the latent value of these information assets, it can leverage its immense scale and rapidly accelerating interest in the need for digital transformation to meet the challenges of these uncertain times (McNair, 2021a). Information stewards and decision makers in the process industry need tools to understand the potentially lower total cost of ownership with lifecycle management of the 3D model foundation that enables the evolution of complex process facility digital twins. This research supports that endeavor by providing insights from academia and industry in a systematic, repeatable process of continuous feedback and solution improvement.

Limitations and Directions for Future Research

The researcher's availability for near full-time participation in this effort was serendipitous as it coincided with a convergence of the project team's need for external perspectives, the researcher's interest in expanding influence beyond a single O&G firm, and the industry's call for standards and viable business case for adoption of them. Circumstances that enabled the intervention to succeed in this case may be difficult to duplicate as this novel solution to a problem that has persisted in the process industry for decades has more to do with a convergence of will and purpose among the participants than the researcher's specific choice of this research design protocol. Acknowledging the researcher's perceived bias towards greater adoption of an innovative category of digital technology may have been offset by the mutually beneficial objective of empowering study participants to pursue better stewardship of information assets throughout the O&G sector.

Conclusions

This design science research article explored the problem of practice associated with understanding the business case for ongoing investment in 3D model management as a foundational element for developing digital twins of complex process facilities. The FL3DMS team identified 'value pockets' related to use cases at each stage in the asset lifecycle and incorporated them into a comprehensive tool to allow decision makers to estimate the total cost ownership reductions available that more than offset incrementally higher 3D model maintenance costs. The engaged scholar intervention of the researcher evaluated the project artifacts and incrementally presented artifacts of analysis and recommended improvements. This intervention led to the working team co-creating a clear definition of specific project deliverables, each targeting the needs of various stakeholders (c-suite executives, facilities informa-

tion managers, operations and maintenance planners, etc.).

The evaluation, reflection, learning, planning, and artifact creation process facilitated the eADR methodology and enabled the FL3DMS project team to develop a tactical plan to create a practical business case for 3D model lifecycle management, the primary objective of the researcher's intervention. The process industry is on a rapid trajectory to transition from outdated legacy content management systems to comprehensive digital twins of complex process facility physical assets. The literature and recent empirical findings (McNair, 2021a; 2021b) now, more than ever, support the need for standards regarding the creation, editing, updating, visualization, and sharing of digital versions of the real world. Complexity and uncertainty in the O&G sector are a daily challenge for decision makers as they seek clarity of information to support tactical actions in support of a strategic vision for the future.

Anders' questions about the lower total cost of ownership justification from reduced ongoing operating and maintenance costs and a use case-based tools to assess the lifecycle value of the 3D model were answered, discovered, and documented in a deliverable plan developed by the project team with the support of the researcher as the best path forward to fulfil the objectives of the FL3DMS team.

References

Cameron, D. B., Tiina, A. W., & Komulainen, M. (2018). Oil and Gas digital twins after twenty years: How can they be made sustainable, maintainable and useful?, 9 – 16. *Proceedings of The 59th Conference on Simulation and Modelling* (SIMS 59), 26 – 28 September 2018, Oslo, Norway. https://doi.org/10.3384/ecp181539

DNV-GL, (2020). Panel discussion: Digital twins – Are they valuable? Can you trust them? DNV website. Retrieved 27 Feb 2021 from https://www.dnv.com/oilgas/webinars/panel-discussion-digital-twins-are-they-valuable.html.

Evans, S., Savian, C., Burns, A., & Cooper, C., (2019). Digital twins for the built environment. The Institution of Engineering and Technology, Stevenage, Hertfordshire, UK. Retrieved from https://www.snclavalin.com/~/media/Files/S/SNC-Lavalin/documents/beyond-engineering/digital-twins-for-the-built-environment-iet-atkins.pdf

Hevner, A., & Chatterjee, S. (2010). *Design Science Research in Information Systems.* Springer, New York, NY. https://doi.org/10.1007/978-1-4419-5653-8

IEA. (2021). Energy Technology Perspectives 2020. International Energy Agency, updated revision February 2021, retrieved 18 May 2021 from https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf.

ISO. (2021a). Industrial automation systems and integration — Product data representation and exchange — Part 1: Overview and fundamental principles. (ISO 10303-1:2021). Retrieved From https://www.iso.org/obp/ui/#iso:std:iso:10303:-1:ed-2:v1:en.

ISO. (2021b). International Standards Organization: Automation systems and integration — Digital Twin framework for manufacturing — Part 1: Overview and general principles (ISO/DIS 23247-1). Retrieved 17 April 2021 from https://www.iso.org/standard/75066.html.

Kohli, R., & Johnson, S. (2011). Digital transformation in latecomer industries: CIO and CEO leadership lessons from Encana Oil & Gas (USA) Inc. *MIS Quarterly Exec., 10*(4), 141 – 156.

Lheureux, B., Natis, Y., Velosa, A., & Halpern, M. (2020). Use 4 Building Blocks for Successful Digital Twin Design. Gartner, Stamford, CT. Retrieved 12 May 2021 from https://www.gartner.com/document/code/466264.

Maxwell, J.A. (2013). *Qualitative Research Design: An Interactive Approach*, 3rd ed., Sage Publications, Thousand Oaks, CA, p. 128.

McNair, W.R. (2021a). Informing Value: Industry analysis for complex process facility digital twins. Chapter 1 in *Informing Complexity: The Business Case for Managing Digital Twins of Complex Process Facilities as a Valuable Asset.* ProQuest Dissertations Publishing, 2021. (pp. 1 – 38).

McNair, W.R. (2021b). Informing Operations: evaluating the need to maintain complex process facility digital twins. Chapter 2 in *Informing Complexity: The Business Case for Managing Digital Twins of Complex Process Facilities as a Valuable Asset.* ProQuest Dissertations Publishing, 2021. (pp. 39 – 94).

Mohaddes, K., & Pesaran, M. H. (2017). Oil prices and the global economy: Is it different this time around? *Energy Economics, 65*, 315-325. https://doi.org/10.1016/j.eneco.2017.05.011.

Mullarkey, M.T., & Hevner, A.R. (2015) Entering action design research. In: Donnellan B., Helfert M., Kenneally J., VanderMeer D., Rothenberger M., Winter R. (eds) *New Horizons in Design Science: Broadening the Research Agenda.* DESRIST 2015, pp. 121 – 134.

Mullarkey, M.T., & Hevner, A.R. (2019) An elaborated action design research process model, European Journal of Information Systems, 28:1, pp. 6 – 20. https://doi.org/10.1080/0960085X.2018.1451811

Saldaña, J. (2016). The Coding Manual for Qualitative Researchers, 3rd Ed. Sage Publications, London.

Sein, M., Henfridsson, O., Purao, S., Rossi, M., & Lindgren, R. (2011) Action design research. *MIS Quarterly, 35*:1, pp. 37–56. https://doi.org/10.2307/23043488

Simon, H., (1996). *The Sciences of the Artificial*, 3rd Ed. Massachusetts Institute of Technology, Cambridge, MA, p. 80.

Sutherland, J., & Schwaber, K. (2020). The Scrum Guide. Rev. November 2020. Retrieved 17 May 2021 from https://scrumguides.org/docs/scrumguide/v2020/2020-Scrum-Guide-US.pdf#zoom=100

Uitgebried Samenwerkingsverband Procesindustrie-Nederland (USPI-NL)., (2020). Facility Lifecycle 3D Model Standard (FL3DMS). Retrieved 12 March 2021 from https://uspi.nl/index.php/projects/fl3dms/293-fl3dms.

Wanasinghe, T. R., Wroblewski, L., Petersen, B. K., Gosine, R. G., James, L. A., De Silva, O., Mann, G. K. I., & Warrian, P. J. (2020). Digital twin for the oil and gas industry: Overview, research trends, opportunities, and challenges. *IEEE Access, 8*, 104175 – 104197. https://doi.org/10.1109/ACCESS.2020.2998723

Review

This article was accepted under the ***constructive peer review*** option. For futher details, see the descriptions at:

http://mumabusinessreview.org/peer-review-options/

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Appendix A: Typical Oil and Gas Business Functions that Benefit from 3D Visualizations

Table A1 outlines how typical Oil & Gas (O&G) Business Functions benefit from Three-dimensional visualizations. The right most column references the target maturity digital twin (DT) level from Figure 2.

Table A1. Typical O&G Use Cases benefiting from Digital Twin Value			
Function	**Use Case**	**Current use in O&G**	**Target DT Maturity Level**
Aviation	**Ground Control**	Limited	4
	Aircraft Maintenance Records	Limited	3
	Fuel Systems	Limited	3
	Helicopter Operations	Active	3
	Drone Management	Archive	4
	Flight Control Simulators	Active	5
Manufacturing	**Fixed Equipment (Pipe, Storage Tank, Heat Exchangers, Insulation)**	Archive	2
	Integrity Inspections	Archive	2
	Process Flow Modeling	Archive	4
	Real-time Remote Monitoring	Active	4
Marketing	**Retail Planograms (Store Layout)**	Active	3
	Underground Fuel Storage Tank & line placement	Archive	2
Marine	**Fleet Management**	Limited	3
	Dynamic Positioning	Active	4
	Heavy Lift Construction	Archive	4
	Weight / Load Balancing	Limited	4
	Floating Platform Tethering Systems	Active	3
	Weather Systems / Prevailing Current tracking	Active	3
	Charting/Aids and Hazards to Navigation	Active	3
	Anchoring/Mooring	Active	3
	Crew Transport Logistics	Limited	4
	ROV/Drone Management	Limited	4
Product Distribution	**Pipeline (Valve control, SCADA)**	Active	4
	Pipe Inspection & Maintenance	Active	3
	Shipping (Load Modeling, Global Positioning, FPSO Vessel location)	Active	4
Production Maintenance	**Power Systems**	Archive	2
	Instrument Control Network	Archive	2
Production Operations	**Subsea Trees**	Archive	4
	Gas/Water Injection Systems	Archive	3
	Remote Command Center Console	Active	4
	Engineering Design Office	Archive	2
	SCADA systems	Active	4
	Product Flow & Storage	Archive	4
	Flaring Systems	Archive	3

Real Estate Management	**Office Building HVAC**	Archive	4
	Workspace Floor Plans	Archive	2
	Electrical and Telecoms Wiring	Archive	3
	Fire Protection Systems	Archive	4
	Transport Systems (Elevator, Escalator, Window Cleaning Davits)	Archive	4
	Alarm & Annunciation Systems	Archive	4
	Building egress / evacuation systems	Archive	4
Resource Exploration	**4D Seismic Reservoir Visualization**	Active	4
	Directional Drilling Systems	Active	5
	Hydraulic Fracturing	Active	5
	Drill Rig Location Planning	Archive	3
Safety	**Lifeboat Systems**	Limited	5
	Fire Suppression Systems	Archive	5
	Temporary Emergency Evacuation Route Planning/Modeling	Archive	3
Training	**Platform Control Room Simulation**	Active	4
	Onboarding – Remote Site Facility Orientation	Limited	4
Warehousing	**Inventory Stock Location Planning**	Active	3
	Automated Stock/Order Management	Limited	5

Appendix B: Selected Artifacts from eADR Project Interventions

ARTIFACT 3: CONSTRUCTION/COMMISSIONING PHASE VALUE POCKET MIND MAP AND NARRATIVE

The mind map in Figure B1 points out potential value pockets for the use of digital twins during the construction and commissioning phase of major capital projects for the development of complex process facilities. It is based on the researchers personal experience and leverages many of the value use cases included as Appendix A. Figure B2 shows the construction/commissioning phase. Figure B3 shows the pre-startup contruction portion.

The numbers marked in red hand-written text in Figure B2 represent the digital twin lifecycle level where the value pocket is most likely to add value. Yellow highlighting depicts value pockets that were either not captured or explored in the 3D model value pocket worksheet artifact at the time it was provided to the project team. Text not included in the original artifact submitted to the project team is italicized.

For this artifact, the map is broken into smaller sets to include the narrative below within that category of value realization. Note that this artifact does not discuss value derived in the pre-FEED or FEED stage as that value is already realized for the most part and where most digital twins have traditionally been archived rather than handed over to later stages of the asset lifecycle for further value creation. See Artifact 4 for value creation during later lifecycle stages.
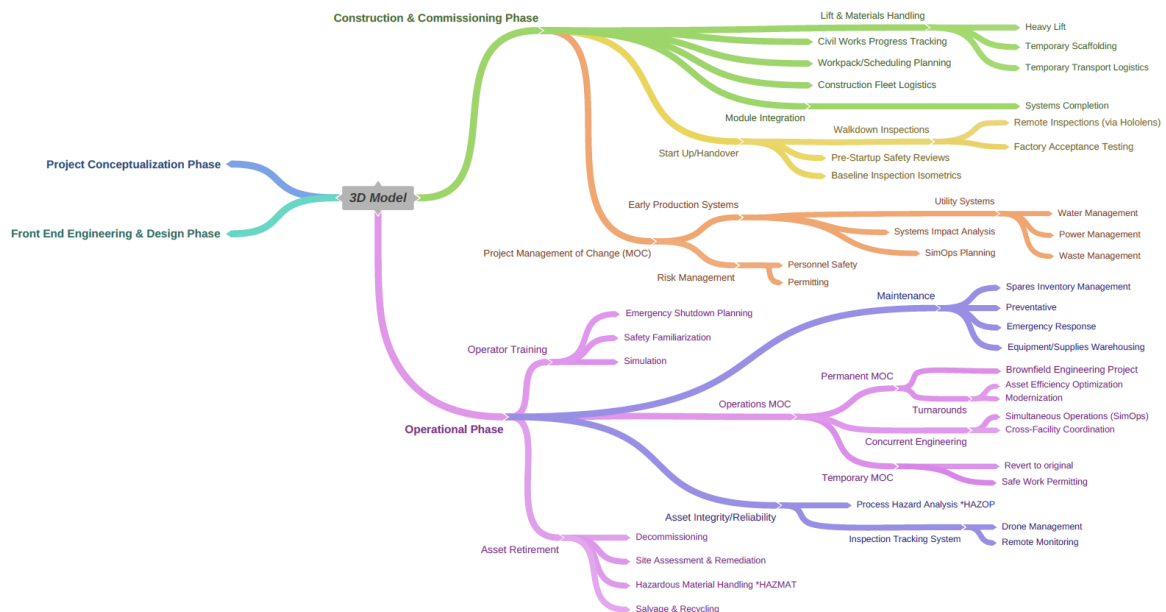

Figure B1. Mind Map visualization of 3D model value pockets considered for two phases.

Construction & Commissioning

Lift & Materials Handling:

During construction, the 3D Model allows for visualization of material handling equipment, temporary and permanent lifting equipment/scaffolding, etc. to position skids and component structure, supports, civil works, etc. This eliminates need for worksite disassembly/reassembly which increases tool time, increase risk of damage, overrides factory acceptance certification, etc.

Example Use Cases:

- Off-Shore heavy lift companies generate sophisticated 3D models to do weight load balancing, modeling of the actual placement of modules/platforms/jackets/equipment
- Logistics and movement of transport equipment through the construction site and/or marine operating area, above and below sea level
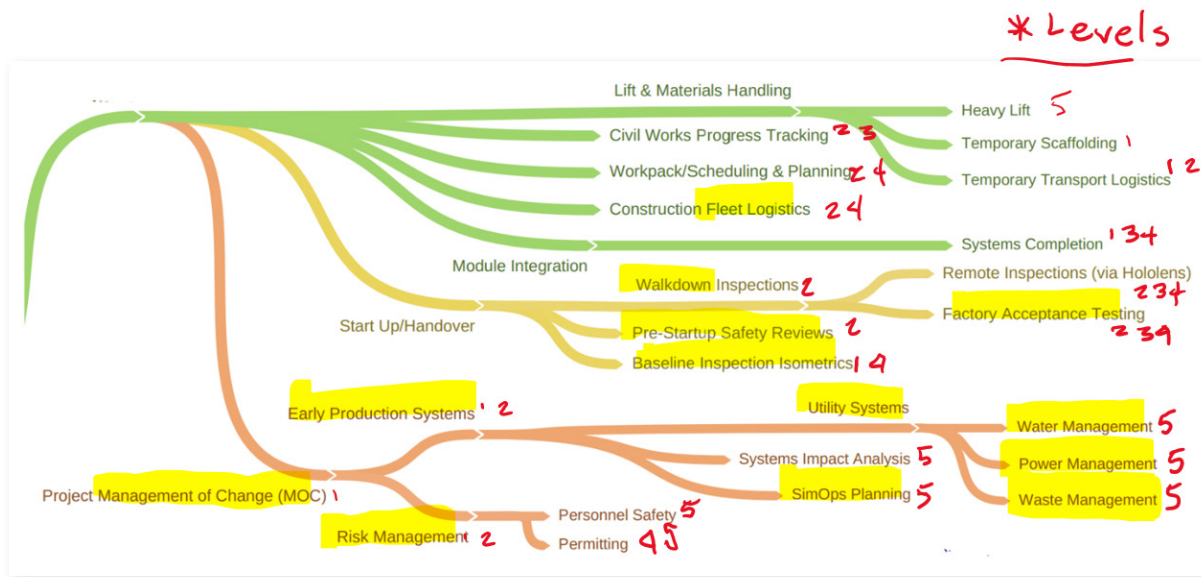
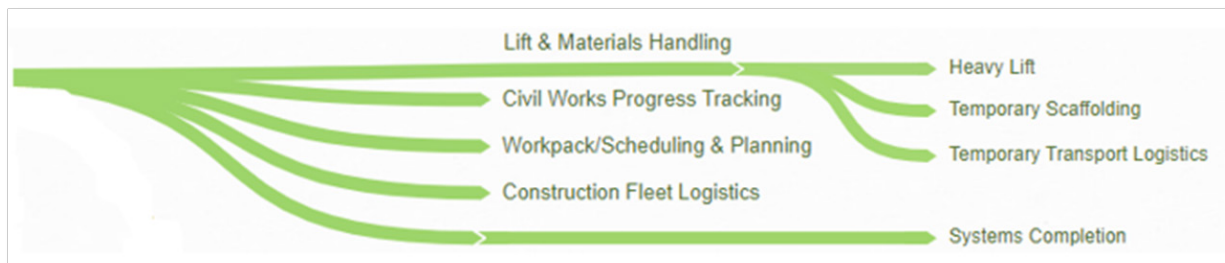**Figure B2. Value Pocket Mind Map - Construction/Commissioning phase**

Figure B3. Value Pocket Mind Map - Pre-Startup/Construction

- Valuable insights to planned vs. actual as a record of construction including anchoring, personnel transports, seabed soil analysis, cable & pipeline "as laid" mapping, container laydown management, etc.

Civil Works Progress Tracking

3D model could serve as a basis to enable 4D systems with time series data capabilities to journal movement of dirt, laterite, foundation elements, obstructions encountered vs. expected, soil conditions, drainage, underground utilities encountered, predetermined warning areas for water jet trenching vs. back hoe (i.e., is a greenfield really "green" vs. brownfield?).

> DA Comment:
> Not sure we would want progress tracking in the 3D model – will leave it bloated – this can be stored in the construction digital twin platform/4D model (derived from the 3D model data). Potentially a case for continuous site monitoring scanning and therefore mesh modelling as opposed to object modeling. That said, object scans can be classified with meta data and thus analyzed as design modelled objects. This can be brought into the 4D CDE. Statement could apply multiple times throughout this document.
> RM Comment:
> Great point @DA - I have made a few modifications to the sentence but you are correct, that is a higher level Digital twin (DT) value pocket. This document probably needs to be reframed to focus on value pockets that are available intrinsically vs. those that require significant evolution of the DT.

Workpack/Scheduling & Planning

3D Models could help planners assess workpack component, prework, dependencies, visual pre-walk-throughs vs. relying solely on reactive results. If actual tool time and worksite activity feedback is loaded into the model, future scheduling/planning accuracy improves with each iteration.

Construction Fleet Logistics

Includes temporary roads/crossings, weight restrictions for vehicles as they transit over underground piping and cable runs, where to park/stage cement mixers, dump trucks, tracked vehicles, etc. Identifies where to position SimOps activities with respect to blast zone, noise, radiation exposure, etc. exclusion areas (particularly on brownfield projects or facilities that start up in progressive stages).

Module Integration *(Systems Completion)*

Plan how the module hookup and commissioning activity will take place using a 4D [3D + time lapse] perspective for resource availability, as follows…

- obstacle/impediments might interact with the dynamic installation
- integration tie-ins to existing systems at various different points in time
- visualizations of the construction/assembly process provides planners with a realistic virtualization environment to avoid conflicts
- streamline and prioritize permitting process and documentation clearances
- aligns the project and operational Management of Change processes, etc.

This is particularly important for the systems completion process as it informs the subsystems commissioning engineers/schedulers with insights that allow them to share resources such as inspection personnel, tools, test equipment, nitrogen generators, etc. in alignment with operator/owner organization personnel availability, etc. Virtualization of the systems completion process would allow for better progress communication (e.g. daily stand up planning meeting content, end of day status debriefs, feedback for next day's activities, etc.)

Start Up/Handover:

Figure B4 shows the Start up/Handover Value Pocket. 3D Models used in the construction and commissioning stage could be handed over to the team managing any Operational Readiness Review assessments that must precede the gradual transition of care/custody/control of capital facility project teams to the operations organization. This includes enabling virtual walk down inspections including validation of as-built documentation and verification of model accuracy. If the factory acceptance testing and asset integrity/reliability baseline process requires inspections prior to shipment from fabrication to the final assembly location, an interactive 3D model connected to the document management system, and asset register, would allow for remote inspections via AR/VR/Mixed Reality tools such as the Microsoft Hololens™. It would also allow the handover team to derive Baseline Inspection Isometrics for piping using the as-built 3D Model (e.g., between isolation points vs. construction spool ISO's which are rarely "as built") would greatly enhance the operational piping integrity & reliability monitoring evaluation process in the operational context.

Pre-start up Safety Reviews leveraging realistic 4D (time series completion data elements of the model forecasted into the future) interactive walkthroughs would allow teams to anticipate what to expect when stepping into the construction zone at a given point in time providing a photo-realistic understanding and appreciation for scale, elevation, layout, scaffolding, or welding habitats and other impediments that might not otherwise appear on 2D P&ID, elevation, general arrangement or layout drawings. This would minimize and optimize the time spent by operations personnel in the construction zone during PSSR walkdowns, and help them dynamically adjust their plan accordingly. For example, they could anticipate and proactively model any logistical risks associated with variations resulting from last minute resource constraints, fast tracking, schedule modifications, or construction, commissioning activity delays.
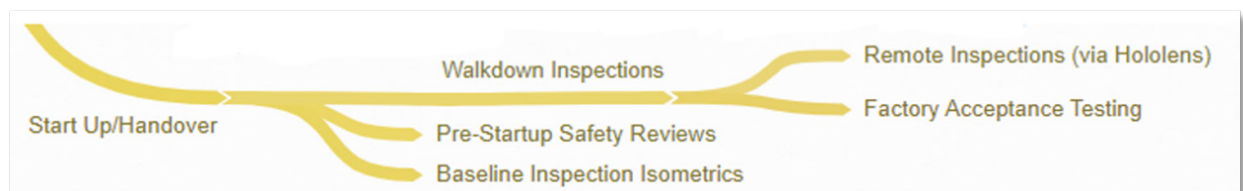

Figure B4. Value Pocket Mind Map – Startup/Handover

DA Comment:

This section doesn't cover in-field capability and is very office centric planning and remote inspection phases in its approach however on-site ambiguity around modelled equipment testing and supporting documentation can be served by continuous constraints management – as addressed below with 5x low hanging fruits. This in-field process ensures that any data remotely accessed can be relied upon for real-time accuracy.

Project Management of Change (MOC)

Figure B5 shows the Start up/Handover Value Pocket. Management of Change across all contexts is a significant potential pocket of value for 3D models. In the project context, they could be used to model how a planned change might affect construction or commissioning work in progress activity. It serves as a relatable environment for identification of opportunities to derive value from work in progress assets.

For example, an early production system (EPS) may be proposed if wells are complete and there is an FPSO or on-shore facility nearby with spare capacity and pipeline connectivity, even if the production platform is months or years away from completion. An accurate brownfield operating area integrated 3D model allows process engineers to assess the assets available for repurposing and lock out/tag out/tie in to import/export pipelines allowing for revenue capture and cash flow to offset the impact of leaving the wellhead asset idle waiting for the greenfield project's planned production capacity to come on line. Power & Control systems using common PSI wiring & configuration standards could be more easily adapted to the existing facilities.

A more accurate assessment of systems lifecycle maintenance / warranty / and reliability impacts is possible if the model includes updates of the design basis and planned facility turnaround schedule. The benefits of an EPS may be outweighed by the lifecycle cost impact if decisions for tactical early start up a facility fail to account for the strategic investment and how those changes in the project context could degrade the overall return on investment of the field or facility. Another decision factor the EPS could expose is that provides empirical feedback regarding actual well pressures and throughput values that could be plugged into the 3D process model to reveal possible modifications needed to validate or modify the final production facility baseline design assumptions.

Original Utility Systems design in EPS environments may need to be modified temporarily to support the requirements for operating the asset. Layers in the 3D model could be designed to provide the planned vs. actual vs. modified vs. restored vs. final configurations of water, waste, and power management systems. These models could better inform the construction, commissioning, start up, preservations, operations and maintenance personnel with a clear perspective on the impact of the EPS on the original project execution plan and basis of design. Analysis of the impact of the EPS on the overall systems lifecycle is enriched by continuous maintenance of the 3D model as its revision history provides an artifact of the project changes so that any future decision to leverage EPS opportunities can be supported by lessons learned from the decisions made before, during and after the EPS is put into operation all the way through its decommissioning and restoration to the original facility design (if applicable). Simultaneous Operations (SimOps) is another factor which must be considered as it introduces greater complexity to the project execution plan and brings with it higher risk of incidents. A 3D model which factors in the exclusion zones, hot work areas, weld habitats, blinds, temporary valves, scaffolding, control systems and utility piping and cable runs would allow visibility into the risk mitigation tactical environment as a tool for planning and worker orientation.

Risk Management can be further enhanced with 3D models as it can be used to visualize how a change might impact human factors engineers' *intrinsically safe* design assumptions. By modeling the change, whether temporary or permanent, it provides a tool to contextualize the perspective the operator, maintenance, or construction worker would have and potentially highlights latent risks that a purely 2D document review might miss. It also enriches the permitting process by allowing the lock out/tag out process to visualize isolation points, even those under construction which might not otherwise be reflected in construction drawings which often don't show work in progress status of physical equipment installations.

Figure B5. Value Pocket Mind Map – Project Management of Change

Note: The content below was added by a subject matter expert from a UK-based third party vendor consortium/consulting company after the researcher posted the original artifact to the project team.

Dynamic Field-Based Constraint Management

Beyond AWP with ability to progress monitor object resource model-based workflows through a construction / handover 4D model visualisation and ability to access Planning Remote Experts to manage constraints immediately.

Digitalized (hands-free) inspections and expedited Root-Cause-Analyses

Through use of model-based data repositories, 4D scheduled/planned inspections can be implemented to compliment plant activities in much the same method as construction planning. However, if supporting maintenance and operational data logs are intrinsically linked to the model asset, it will be possible for a deeper planning assessment to be made in context of the operating plant. Handsfree inspections can access this information via Remote Expert to query issues and call related modelled systems information to better on-site decision making.

Improved FAT/SAT activities and management

Often overlooked in terms of 4D model planning, the FAT/SAT process can have a high impact on schedule if documentation highlights any issues in terms of performance testing, installation, systems testing and handover. A 4D object resource strategy can bring life to key stages in releasing systems for operations and ability to track the history for downstream operational maintenance queries.

Improved/Digitalized LOTO Management

Similar to the FAT/SAT use case, LOTO management whether during construction or operations phase, a 4D model-based approach provides clear visibility of both spatial and temporal clashes for analysis for optimizing minimal impact.

Status Visualization for Project Stakeholders' (and supply chain) transparency

Through a comprehensive model & time-based approach, the model CDE can then be configured to provide role based stakeholder visualisation and cross-functional impact analysis. This modelling approach aggregates all information and leverages the investment beyond engineering to provide a true digital twin medium for all stakeholders throughout the project lifecycle.
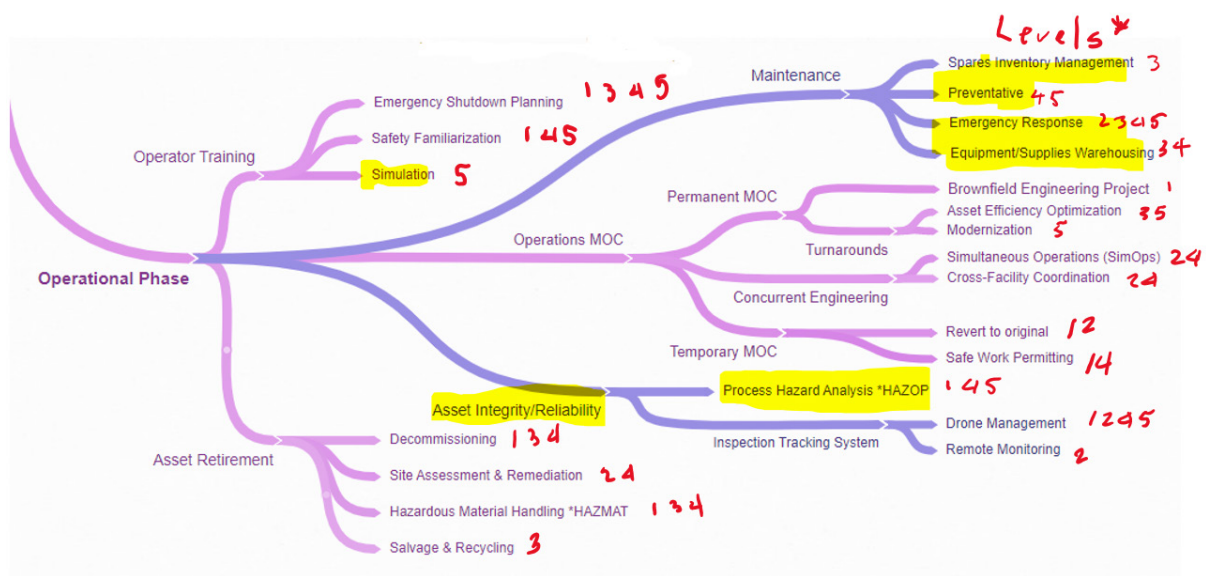

Figure B6. Value Pocket Mind Map – Operational phase

Artifact 4: Operational Phase Value Pocket Mind Map and Narrative

Operator Training

Figure B6 shows the value pocket mind map for the operational phase. Figure B7 shows the value pocket mind map for operator training. The use of 3D Models in the development of virtualizations is rapidly becoming commonplace in other industries and the oil & gas sector of the process industry is no exception. As gamification of learning activities is proven to be an effective way to orient a new generation of personnel to the complex situations and conditions they are likely to encounter in a process facility, the benefits from this innovative addition to the learning and development toolkit will require more realistic models for operators of remotely managed and semi-autonomous facilities. As a bridge to industry 4.0, the model provides visualizations to assist emergency shutdown response, familiarization to safe work practices, and simulation of complex facility control rooms and physical environments or procedures. Just like the aviation and nuclear power industry requires completion of qualifications including "seat time" in a simulator before being given responsibility for the safe operation of a plane or a plant, the operator in the complex process industry will someday have to meet similar standards.

Figure B7. Value Pocket Mind Map – Operational phase / Operator Training

Maintenance

Figure B8 shows the value pocket mind map for maintenance. Modern materials management systems are beginning to include more robust visualizations to include on line data sheets, interactive asset registers and connectivity to photogrammetry and 3D models to provide maintenance crews a holistic view of planned, preventative, reactive, and inventory management/warehousing. As maintenance personnel interact with the physical systems, they are a critical link to the accurate maintenance of the virtual systems as well. They can detect and correct records for missing equipment, environmental variables that might impact future construction/modification (corrosion, coatings, and structural decay/settlement).

Figure B8. Value Pocket Mind Map – Operational phase / Maintenance

Operations Management of Change (MOC)

Figure B9 shows the value pocket mind map for Operations Management of Change. Management of Change has many use cases for leveraging the value of 3D Models. Permanent changes such as Turnarounds or Brownfield engineering projects often require models to adapt the legacy facility to accommodate the new systems that will be replacing or connecting to the existing facility systems or structure. With concurrent engineering protocols in place, regular field updating of the model before, during and after the change allows remote engineering teams to manage the logistics, visualizations, work package creation and coordination
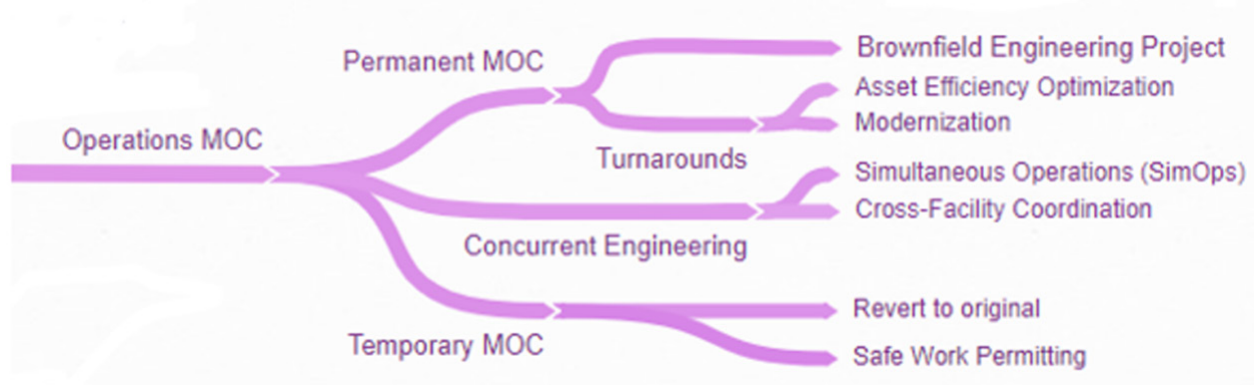
Figure B9. Value Pocket Mind Map – Operational phase / Management of Change

of operations and facility interdependences. Temporary MOCs allow the creation of a roadmap/layer for visualizing the impacts of the change before it is executed and provides insights to support permitting, lock out, tag out, isolation, rerouting and reversion back to the original after the change is no longer required.

As a critical safety process, MOC should govern all changes in an operating area, including large scale major capital projects all the way down to minor temporary modifications to a component item. A rigorous MOC process ensures that changes are tracked and lessons learned from those changes and how they are conducted can be applied to other projects in other locations or points in time as a perpetual feedback loop that allows for iterative improvements based on empirical findings through the experience of those conducting or managing the modifications.

Asset Integrity/Reliability

Figure B10 shows the value pocket mind map for asset integrity and reliability. As a separate, but related discipline to maintenance, Asset Integrity/Reliability leverages 3D models to generate accurate baseline inspection isometrics used to evaluate corrosion and assess vulnerability to failure caused by unforeseen environmental variables. Maintaining the model based on regular inspection data ensures that plans to conduct process hazard analysis activities account for real world conditions. Non-destructive entry and drone based remote inspections and monitoring systems must be trained with accurate mappings of layouts, spatial relationships between objects and structures as well as temporary structures which might otherwise obstruct a drone's flight or transit path.

Figure B10. Value Pocket Mind Map – Operational phase / Asset Integrity/Reliability

Asset Retirement

Figure B11 shows the value pocket mind map for asset retirement. During the final stage of the facility lifecycle, the 3D model helps plan for the decommissioning, assessment of the environmental condition, remediation of any hazardous releases (e.g. 4D tracking of extent of impact), handling of hazardous material, and identification of and disposition of salvage and recycling opportunities. The 3D model's change history record also provides a final visualization and artifact of the facility which could be used to help an enterprise compare original basis of design to the asset's ultimate contribution to profit/loss and capital investment return. In the future autonomous facility environments, Time-lapse analysis 3D models and photogrammetry will contribute significantly to the body of knowledge for how things were built and deployed, long after the personnel who built and maintained the facilities have moved on to other roles or organizations.

Figure B11. Value Pocket Mind Map – Operational phase / Asset Retirement

Appendix C: Glossary of Terms used in Articles and Appendices

Table C1. Glossary of Terms Used in Article and Appendices			
Term	**Acronym**	**Definition**	**Reference/Source**
2-Dimensional	**2D**	**Flat document or data visualization in two dimensions (typically length and width). Though it may refer to a hardcopy (printed) format, it also includes pdf or native renderings of drawings and documents as files that are viewable or accessible from a** *system of record* **that governs their care, custody, control.**	
3-Dimensional	**3D**	**Data visualization in three dimensions (typically length, width, & height)**	
4-Dimensional	**4D**	**3D with an additional dimension, typically time-based**	
Action Design Research	**ADR**		**(Sein, et al., 2011)**
Application Program Interface	**API**		
Artifact		**Content created during a project to support a design objective**	
Building Information Modeling/Management	**BIM**	**Collaborative process to plan, design, and construct a structure or building within one 3D model**	
Computer Aided Design	**CAD**		
Capital Facilities Information Handover Standards	**CFIHOS**		Home – JIP36: CFI-HOS (jip36-cfihos.org)
Data Exchange in the Process Industry	**DEXPI**		DEXPI – Data Exchange in the Process Industry
Digital Twin	**DT**		**(McNair, 2021a)**
Design Science Research	**DSR**		**(Hevner & Chatterjee, 2010)**
Elaborated Action Design Research	**eADR**		**(Mullarkey & Hevner, 2019)**
Engineering Procurement Construction	**EPC**	**Contractor**	
Facility Lifecycle 3D Model Standard	**FL3DMS**		Fl3DMS (uspi.nl)
Final Investment Decision	**FID**	**Capital Project term referring to the point when the project is approved**	
Floating Production Storage Offloading	**FPSO**	**Vessel**	

Front End Engineering & Design	FEED	Early stages of a major capital project (including pre-FEED) when concept is improved and virtual asset is created and modeled to reach a Final Investment Decision (FID)	
Graphics Language Transmission Format	gITF	Open standard file format for 3D computer-based graphics	glTF Overview – The Khronos Group Inc
Heating Ventilation Air Conditioning	HVAC		
Industry 4.0		Fourth Industrial Revolution represented by autonomous facilities up and down the supply/product chain	
International Standards Organization	ISO		ISO – Glossary
International Standards Organization, Draft International Standard	ISO/DIS		ISO – Glossary
Level of Development *(Detail)	LoD	Part of BIM	BIMForum - LOD
Management of Change	MoC	Internal governance over changes to assets or information	
Oil and Gas	O&G		
Owner-Operator	OO		
Supervisory Control and Data Acquisition	SCADA	A control system architecture consisting of computers, graphical interfaces, networked communications for remote or centralized process management	Boyer, S. (2010). **SCADA USA: ISA – International Society of Automation. P. 179.** ISBN 978-1-936007-09-7.
Safety Integrity Level	SIL	A system of monitoring and tracking the safe operation limits of an instrument or vessel throughout its lifecycle	
System of Record	SoR	The official storage and access location for documents and other records related to a business asset	
Total Cost of Ownership	TCO	The aggregate of all costs throughout a facility lifecycle (capital and operating expense)	
Uitgebried Samenwerkingsverband Procesindustrie-Nederland	USPI-NL	Process Industry Standards Consortium based out of the Netherlands	https://uspi.nl/