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Informing Operations: Evaluating the Need to Maintain Complex Process Facility Digital Twins

By
William Randell McNair

During the design phase of major capital projects, information content about complex process facilities is created and used to model how the facility will operate once completed. In the Oil and Gas (O&G) sector, this digital design data is referenced to plan material orders, stage testing, and track commissioning of the facility components. It can also inform decisions related to construction, installation, and ongoing operational activities of these facilities across multiple locations around the world. Training the workforce to build and maintain this content in the operational context is one of the critical infrastructure challenges of the Industry 4.0 digital transformation. This empirical findings study evaluated a large integrated petrochemical process industry (PcPI) firm as it struggled to understand the need to manage three-dimensional (3D) design models as digital twins after custody of facilities transitioned from project to operations. Results from an exploratory case study at that firm were compared to a transcript of a project kickoff meeting hosted by process industry standards organization. Consistent themes and recommendations surfaced across both sessions and validated findings. Understanding how firms in this sector perceive the need to manage 3D models as digital twins throughout the facility lifecycle supports the need to determine the status of this important category of digital assets.

Ops never maintained 'Digital Twins' in the past, why invest scarce resources now? We ask industry experts for their take on lifecycle information asset management of this rapidly emerging techno-trend.

Keywords: 3D Model, Digital Twins, Information Asset Management, Industry 4.0, Visualization, Value, Lifecycle, Maintenance, Oil & Gas, Process.

Paula was frustrated. In her circumstances, anyone would have been. As the regional business unit's facilities engineering information manager, she knew a complex $5 billion off-shore oil and gas processing facility was rapidly approaching its first major maintenance turnaround event and she still had not received an expected final 'as-built' (updated to accurately reflect what was installed) version of the 3D model that was used to design and build it. How could Paula realistically prepare for this 'planned' facility shutdown if she did not yet have care, custody, and control of an accurate comprehensive electronic record of the asset? Although she had received the core process safety information deliverables required at start up to operate the new plant, access to this fundamental yet valuable 'digital twin' version of the physical asset eluded her and her team of engineering data analysts. From recent experience on other large capital projects, Paula understood that when more complexity is introduced to the overall systems environment, more rigor is required to manage the modern facility efficiently. Specifically, accurate three-dimensional (3D) visualizations of complex facilities must be continuously maintained as digital twins throughout the facility lifecycle (from initial design through asset retirement). Paula wondered if her situation was unique and thought, "How can anyone make important decisions about operational management of these new high-tech facilities without access to accurate information?"

This article explores the situation Paula faced. Is she alone? If not, what is the root cause of this recurring capital project information handover issue? Even if she gets the final as-built model, would Paula have access to the technical skills to bring it up to date with what has changed since start up and maintain a 3D computer aided design (CAD) model once she accepted custody of it? Will Paula's organization have the operational discipline to incorporate key elements of these models into its management of change (MoC) process? Could the organization justify the operating expense to maintain them? Can it afford not to?

Accurate asset information enables decision makers to allocate resources where they are needed most. This empirical research is the second of a three-part investigation to understand the value of information assets through analysis of a specific category of business data known as digital twins: the virtual or electronic representation of physical assets (Grieves, 2019). Despite the immense scale of the oil and gas (O&G) sector, there has been limited academic research or documented empirical evidence of firms that have implemented a practical approach to address this problem for highly complex operating environments (Cameron et al., 2018).

Firms in the O&G sector are rapidly adjusting to greater emphasis on digital innovation and automated decision support systems. Organizational capability (OC) to manage digital twin visualizations of assets as 3D CAD models is becoming a strategic imperative that O&G firms must procure or cultivate to prepare for the demands of designing, developing, deploying, and maintaining the complex facilities of the future (Cameron et al., 2018). This article documents evidence of this important technology trend in the O&G sector at a large firm and an industry standards organization evaluating the business case to maintain digital twins of complex process facilities as a valuable business asset.

Problem of Practice: project information handover and management

Firms in the O&G sector are facing complex challenges associated with decades of entrenched practices that often ran counter to strategic intentions. Design documents are typically handed over as point-in-time accurate (or as-built) information, primarily 2D renderings or fact reports. However,

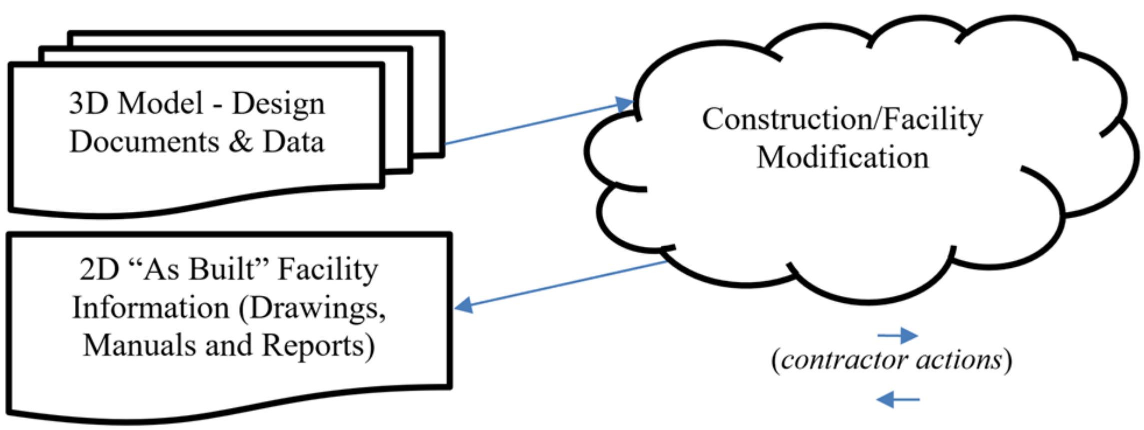

Figure 1. Typical Project As-Built Document Handover Workflow

even as firms in this sector become more fluent in digital innovation and decision support systems, the systems of record for managing facility information have not traditionally kept up with the complexity required to efficiently manage the modern facility (McNair, 2021). One such innovation is the 3D model-based visualizations of the asset created when a facility is designed or undergoes major modification.

Figure 1 shows a workflow of how 3D models used for the facility design phase typically do not survive the facility construction or modification phase. In many cases on O&G projects, these 3D models are generated by external engineering contractors as design tools to help them visualize the facility so that they can create material and equipment orders, construction plans, drawings, and reports for how the facility will function after completion (McNair, 2021). Although it may increase engineering cost to update and maintain these 3D models as digital twins after initial construction is complete, future semi-autonomous facilities will not be possible unless the capacity to visualize these facilities and conduct real-time analysis of status and performance is built into a day-to-day systems management process (SMP). Figure 2 depicts how the SMP will need to flow to enable the technical competence or organizational capability to maintain and operate higher level digital twins. Note that the SMP may include contractor or owner/operator actions or a hybrid combination of both depending on the firm's engineering services sourcing strategy.

Background

Beginning with the first commercial production well in 1869 (Stevens, 2013), the rise of the nascent petrochemical process industry (PcPI) was, in hindsight, a disruptive influence similar to how relatively cheap coal fueled the first industrial revolution (Wrigley, 2010). The demand for reliable sources of energy to fuel the second industrial revolution resulted in multi-billion-dollar investments in exploration, production, distribution, and marketing of petroleum-based products. In the latter half of the twentieth century, the third industrial revolution increased demand for fossil fuels, lubricants, complex plastics, and other petroleum-based chemical compounds. About the time forecasters were predicting that the world had reached "peak oil" (Aleklett & Campbell, 2003), innovations in unconventional drilling and recovery technology unlocked vast reserves of hydrocarbons, extending the life of mature fields and opening new frontiers for exploration and exploitation (Baumeister & Kilian, 2016).

As the digital age has expanded humanity's capacity for managing complex systems, we find ourselves on the verge of a fourth industrial revolution: Industry 4.0 (Magruk, 2016). Traditional tools for analysis and discovery have been set aside in favor of technological advances, such as big data, artificial intelligence, and machine learning (2016). Remote sensing instrumentation, the industrial internet of things, advanced robotics, drone technology, and countless other modern innovations are fueling aspirations of autonomous production and distribution facilities spanning the globe (2016).

Though lagging many other industries (Kohli & Johnson, 2011), major O&G firms are undergoing a "digital transformation" (Dickson, 2020, p. 5). Urgency to catch up is driven by technological advances leveraging data analytics across the industry's value chain to cope with an expected protracted down cycle in energy prices (Mohaddes & Pesaran, 2017). PcPI influencers must proactively increase awareness of benefits, competitive advantages, and improved asset integrity and reliability that could be gained by

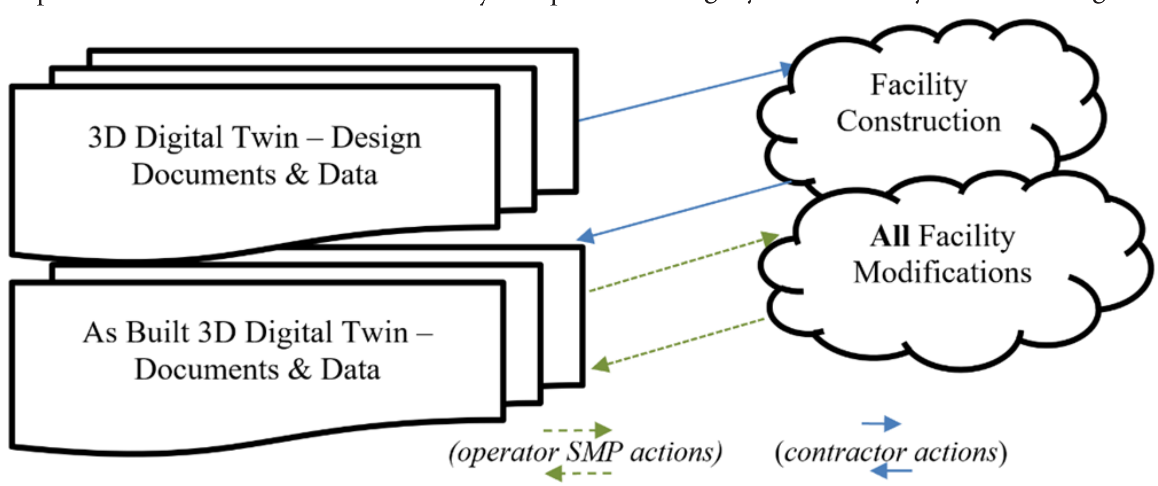

Figure 2. Proposed As-Built Digital Twin Handover Workflow

moving from unstructured 2D document-based information management systems to semi-structured 3D data, metadata, and model-based facility information management systems. However, to fully realize those benefits, firms must be willing to increase investment in OC and MoC. Industry standards organizations such as USPI-NL, IOGP and DEXPI have each completed efforts to coalesce around a standard for capital project information handover to operations (Cameron et al., 2018). In April 2020, USPI-NL initiated a project to develop a standard for 3D Model management throughout the lifecycle of complex process facilities and document the business case/value proposition for implementing that standard across the process industry (USPI-NL, 2020).

Over the past two decades, researchers have proposed general cost accounting-based approaches to information asset valuation (Moody & Walsh, 1999); however, the PcPI recently has embraced a strategic imperative to regard information as an asset (Kohli & Johnson, 2011). As more firms adopt a growth mindset (Canning et al., 2020), the business climate has become more receptive to bringing innovative and iterative research techniques to this problem. The O&G sector is also experiencing political and economic pressure to reduce environmental impact on the planet while increasing investment in technologies to automate facilities (Goldthau et al., 2018). This trend of supporting the development of autonomous operations could also reduce reliance on human performance factors that would mitigate many of the occupational health and safety risks associated with complex facilities (Stevens, 2016). The transition to Industry 4.0 is underway; thus, digital twins and the organizations that support them must evolve beyond the lower levels of the digital twin maturity lifecycle model (McNair, 2021).

Management of Change Dilemma: accumulation of technical debt

According to Seaman et al. (2012), the metaphor "technical debt" (p. 45) refers to the situation in practice when an engineer, operator, or other technical information steward compromises the maintainability of a technical artifact (e.g., electronic documentation) to meet the demands of delivering a physical product, service, or modification on time to the receiving organization. This trade-off does not mean that the work to update the documentation is never accomplished; it may be postponed indefinitely due to more pressing client or operational expectations. This compromise creates a "debt" that must be accounted for and eventually settled to ensure the ongoing health of the installed or modified physical system. The "interest" that incurs while this debt is outstanding is realized in the form of impaired decision making, compromised maintainability, or higher risk of incidents resulting from inaccuracies in information stored in the official system of record for that content (Seaman et al., 2012). Although not typically part of the O&G facilities engineering technical information management jargon, the information systems concept of technical debt has generalizable applicability to the maintenance of information in the O&G sector as documentation has become a key digital component of process systems that have evolved into complex cyber physical entities at a higher order of abstraction than traditional document management processes, systems, and standards were designed to accommodate.

Owner-Operators amass technical debt whenever information accuracy changes due to modification of the physical asset, but the operations organization does not update the corresponding version of the asset in the virtual space. The global and dynamic nature of the workforce in the process industry often translates to subjectivity of expectations as to what constitutes minimum requirements. For example, the U.S. Department of Labor's Occupational Health and Safety Administration (OSHA) has "recognized and generally accepted good engineering practices" (OSHA, 2016) that outline the codes, consensus standards, and practices to protect personnel in the operational context of certain hazardous conditions that may exist in a workplace. However, the guidelines may be subject to ongoing variation in interpretation or enforcement from one federal executive administration to the next.

From the researcher's professional experience in evaluating the handover requirements governing for more than 100 major capital projects over the past two decades, in a single complex process facility, it is not uncommon for several hundred thousand documents to be created during the project design, construction, and commissioning phases. These documents were traditionally provided to operations at handover as several hundred binders containing volumes of printed drawings, diagrams, data sheets, manuals, and reports, filling shelves from the floor to the ceiling with content that represented the facility at the state it was when it left the fabrication yard. The handover document binders would typically be revised and updated to include the final as built version of content and delivered to site, maintenance, and project archive libraries within a few years after completion and start up. These palletized and boxed capital project design and construction implementation documentation sets were often also shipped to other recipients and stored as archival records located at operations and maintenance (O&M) warehouses, facilities engineering libraries on-site, offshore, on-shore, or in the owner-operator's home country in massive long-term contract document storage facilities (see Appendix 3).

With the advent of electronic record keeping, these point-in-time accurate printed versions of complex facilities are rarely maintained as accurate representations of the operational asset unless local policy or regulations mandate that firms do so (in some cases, requiring content to be printed and maintained in multiple languages and always consistent with the corresponding electronic versions). The paradigm of physical records storage persisted through the mid-2010s. However, the rise in complexity at these facilities combined with legacy hardcopy library record keeping requirements embedded in project handover contract deliverables written for a different era created a logistical storage dilemma that simply failed to anticipate the volumes of mostly unread documents filling shipping containers, storerooms, operations centers, offices, and in at least one case – a crew recreation room (see Appendix 3).

The normalization of hard copy content being out of sync with the changes to physical assets often would eventually spill over into the electronic arena as well. MoC activity at complex facilities often encountered subjective requirements regarding what defined a completed change event. For owner-operators, the MoC approval and sign off process, typically governed by local occupational safety and health requirements, focused on managing the physical safety of the personnel or processes involved change event rather than consistently ensuring that documentation of the changes was updated to reflect the final as built version after the change was complete. The submission of scanned versions of redlined drawings and documents may have sufficed for close out of the MoC work package, expecting that the operations or engineering team would later incorporate those changes into the system of record versions of the master electronic files. For process safety information (PSI), it was common for organizations to mandate extensive master file documentation updates to prepare for periodic process hazard analysis events and compliance audits, but the status quo demanded that engineers and operators focus on the next project or task in front of them; thus, the completed 'paperwork' may lag months, if not years, behind the temporary or permanent modification. This persistent lag in updating the system of record with the dynamic activity happening is an ongoing source of latent technical debt.

The impact of technical debt on the process system's intrinsic complexity quickly complicates the calculus for compliance in this arena. Variation in the definition of terms of compliance (requirements, mandates, standards, guidelines, specifications, regulations, etc.), variability of jurisdictions regarding the authorities responsible for enforcing compliance (regional, municipal, federal, governmental, industry, corporate, etc.), and diverse opinions as to what constitutes 'process safety' demand that certain PSI is maintained as a continuously accurate version of the truth. However, the standards of what constitutes PSI varies from region to region, operator to operator, asset to asset, potentially individual to individual. The adage 'no job is finished until the paperwork is done' has not consistently kept up with the shift to the electronic realm. As work package completion and MoC accountability often focus on what is happening in the physical world in terms of planning for safe operation of the change event, the MoC process must also include accountability for timely update of the virtual or interest from technical debt compounds as the potential of increasing incremental brownfield project and operational maintenance costs accumulate over time. The cost of time spent doing physical or virtual 'paperwork' vs. the risks and technical debt incurred because of postponing or avoiding it should be part of the organization's overall facilities engineering information management strategy.

The owner-operator must have a clear governance process in place to determine if a change demands updates to key documentation, such as asset registers, instrument index, data sheets, Piping and Instrumentation Diagrams (P&ID), layout drawings, location plans, wiring diagrams, cause and effect charts, or alarm and trip lists. Differing opinions at the human level as to what level of detail must be updated to meet the required definition of done for an MoC project may adversely impact informing value of the content for future decisions or the systems that feed from that information. In the design phase of a large capital project, much of PSI content is generated from a source design tool such as a smart P&ID system, 3D CAD model, chemical engineering model, intelligent instrumentation, or electrical database. The fact that many of these design tools do not transition into the operational context is a source of technical debt. For example, PSI, such as the instrument index, cause and effect chart, instrument data sheet, or instrument wiring diagram, are significantly more difficult to update/maintain in the 2D native CAD or PDF version of the document than in a smart instrumentation database that created and rendered those documents at project handover. The 3D CAD model is another one of these foundational semi-structured information tools that has the highest potential for returning tangible value on investment in maintenance in the operational context of complex process facilities.

Past Research: digital twins defined

The term 'Digital Twins' emerged in recent years as a buzzword in popular technobabble vernacular, yet it has not attained universal consensus regarding its meaning. It is rooted in the manufacturing industry, as the concept was introduced by Michael W. Grieves during his presentation to the Society of Manufacturing Engineering Management Forum in

2002. He defines the Digital Twin as follows:

[T]he information construct of the Physical Twin. The intent of the Digital Twin is that it can provide the same or better information than could be obtained by being in physical possession of the Physical Twin. The key assumption is that the type, granularity, and amount of information contained in the Digital Twin is driven by use cases (Grieves, 2019, pp. 176 – 177).

Grieves' initial research for the manufacturing sector, based on the work done at NASA on the Apollo Program, emphasizes the information efficiency gains possible when the virtual space aligns with the physical space. He describes how the virtual version of the 'product' exists in the design stage and can be very useful in determining what can or should exist in the physical version. As the complexity of the virtual model improves, a feedback loop forms in that data flows from the physical to the virtual model, and information to enhance decisions making flows from the virtual model to the physical environment (Grieves, 2019).

Conceptual Framework: digital twin maturity throughout asset lifecycle

When an O&G firm chooses to build and maintain digital twins for an existing asset, the value available to realize from that investment is dependent on its level of maturity. Figure 3 is derived from a DNV-GL (2020) "evolutionary stages" slide (p. 5) and a model proposed in a white paper released by the Institution of Engineering and Technology encouraging digital twin infrastructure adoption. It depicts these stages as a step-by-step maturity level progression beginning with the 3D model developed during the design phase (level 1). If the design model is not available, the O&G firm may have to start at a lower level with reality capture tools (level 0). The digital twin evolves in complexity as organizations incrementally integrate technologies and standards to support the full facility lifecycle of physical and digital assets (levels 2 – 4) with the aspiration of fully autonomous facilities at the highest level of maturity (level 5). Each level of maturity "further enables removing humans from hazardous processes or tasks, intrinsically improving safety" (Evans et al., 2019, pp. 10 – 11).

Firms that want to create and evolve to higher order digital twins of existing facilities typically resort to reverse engineering them from level 0 since it has historically not been widespread practice for the level 1 digital twins (3D design models) used to create these facilities to be included in the final handover to operations nor maintained after facility construction and commissioning. Thus, modern laser scanners are often deployed to develop a point cloud to create more accurate 3D models based on the as-built facility in its current state and linking them to static data

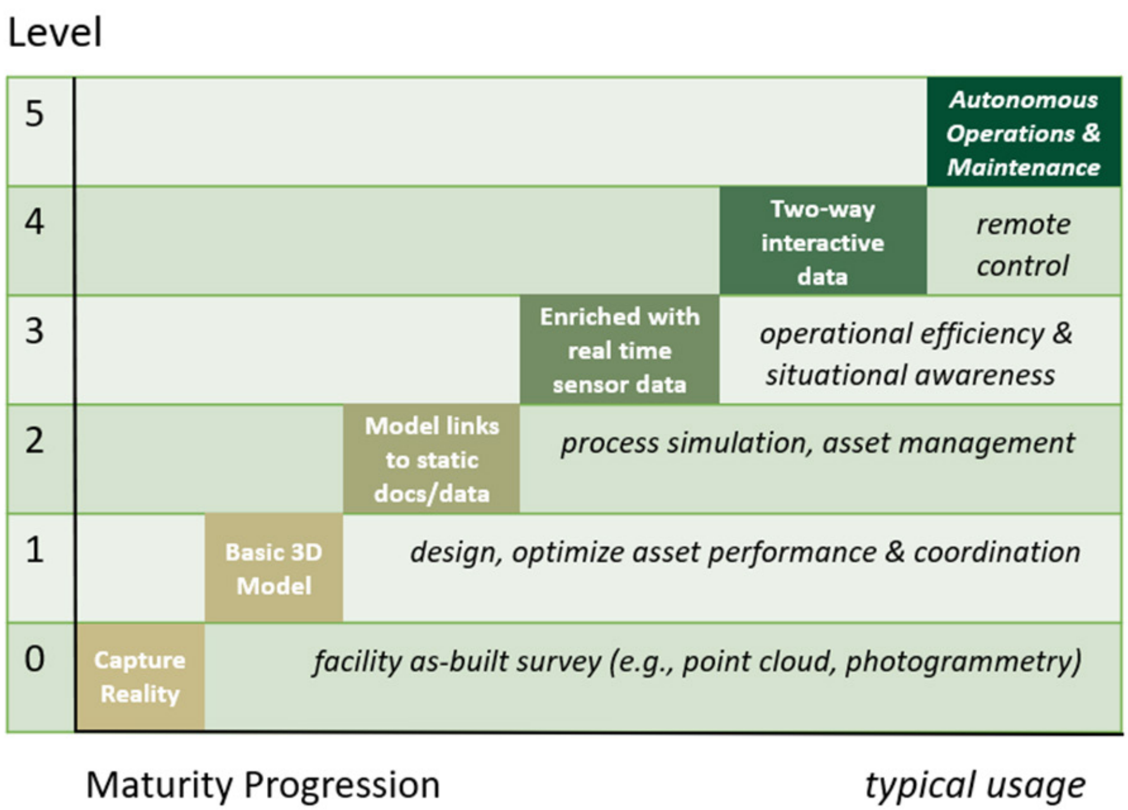

Figure 3. Digital Twin Maturity Model (Adapted from Evans et al., 2019)

to produce a level 2 digital twin (McNair, 2021). This task requires a high degree of technical skill due to the complexity of managing and encoding the data to interpret it correctly (Chowdary et al., 2011).

Uhlmann et al. (2017) identified a significant need for pursuing alternative methods to realize what he called "a Cyber-Physical Production System (CPPS)," thus making the system process visible enough to enable "real-time production control" (p. 336). Realization of what amounts to a level 3 digital twin of the production system is a key factor in achieving Industry 4.0 readiness as it ensures the appropriate level of data quality to implement greater systems integration without compromising the benefits of having a digital twin and, by extension, the CPPS (Uhlmann et al., 2017).

Once a level 3 digital twin is achieved, the next evolutionary step includes adapting to the challenges of moving dynamically between the virtual and physical through simulation so that a trusted level 4 digital twin will be a training and process optimization tool. For example, according to Schuster et al. (2015), industry needs to begin preparing for the future now by training engineering students to meet the demands of Industry 4.0 by exposing them to CPS, "Internet of Things," and "virtual learning environments (VLEs)" (p. 14). To overcome the complexity of current systems, they will need to be able to navigate the transition from document-based learning systems to interactive "collaborative VLEs" (p. 14). This trend towards more eLearning (electronic technology enabled learning systems) extends beyond basic skills acquisition to provide greater linkage to higher education.

Cooperative and collaborative learning creates a new knowledge baseline. VLEs can include gaming type environments that run fictional scenarios modeling against real facility simulations. Even real-time activity can be monitored for instant feedback and improvement of skills through artificial intelligence (AI) and augmented reality. Schuster et al. (2015) also point out that modern society has created a generation of learners who have grown up with digital learning technologies and are better equipped for the Industry 4.0 jobs of tomorrow as this generation of learners has developed greater hand/eye/cursor coordination skills than those who first learned primarily using traditional pencil and paper methods (Schuster et al., 2015).

Thus, digital twins are rapidly becoming an expected mode of human interaction with physical systems and heightens the importance that firms grow OC to ensure that digital twins are maintained as accurate representations of the current state throughout the asset lifecycle. Level 4 digital twin technological advancements could produce an "automated production plant" that, through simulation, reduces cost in the design and implementation phases by leveraging multiple technologies (Programmable Logic Controllers, automated material handling systems, wireless warehousing, and radio frequency identification), enabling error reduction in the physical and simulated domains (Encinas et al., 2012, p. 849).

Oztemel and Samet (2020) define "Cyber-Physical Systems" (CPS) as a term to describe a fully integrated evolution to a level 5 twin of the digital and physical asset that must have robust "Machine-to-Machine" (M2M) connectivity and an efficient language bridge so that it can operate interactively with optimal efficiency. Pursuing that pinnacle of digital twin development offers the most direct pathway to the Industry 4.0 facility environment available today. Thus, they define Industry 4.0 as "a collection of values of objects, internet services and cyber-physical systems. At the same time, this structure plays a major role in the formation of intelligent [primarily unmanned autonomous facilities]" (Oztemel & Samet, 2020, p. 132.

Research Questions

This empirical findings article focuses on two research questions that explore the problem of practice associated with evaluating the need to maintain accurate digital twins throughout the lifecycle of complex facilities in the oil and gas sector.

Research Question 1 (RQ1): ***How do Oil & Gas industry experts perceive the need to maintain a digital twin of complex process facilities throughout the asset lifecycle?***

Many industries are waking up to the Industry 4.0 evolution of business in the modern world; the O&G sector of the PcPI is no exception (Wanasinghe et al., 2020). They are prioritizing technology investments to enable advanced analytics, restructuring business processes, and transforming organizational hierarchies to accommodate modern workflows with agility leveraging recent digital innovations (Dickson, 2020; McNair, 2021). However, these same organizations often struggle to extend transformation across their entire enterprise because it requires a cultural shift in how work is resourced, how people collaborate across business function silos, and how business product owners communicate their needs and expectations of delivery organizations (Wanasinghe et al., 2020).

Research Question 2 (RQ2): ***What insights can be acquired from examples of how 3D models of complex facilities are managed in the Oil & Gas sector after these assets are handed over to operations?***

This research question delves deeper into the specific problem of practice that is primarily focused on digital information asset management challenges that surface after handover to facility operations. Future design, construction, and maintenance of automated or remotely controlled complex facilities will increasingly require realistic operational simulations, continuous training supplemented by augmented reality, modern collaboration, advanced ideation, and perpetual iterative innovation. Firms in this sector must actively invest adequate resources to manage this information throughout its lifecycle. Common data sharing platforms across an enterprise allows for greater transparency and clearer insight into the value drivers for progressing to higher levels of digital twin maturity (Wanasinghe et al., 2020).

Research Protocol

The researcher applied qualitative design (Maxwell, 2013) and "action research" (Hevner & Chatterjee, 2010, pp. 182 – 183) methods to investigate how a firm collaborated across multiple organizational silos to assess OC for effective management of facilities engineering information assets. Specific emphasis has been applied to understand how 3D CAD models were being managed after the care, custody, and control of complex facilities were transitioned from the project to operations context since these 3D models are "foundational elements" (level 1) of a firm's digital twin assets. (McNair, 2021).

The two research questions were evaluated from analysis of the transcript of an O&G company focus group session that was convened to brainstorm how to grow OC to manage 3D models of complex facilities. The makeup of the group included subject matter experts and spanned functional boundaries and resulting information silos. To test external validity, the results of this analysis were compared to a transcript of a kick-off meeting composed of subject matter experts at an industry standards organization based in the Netherlands; the experts were tasked with developing a standard for managing 3D models throughout the complex process facility lifecycle (USPI-NL, 2020).

Primary Research: qualitative case method

Primary research for this article began with a small exploratory qualitative case study focused on answering research questions as recommended by Joseph A. Maxwell (2013). Maxwell contends that this type of inquiry is necessary to gain an understanding of the "concepts and theories held by the [individuals within the organization] being studied" (p. 67) because those perceptions may change as more information is discovered in the process of learning about the problem under consideration. Maxwell cautions that internal generalizability of findings from case research is an issue that must be evaluated to "adequately understand the variation in the phenomena of interest in the setting or group of people being studied" (p. 137). This type of generalization helps ensure "validity of the conclusions" (Maxwell, 2013, p. 137).

Exploratory Case Study: focus group session regarding digital twins

In this case study, as shown in Figure 4, the researcher sent out a meeting request to ensure that the right subject matter experts (SMEs) and interested stakeholders were available and represented in the discussion. Pre-read materials were posted via an internal on-line discussion board encouraging participants to forward the invitation to others who might be interested and could speak to the scope of the problem within their business unit or corporate functional area.

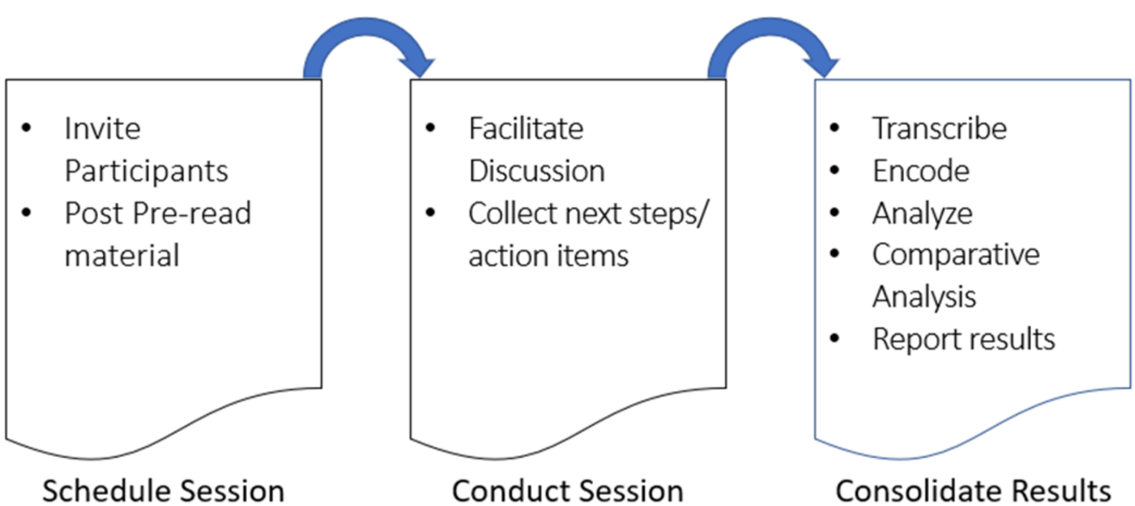

Figure 4. Focus Group Engagement Plan

Next, the session was conducted as a ninety-minute recorded (voice only) teleconference combined with ten participants, including the researcher, meeting face-to-face in a large conference room, and about 25 others dialing in via Cisco Webex®. The session was facilitated by the researcher as an ad hoc information management community of practice (IMCOP) focus group meeting with SMEs and interested stakeholders. Evaluation included using voice recognition software to build an initial session transcript. The researcher then manually edited the transcript to ensure it was an accurate record of the conversation and context. That document was disseminated to all participants, and they were given an opportunity to validate its accuracy and comment or post any corrections or clarifications. For this article, the document was anonymized and encoded following Saldaña's The Coding Manual for Qualitative Researchers techniques. The researcher initially applied grounded theory (emergent categories from holistic coding) to detect themes discovered during the literature review and then applied structured coding techniques on the transcript, leveraging those themes to see if the experience of the subject matter experts aligned with or contradicted those themes (Saldaña, 2016). See Appendix 1 for the qualitative analysis report resulting from the focus group session that was conducted via teleconference call in October 2019.

The researcher used QDA Miner software to conduct semantic analysis and descriptive coding in multiple iterations through the transcript until saturation was achieved. This process helped craft research questions for future studies and provided a framework for follow-on discussions with the community that was formed out of this engagement (Saldaña, 2016). New themes or sub-texts that arose through in vivo analysis of the transcript were added as categories or codes respectively and compared across the transcript to detect if they exposed new insights specific to the PcPI not previously detected in the literature, given the limited scholarship published regarding the maintenance of digital twins in the O&G sector (Cameron et al., 2018). The focus group session was comprised of practitioners representing the following corporate business areas: enterprise information management, enterprise facilities engineering, regional (including international) strategic business units, field engineering, information technology architecture, digital innovation, major capital projects information technology (IT), contract administration, and facility operations. Facilitated discussions were ad hoc but centered on determining the current state of OC for storage and management of 3D models (semi-structured design data) since most of the firm's operational content management systems and processes were designed for 2D documentation (unstructured information repositories).

Generalizability of Findings: comparative analysis

To ensure external validity to aid in generalizability of the findings, archival analysis was used to complement the "what" element in RQ2. Yin (2018) recommends that documentation for case analysis can include articles, mass media releases, internet content, letters, agendas, reports, or records of meetings if the researcher factors in bias and tests for validity. Yin further recommends comparative analysis for external validity in another case with similar subjects (e.g., subject matter experts in another organization within the same industry). He contends that for case studies, "the most important use of documentation is to corroborate and augment evidence from other sources" (Yin, 2018, p. 115). However, Maxwell (2013) cautions that "the value of a qualitative study

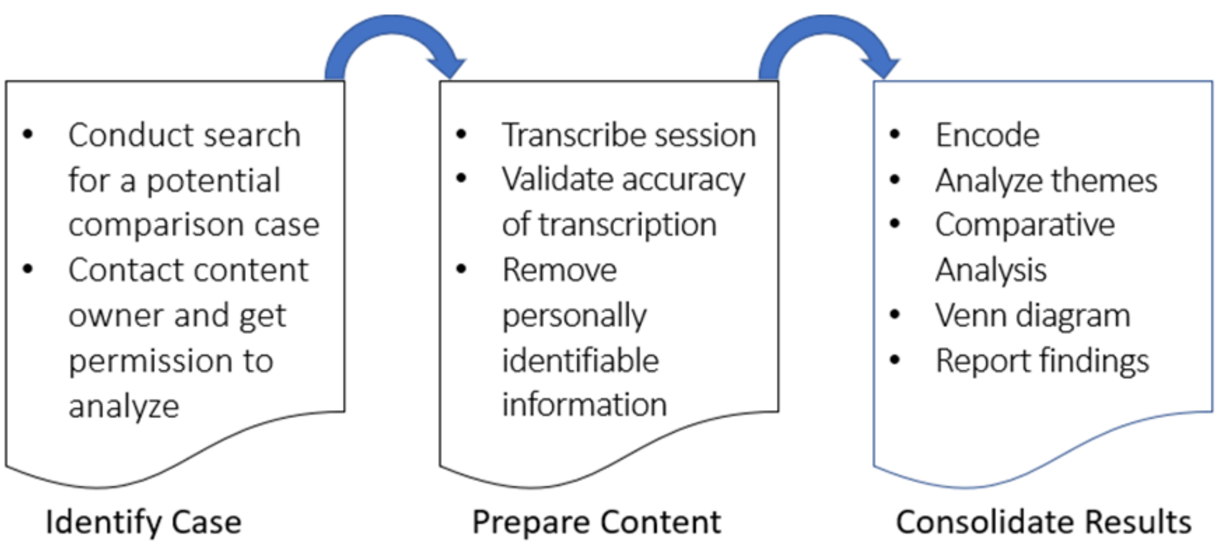

Figure 5. Comparative Analysis Plan

may depend on its lack of external generalizability" (p. 137). Maxwell's caution does not assert findings that demonstrate external validity are not meaningful, but they may not help the researcher formulate a unique theory that may not apply under different circumstances. With this admonition in mind, the researcher tested for external validity through comparative analysis.

Thus, comparative analysis for the exploratory case includes review of documentation from a project commissioned by USPI-NL, an industry standards organization, as the Facility Lifecycle 3D Model Standard (FL3DMS). This project set out to document the business case for implementing a new standard for maintaining 3D models throughout the facility lifecycle (USPI-NL, 2020). The specific content chosen for analysis was an audio recording and the resulting transcript of a business case analysis kickoff meeting with key stakeholders (SMEs from major O&G firms, Vendors, Suppliers, and contractors) recorded in August 2020. Note that the researcher gained access to the archives of the FL3DMS project through a contact at the O&G firm in the initial case study. The director of USPI-NL agreed that their business case development efforts could benefit from the researcher's external perspective to help ensure they were accurately documenting the informing value of 3D models.

As shown in Figure 5, the results from coding the internal firm's focus group session were compared side-by-side to coding and narrative analysis of the kickoff meeting transcript. Insights from analysis of the transcript of this recording are included with Appendix 1. The researcher initially coded for the same themes, categories, and codes to compare them against the findings from the exploratory case study transcript. Nine new themes emerged during the analysis, and a second coding pass through the exploratory case study transcript was conducted to assess whether those themes were present, but not detected in the first pass; four of these themes were found in the exploratory case study transcript, and five were unique to the kickoff meeting transcript. Each subsequent pass through both transcripts (until saturation was reached) served as a comprehensive refinement of the overall themes and findings expressed in the final report and other artifacts.

Results

The analysis (included as Appendices 1 and 2) demonstrates how the convergence of recent technology improvements and increased awareness of information asset value presents a strong use case for greater investment in information assets and proposed opportunities for how the organization studied could grow OC to maintain accurate digital twins. For example, internal findings suggest that the organization should intentionally share lessons learned, best practices, and opportunities to collaborate with other business units while improving visibility of corporate sponsored digital twin research and development efforts. To validate generalizability of findings, analysis of an internal focus group discussion was compared to qualitative analysis results of a kickoff meeting transcript for an international industry organization developing a standard and exploring the business case for investment in maintenance of 3D models throughout the facility lifecycle (USPI-NL, 2020).

Comparative Analysis: evidence of external validity

In the exploratory and external case study transcripts, the subject matter experts discussed challenges getting operations to invest in maintaining 3D CAD model content from the project context. There were a few examples where operations had initiated a level 0 digital twin from photogrammetry or laser scan point cloud data. The focus group indicated that several efforts were underway to develop an 'engineering portal' for linking asset register (tag data for facility systems) 2D technical drawings and data sheets. Issues incorporating 3D CAD models into the portal included data that was not maintained as part of the change management process, so the information was not reliable; often, the 3D model was not as built before the project team or contractor that created it had demobilized.

In the industry standards group session, many of the organizations represented indicated that they rely upon contractors to maintain the 3D Model. There was a perception that contractors had to have their own version of an accurate 3D model to support their technical engineering activities for the owner-operator. They asserted that it probably provided the contractor who designed the facility a competitive advantage when bidding for brownfield and MoC work in the operational context as they would have a better tool for estimating work packages and avoiding spatial relationship conflicts that may not be apparent in 2D drawings.

When combined as a theme, the need for better specifications/standards was the most frequently mentioned requirement to nurture development of OC to maintain digital twins (3D models). This result supports the premise the FL3DMS project is undertaking as it has developed a standard and are actively defining the business case for implementing the data standard (open architecture) as well as the use cases for a full facility lifecycle approach to maintenance of the model. There was overall agreement between the two transcripts in terms of tone, strategic direction, frustration with the status quo, and general desire for improvement. The uncertainty and complexity firms in this sector face demands a unified response as calls for digital transforma-

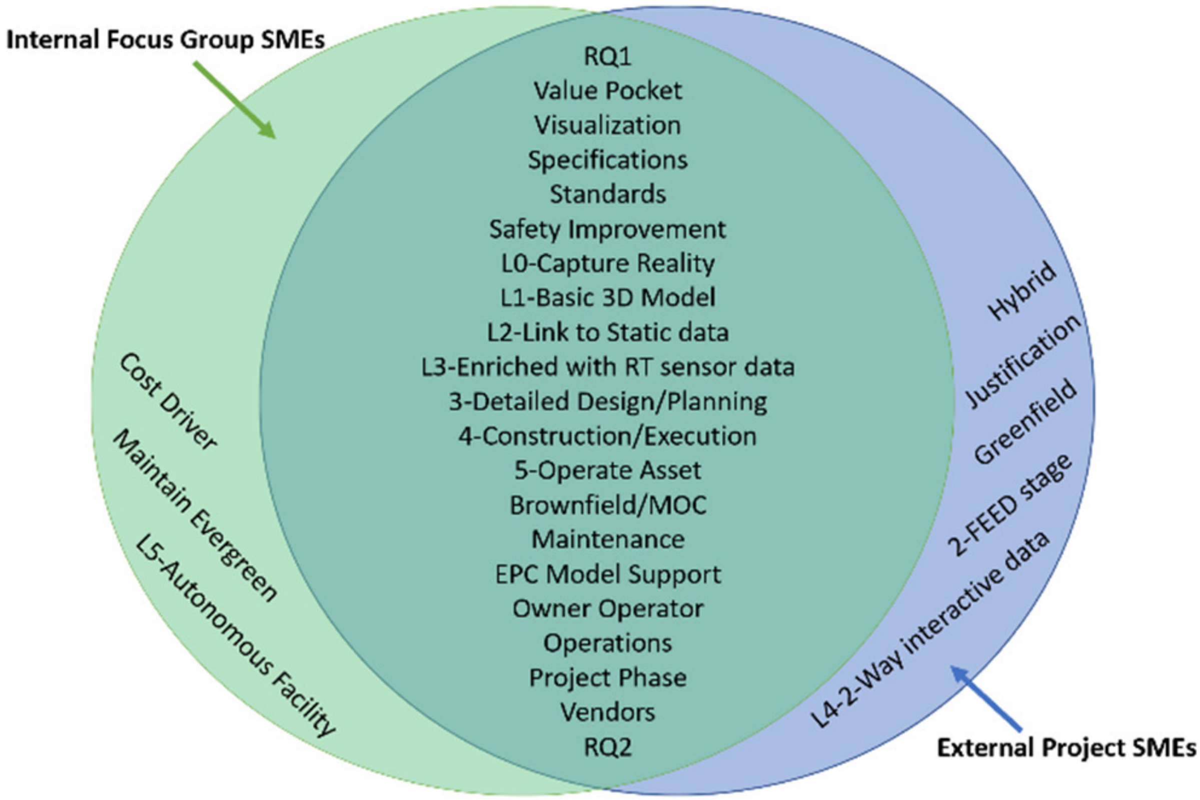

Figure 6. Venn diagram showing intersection of key themes identified by coding transcript of internal case study conducted in 2019 vs. FL3DMS project kickoff session recorded in 2020

tion echo through board rooms and out to industry stakeholders up and down the value chain, particularly owner-operator organizations hit hard by recent commodity price volatility (Dickson, 2020)

Two recorded teleconference gatherings of SMEs within the same industry were independently initiated to discuss the need for maintaining 3D models of complex process facilities. They were hosted and facilitated under completely unique circumstances; however, the questions raised, the topics discussed, and the outcomes from transcript coding analysis of each indicated high correlation of the key themes listed and illustrated in the large intersection area of the Venn diagram in Figure 6. The gatherings also suggested consistent approaches to mitigate the legacy challenges that information managers across the O&G sector have faced with ensuring that this key source of insight into facility maintenance, operation, and eventual retirement is trusted to inform decisions throughout the facility lifecycle. Figure 7 presents this data from another perspective to show how the majority (over 72%) of the themes discovered during the analysis were shared by both groups.

The themes analyzed in the two cases were categorized by topics and the frequency the theme appeared in the coded transcript was ranked within the topic for each case. Three of the eight categories explored had 100% agreement with respect to the relative rankings of the responses within each case. The two that did not align were interesting because they accurately reflect the contextual differences between the stated objectives of the two meeting sessions. Figure 8 is a screen clip from a spreadsheet used to analyze topical fidelity between the two case studies. Appendix 2 discusses the differences in each of these categories and the relative rankings in greater detail.

Findings

RQ1 asks, How do Oil & Gas industry experts perceive the need to maintain a digital twin of complex process facilities throughout the asset lifecycle? The transcripts from each session and the coding results were in full agreement that the time has arrived when the O&G sector is reaching a tipping point where demand for insights from digital twins is highlighting the gap in the ongoing maintenance of 3D visualizations after the project that created them has demobilized. Experts in both transcripts agreed that efforts to recreate them as needed and maintain them evergreen has met with mixed results when firms in this sector attempt to do so on a local, facility by facility basis. Industry or corporate standards

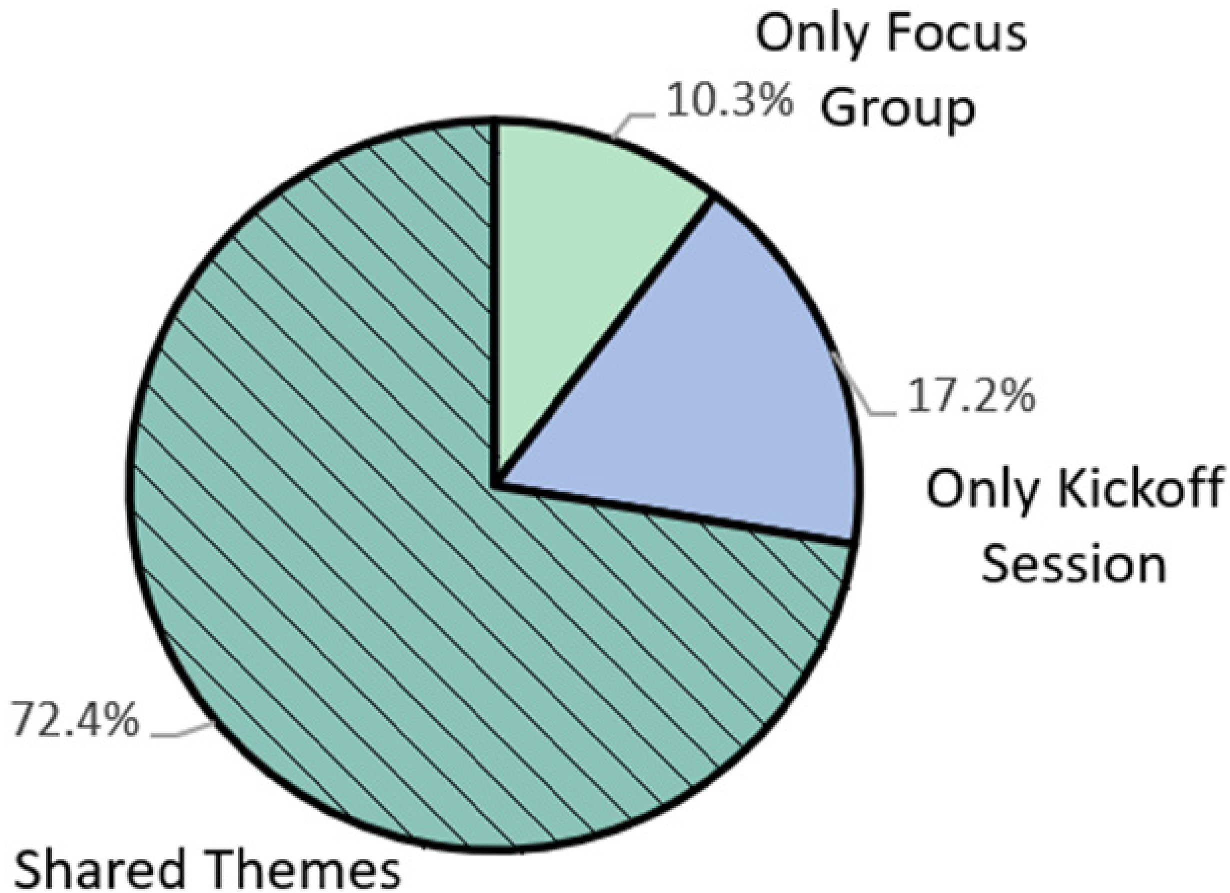

Figure 7. Themes shared by both groups vs. only in each group

Explored Categories	Topical Fidelity
Research Questions	100%
Stakeholders	100%
Organizational Capability Responsibility	100%
Project Type	67%
Business Case Alignment	25%
Maturity Levels	17%
Phase	0%
Digital Organizational Capability	0%

Figure 8. Relative ranking agreement of case theme frequency by category

governance or intervention may help the business case to maintain digital twins alignment with the perceived need to do so.

RQ2 takes this line of inquiry a bit deeper by asking, What insights can be acquired from examples of how 3D models of complex facilities are managed in the Oil & Gas sector after these assets are handed over to operations? This question seeks insights from O&G sector use cases that stem from examples of past 3D model management to help fill some of the cross-silo informing gaps that have traditionally hindered adoption of a full facility lifecycle management strategy. The two case studies outline instances where latent efforts to manage 3D models in the operational context exist, but were unknown to other participants in the session (see Table 1). The act of participating in the discussion sessions in both cases created solidarity regarding this subject matter, engendering a sense that these experiences were part of a bigger story that merited greater transparency and further investigation.

Discussion

The experts participating in the exploratory study session expressed concerns that there are diverse ways that organizations use 3D models during the operational context. One facilities engineering (FE) expert in the exploratory case study focus group discussion stated,

I have had an FE manager tell me recently, "I'm going to add a new pump [to a process facility], so I am going to model just a small portion of the facility and then do my project and move on". So, it's not necessarily an actual model of the facility; it is just a model of a portion of the facility to do the project. That is a very different model from maintaining a full facility 3D model as a digital twin ... And so, I had to ask the manager "Do you expect this model to be exactly what you have in the field? or kind of close? or just [updated] for a certain project?" … There is a mix of models out there for the same facility at various levels of accuracy, some created by contractors, others in house, and others a bit of a hybrid mix of both (transcript of IMCOP session, 2019).

This sentiment was echoed by the experts in the kickoff session with the industry standards organization. For example, a digital innovation manager for her O&G firm's global projects organization commented,

Within operations, we have essentially three [stakeholder groups – upstream, downstream, midstream] ... and there is not alignment necessarily between them on what the value of a 3D model is for their different business units. [There is no] centralized [standard] for 3D models in order to enable their use in these assets… We have a number of business units in chemicals and refining that are quite old, so they don't have native 3D models... [We asked them,] "Do your use cases have value, and do we want to generate them through laser scanning or retroactive build of the 3D model?" [We also asked,] "What kind of capabilities do we need to meet those use cases?" … But we haven't necessarily gotten to conclusions on sustainment, capture, or 3D model value cases yet, so. But we're in progress (transcript of FL3DMS kickoff session, 2020).

Although these two perspectives seem to support the need for maintaining 3D models, the opinions of two people and their explanations about their stakeholders' needs may not represent the entire O&G sector. However, by looking closer at the 69 statements in the two cases coded to RQ1 (expert perceptions of need to maintain digital twin) as a theme (more than any other code), a more complete picture comes into focus.

One engineer with over 35 years of experience in the process industry, most of it working for a major capital projects contractor, stated that the biggest chal-

Table 1. Examples of 3D Model Management in Operations Context

Source of 3D Model	Insights regarding scope of use in operational context
Design stage of greenfield projects	**Field Operations did not have the OC to manage models (>12 instances)** **Models resided on an on-premises server at the corporate central office** **No access to field personnel provided (nor aware the repository existed)** **Models not connected to field MoC process – project archive only**
Brownfield modification of a complex facility	**Model created from a laser scan for planning a brownfield project** **Project canceled, model was not maintained evergreen** **Design model was archived/never handed over from EPC to operations**
Design stage of a single modern facility	**Model developed as digital twin – connected to sensor data and asset info** **Operations tracked locally, but no sharing/visibility outside of that asset**
Execution stage / As laid survey	**Pipeline 3D model created from photogrammetry and laser scan after construction – used for maintenance tracking and drone guidance**

lenge he faces is how to efficiently get the digital twin they create in the project context transferred across to the operator, implying that the demand and process is not there. The facilitator then posed the following question to digital domain experts at two of the largest owner-operator O&G companies in the world, "Are the ambitions [of maintaining a digital twin] mainly still related to the projects? Or are they also related to the operational phase already?" They responded, almost in unison, "It's both!" They laughed, and one continued, "It's actually heavily pushed by operations, but obviously, in projects as well, so starting projects, but moving on with a digital twin into the operate phase" (transcript of FL3DMS kickoff session, 2020).

The facilitator prompted the one who had stopped speaking to listen to her counterpart's response, "I believe you wanted to say something else?" She graciously replied, "No, I think we're all agreeing, I was just saying, definitely full lifecycle" (transcript of FL3DMS kickoff session, 2020). When later asked a follow up question as to whether her firm's digital twin ambitions in operations were only on newer facilities (or did they include other legacy assets), she responded emphatically,

I have received very similar feedback on what they would use the 3D model for. Obviously, the assets are on a different time scale; all our production units are primarily modern, all of our refining and manufacturing sites are primarily old. So, the tools that they can use today vary significantly. But when we ask them what they would do if they had a 3D model, and to envision what kind of things they would like to be able to do, they are very much aligned. I haven't heard different stories (transcript of FL3DMS kickoff session, 2020).

The term 'digital twin' was often misunderstood, and many of the SMEs in both transcripts expressed a tendency to avoid using it with their stakeholders because it has so many different connotations depending on the context and digital twin maturity level

A lengthy discussion ensued where each of the twelve participants on the call chimed in and echoed the need for full lifecycle management of 3D models. A few mentioned how connectivity to other data sources to reach what would be a higher level of digital twin maturity was needed before it would provide meaningful insight, but all agreed that it was a gateway to informing that needed standards and better stewardship throughout the facility lifecycle to achieve the latent value potential they knew was possible, but just out of reach of many owner-operators in the O&G sector. Contractor firms seemed to take maintenance of the model more seriously as they saw it as a competitive advantage in bidding for maintenance and brownfield project work, but they all agreed that OC to maintain the 3D model has not typically been prioritized in the past (transcript of FL3DMS kickoff session, 2020).

A similar conversation occurred in the exploratory case focus group discussion. An FE expert stated that whenever he receives a 3D model from a project, it makes a lot of sense to maintain it,

As [BD] stated, a lot of times we threw it away because we didn't see the value in it, and 3 to 5 years later were seeing [how much we miss it]-- once the projects handover the data, they don't necessarily hand over all the data, they just hand over the critical PSI, but there are engineers that say, "Well, this is nice to have, I would like to-- even if the model is not up to date, it's good to look at, because it is probably going to be 80 - 90% up to date." The facilities don't drastically change. So, it is easier to maintain them once you create them. But it is millions of dollars to create it in the operations [context] vs. hundreds of thousands [of dollars] to maintain it (transcript of IMCOP session, 2019)

He then asked, "Do you use it in your business process to get the value out of it?" (transcript of IMCOP session, 2019). He indicated that a lot of the business units update drawings and documents with "redlines", and they may have paper files that they keep up to date. He noted that asking field personnel to do that level of upkeep on a 3D model would be an even greater challenge.

This dialog demonstrates that interest exists, but the resources at that point in time seemed to be lacking at the operating expense level. A discussion then ensued about whether it was due to a lack of OC or corporate funding for that effort. The manager of the firm's 'smart facilities' program spoke up, proclaiming,

If there are business units [(BUs)] going through that process right now and want to be able to do more with their 3D models during 'operate and maintain,' we do have some funding from an R&D corporate funding perspective to try and support BUs in that process and I would be happy to try and support some of those activities (transcript of IMCOP session, 2019).

This bold statement from a key decision maker with a budget demonstrated the value of simply starting the conversation in a collaborative setting. The statement led to follow up engagements and tangible progress in the effort to bring the importance of this line of research inquiry to the forefront, even during the challenging economic environment the firm and the industry would face in the months ahead.

Other examples from the exploratory case study indicate there has been a breakdown in perceived value of investment in lifecycle management of models after the projects that created them has demobilized. The findings from industry analysis indicate that maintenance of 3D models improves the likelihood that the firm will be able to leverage innovations, such as an engineering 'portal' in the exploratory case study (McNair, 2021). The FE expert said that for one business unit, "We're getting the 3D models they have, and tying some of that real-time data to it as well as well as the portal. We're building all that and trying to see how that will work, but a lot of it requires a 3D model." He also indicated that "you would be behind the 8-ball" if you tried to do that with just visual capture tools such as laser scans or photogrammetry (transcript of IMCOP session, 2019). This perspective supports the premise that a localized effort to move from level 0 to a level 3 digital twin maturity would be less complicated if the starting point is a 3D model (level 1) and then incrementally integrating more data into it to achieve higher stages of maturity.

The term 'digital twin' was often misunderstood, and many of the SMEs in both transcripts expressed a tendency to avoid using it with their stakeholders because it has so many different connotations depending on the context and digital twin maturity level (see Figure 3). As shown in Appendix 2.2, most SMEs acknowledged an operational need for asset visualization (level 0) while others only referred to a stand-alone 3D model (level 1). A few SMEs mentioned the model or laser scan connected to static data as a digital twin (level 2), and some even had connected their model to sensor or process information (PI) data servers (level 3). One of the SMEs stated he had attained a bi-directional digital twin with remote control capability and some automation of decision making (level 4), but none at the time of the call indicated a fully autonomous facility (level 5) was part of their aspirations for digital twins. Note: The researcher found documentation in a later follow up conversation stating one participant who joined the call after this line of inquiry concluded is employed by an O&G firm that has deployed a level 5 digital twin of a fully automated facility in one business unit, but it has not yet been integrated to inform enterprise level decisions, so its benefits are localized. Existing (legacy brownfield) assets are highly unlikely to reach level 5 digital twin maturity unless they were designed with that end in mind.

Many organizations have found that evolving a 3D model to at least a level 2 digital twin has been shown to pay dividends in management of key operational decisions. For example, the FL3DMS kickoff session mentioned several cases where digital twin technology is improving enterprise understanding of the asset and enabling engineers and contractors to make better estimates on brownfield projects that are trending as a more common way to extend or optimize the useful life of existing assets, given how current economic uncertainty and external pressure to decarbonize O&G investments are constraining resources that would otherwise have gone towards greenfield developments projects in potentially more complex operating conditions (transcript of FL3DMS kickoff session, 2020).

As shown in Table 1, there were latent examples where digital twins were being used in the operational phase of the asset lifecycle (after the project context) but not consistently across business and functional silos. Benefits were localized and not shared widely, often limiting value to individual facility decision support. The exploratory case study revealed enough anecdotal evidence of localized success stories and missed opportunities to strongly support the recommendation to conduct an in-depth analysis of prior project archives. The participants agreed that it would yield valuable insights that could enhance the use case for better stewardship of 3D CAD models and other semi-structured data (such as 'smart' Instrumentation or Electrical design databases) into the operational context.

The industry session corroborated the premise of localized perspectives when one of the participants from a field engineering office of a major O&G firm stated that the organization seeks a standard that will mitigate this gap. "[Now, whenever] we want to add something [to a facility asset], whether it's about permitting, isolation, identification, etc. We look… not necessarily in the 3D model specification space,

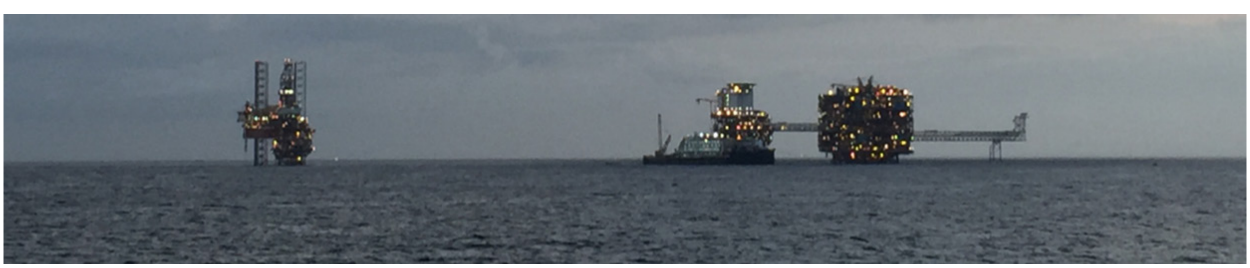

Figure 9. A drill rig attached to a completed wellhead platform on left; production complex under construction on the right

we look at this in what we call the 3D visualization space" (transcript of FL3DMS kickoff session, 2020).

During the internal group discussion, one member raised an example of a 3D design model used during the transfer to operations to help design, test, build, and deploy an early production system. Its use resulted in significant value realization plus validation of the reservoir's production forecast nearly 12 months ahead of schedule. He stated that the effort to keep the 3D model current beyond the design stage and into the construction and commissioning phase allowed engineers to creatively evaluate the feasibility of using a temporary drilling rig tethered to a new wellhead platform to direct oil on-shore from initial wells for processing (with minor modifications) even though the production platform was over a year away from readiness for processing oil and gas off-shore (see Figure 9).

The irony at the time of the meeting was that the final as-built version of the 3D model for these same assets had not been delivered, so the opportunity to exploit its value for the upcoming maintenance turnaround planning activity was moot until the model was finally delivered by the contractor to the owner-operator engineering team 15 months later.

Reflection on the results from the exploratory case study included completion of action items and ensuring that the key participants responsible for progressing the conversation had access to the transcript, recording and analysis so that they would be better equipped for follow up on the recommendations, and insights that it provided. Near the end of the focus group session, it was revealed that the firm's central Major Capital Projects IT team had created a repository of past project 3D models of selected complex facilities for analytical purposes. However, the data quality for operational use was suspect since the content had not been updated since the design phase of the projects in many cases. The fact that this data was available for analysis and potential integration into operational systems was news to many of the field operations and facilities engineering personnel on the call.

Although there was interest in field personnel to get licenses and network access to exploit the data, a process to do so had not yet been created and policy regarding care, custody, and control of the content had not yet been developed. Absent a clear strategy to mitigate this gap only highlighted the limited organizational capability in the business units to host this content and make it available to other stakeholders in the organization. Training in how to use the 'portal' was also limited. The risk of misinformation (potential decisions made from inaccurate or incomplete data) was high and thus, an interesting informing challenge surfaced meriting follow up discussions with interested parties to develop an enterprise 3D model hosting strategy. Thus, the researcher shared this finding with key decision makers in the firm's digital transformation team as an example of how a centralized effort to support portal development would foster greater stewardship of this valuable information as a company asset.

Directions for Future Research

The high correlation of themes in common between the internal focus group and the external kickoff session highlights the need for further investigation and greater transparency across large multinational organizations regarding the scope of the problem of practice documented in this article as well as the overall struggle to manage valuable information assets. As future design science research grows out of this effort, the researcher will use "elaborated Action Design Research (eADR)" (Mullarkey & Hevner, 2019, p. 8) to assess value pockets for implementation of standards and help USPI-NL influence their consortium of owner-operators, contractors, suppliers, and vendors as they promote the process industry's adaptation to the transformative technology known as digital twins. The report of this research is the third installment of a trilogy of research highlighted in the following research roadmap (Figure 10).

Limitations

In late 2019, shortly after the internal publication of initial findings and recommendations to the exploratory case study sponsors, the firm announced an enterprise-wide digital transformation. This diversion from status quo was followed in early 2020 with an unforeseen oil supply glut resulting from a price control dispute between Russia and Saudi Arabia coupled with the unprecedented global impact of reduced energy demand as most industrial nations shutdown their economies as a reaction to the COVID-19 pandemic. The firm adjusted quickly with a telework mandate directly impacting the researcher's access to most of our study participants. Although the pressure to cut costs, cancel non-essential activities, and make tangible preparations for a prolonged disruption to normal activities amplified the distractions the firm faced, SuperMajor never compromised their core values to protect people and the environment while continuing safe O&G operations around the world.

Another limitation is the fact that opinions of the selected experts within the organizations studied may be biased towards digital twin adoption given their participation in either of the two ad hoc discussions. The topic for each session was focused on ways to encourage digital twin or 3D model lifecycle management adoption, rather than random perspectives of experts from the O&G sector at large. Future research may consider a broader industry expert survey to determine if there are perspectives that might

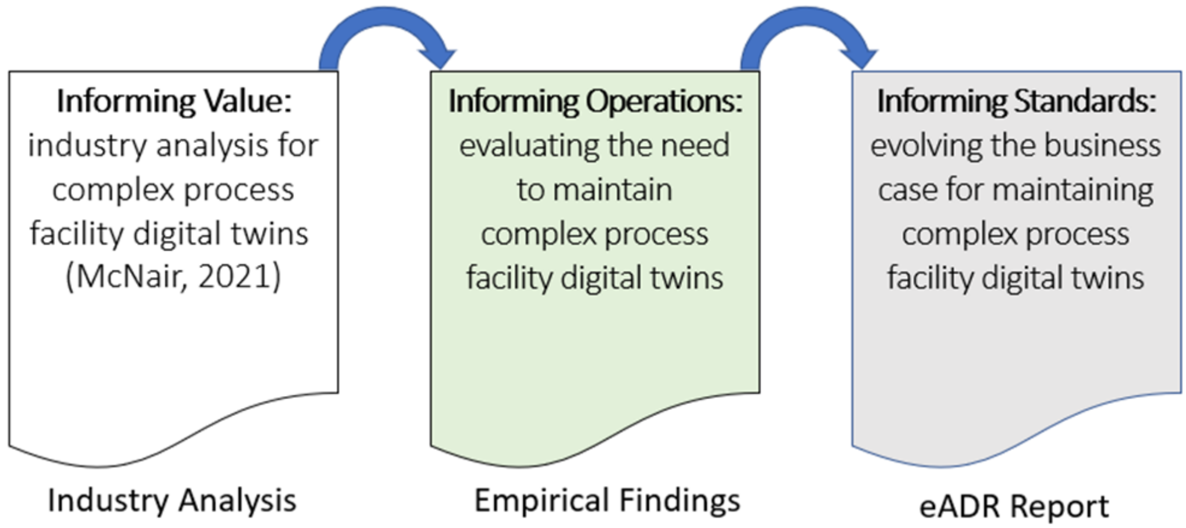

Figure 10. Research Trilogy Roadmap

present impediments to adoption that might need to be overcome through behavioral change management strategies or industry workforce engagement efforts.

Conclusions

The literature reviewed indicates firms that aspire to meet the technology demands and organizational capability required for Industry 4.0 innovations, must maintain digital twins of complex facility assets. The researcher worked collaboratively with a firm's SMEs and confirmed findings of the exploratory study with external industry experts. The exploratory study findings include:

- Experts agree that there is expected informing value in maintaining accurate 3D CAD models throughout the facility lifecycle
- Efforts to build organizational capability already existed within the firm, it simply lacked transparency (visibility) across organizational and business function silos

Like we observed in Paula's situation, when decision makers did not have access to the full lifecycle informing value of a 3D model of their facility assets to operations, handover of facility information at project closeout typically only prioritized the minimal format required for safe operations and physical maintenance based on past experience or regulatory requirements (McNair, 2021). However, this research validated that facilities engineering design tools, such as the 3D CAD model and 'smart' design databases, were frequently archived and rarely maintained after construction completion and facilities began day-to-day operation. In Paula's case, the complex facility construction contract called for an as-built 3D model, however its ultimate handover was not prioritized until several years after the facility was in full operation. This created a technical debt backlog of changes since start up that needed to be addressed before the model could be used for decisions related to 5-year maintenance turnaround planning. Even if the 3D model was provided by contractors, organizational capability and operational MoC processes often only focus on maintaining accurate process safety related content.

These findings alone will not transform the way information is managed at any one firm, but as a catalyst for greater cross-silo engagement, it is evident that there is value in identifying and illuminating latent lessons from a greater understanding of how information has been managed in prior cases. As further innovation in the digital space is recognized as a strategic imperative, scarce resources will be allocated for further investment in solutions such as those proposed by this research effort. Key contributions from this research include:

- The concept of digital twins is now better understood within the exploratory study firm influencing how its new organization manages project information handover to operations
    - Projects organization opened up limited access to central repository of 3D CAD models
    - Use of 3D model in planning stage of operations and maintenance gains higher visibility
    - Greater stakeholder visibility into corporate sponsored programs to research and develop full facility lifecycle digital twins as a valuable business asset
- The exploratory research documented the need for a deeper understanding of the value of maintaining 3D design models as the foundation for digital twins across the enterprise

- The internally expressed sentiments and findings in the exploratory case study achieved external validation with analysis of industry SMEs facing a similar decision point

Reflections and Next Steps

The literature reviews showed a rapidly growing global trend within the O&G sector to evolve its physical and digital facility assets by adapting them to accommodate the innovative technologies that will be required in the future. As firms transform in preparation for Industry 4.0, they must strategically plan and take actions to grow OC to support the dynamic nature of the modern industrial landscape.

Complex systems interact with various elements across the enterprise. Insights from examples such as those explored in this case study, regardless of whether they are internal or external, succeed or fail, can inform decisions and provide a means to influence outcomes with greater efficiency. The USPI-NL community is a fertile ground for such follow up research, and their commitment to influence the industry to invest in lifecycle management of digital twins as evidenced by the business case project kick-off discussion that demonstrates the moment of an "information cascade" (Gill, 2008, p. 318) is at hand as the industry reaches a "tipping point" (p. 312) in adoption of full facility lifecycle digital twins.

Primary research for this article focused on the way a firm in the O&G sector struggled to maintain accurate 3D CAD models of facility assets that were created during the design phase of complex facility projects. This effort highlighted an increasing demand for growing organizational capability to support digital twins in the operational context. With this insight, further study is needed to determine how these perceptions and other use cases of successes or failures could inform future decisions regarding the retention and maintenance of 3D models as foundational digital twins beyond the project context and into the operational context through asset retirement.

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Review

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

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Authors

William Randell McNair, D.B.A. is a 2021 graduate of the University of South Florida, Doctor of Business Administration Program in Information Systems Management. He is an author and practitioner-scholar researching stewardship of insights from information assets such as digital twins, engineering databases, and document management systems. A dedicated, compassionate, and innovative consultant with a consistent track record of building and maintaining influential relationships. Experience includes over 32 years in the oil and gas sector communicating effectively with all organizational levels across diverse cultural backgrounds to achieve exceptional results and improve productivity and sustainability in complex systems environments.

Appendix A – Raw Analysis: Session with SuperMajor SMEs

Initial analysis of the focus group session with subject matter experts (SMEs) in a large O&G firm (anonymized as "SuperMajor") is provided as Figure A1 below. To better understand how digital twins are managed at the firm the researcher investigated from the context of these two basic questions: Who maintains the models and where is digital twin data stored?

As screen capture (Figure A2) from QDA Miner of a table of coding segments shows, the Engineering Procurement Contractor (EPC) or any external contractor or out-source provider currently provide the majority of the 3D Model support at SuperMajor. Internal (owner-operator) organizations such as business units, project personnel, and engineering support teams provide or plan to provide that support in the future. There is some interest in a hybrid combination of internal and external maintenance of the 3D model depending on the use case. Note, because this category focused on Organization Capability (OC), some of the comments reflect aspiration rather than current state.

A firm's organizational capability (OC) regarding maintenance of digital twins is dependent on systems infrastructure in place to provide data sources for them. The responses above show that Document Management Systems and the level-2 maturity digital twin at SuperMajor coded as a Digital Twin Portal were

Category	/	Case	Text
EPC Model Support			
OC Responsibility		1	theirs is kind or unique where they have the EPC (engineering procurement contractor) manage the model
OC Responsibility		1	BU was using 3D models, because that is a deliverable from engineering contractor these days
OC Responsibility		1	the contractor comes into D2 to update the drawing and they don't pull it off of the net
OC Responsibility		1	third-party contract engineering
OC Responsibility		1	"Bring your own... and we will just integrate into our business
OC Responsibility		1	contractor what tools that they should be using
OC Responsibility		1	and give those over to the contractors
Hybrid			
OC Responsibility		1	is a mixture of both.
Owner Operator			
OC Responsibility		1	use in-house engineering,
OC Responsibility		1	committing to leveraging 3D models in that context where it becomes part of you the fabric of how you maintain and operate a facil
OC Responsibility		1	comes to having organizational capability in the business unit to catch and maintain it
OC Responsibility		1	not seeing that broad commitment yet to standing up maybe to the internal resources required to do it.
OC Responsibility		1	door in the 2D world and a foot in the door in a 3D world, and they're going to be asked to commit to both, and sustain/maintain both
OC Responsibility		1	the business units do necessarily want to figure out how to do it for themselves. They just want to know what it is they need to do. Some of them have that level of organizational capability to do it themselves

Figure A1. Who Maintains 3D Models at SuperMajor? Screen capture of QDA Minor analysis showing detailed text extracts by category for case 1

the two most mentioned repositories for models, tag, and unstructured engineering technical content. Asset Registers needed to fully realize level-2 maturity were only mentioned in passing. Point clouds are mentioned another source, frequently generated by brownfield projects seeking to modify existing assets.

Code		Case	Text
Systems			
Asset Register		1	on their tag to document relationships, for example --and their tagging information-- creating asset registers and such. This would just be a natural extension of that.
Digital Twin Portal		1	e the Aveva portal with all of the document… and potentially pulling the Pi Data as well. So you have that that living, breathing…
Digital Twin Portal		1	well as well as the (Aveva) portal. We're building all that we are trying to see how that will work, but a lot of it requires a 3D model, you would kind of be "behind the 8-ball".
Digital Twin Portal		1	nd hopefully Aveva can openly
Digital Twin Portal		1	with the Aveva portal. At this point we're not necessarily saying that you have to use Aveva. We're looking at ways to bring in all of the software -- be it CADworx, SmartPlant… into the Aveva portal. So, w
Digital Twin Portal		1	u have to use Aveva. We're looking at ways to bring in all of the software -- be it CADworx, SmartPlant… into the Aveva portal.
Digital Twin Portal		1	Aveva
Digital Twin Portal		1	navisworks, and Aveva and AutoCAD and Truview, and all these…
Digital Twin Portal		1	whether its AvevaNet or some other way to make use of those 3D models
Digital Twin Portal		1	e Aveva LFM that can integrate the 3D model and the laser scan
Digital Twin Portal		1	it to things like AvevaNet, there are some OC aspects that the BUs are going to need to address. I think BU3 is a good model for maybe how we need to do that and were trying to learn from the ETC side, what's involved in doing that
Document Management		1	from document-based syste
Document Management		1	AutoCAD plant 3D managing that inside D2,
Document Management		1	D2 to update the drawing
Document Management		1	them in a document system? and How would that work
Document Management		1	o that is the new EDMS (electronic document management system) And we are having the discussions-- one of the issues is not all business units create 3D models and all of them use
Document Management		1	D2 --like a SmartPlant P&ID file from within the D2 environment, make modifications and then re-save it into D2. I think you have to pull it off, open it up in SmartPlant P&ID make the modifications and then reissue it into D2.
Document Management		1	files into D2 somewhere on our cloud and store it and not necessarily and give those over to the contractors --that would be another change that we're seeing
Document Management		1	hese document management systems is to keep it in house, in our network and they update it real-time from our cloud.
Document Management		1	we have it in Documentum. And we have it in Documentum because we know we are in progress, we are trying to find a new system of record for that so that is why we have those in Documentum (GDS).
Document Management		1	in Documentum. And we have it in Documentum because we know we are in progre
Document Management		1	as far as D2)… I don't know if D2 can effectively
Document Management		1	] …Documentum, I think that is what you are saying? No, I think this would be a new one because not everybody is a participant of that current D2 Teams site.
Document Management		1	it. So, one of the places we are looking at is the document management system,
Document Management		1	document-based system to a data-based system and you know
Photogrammetry/Point Cloud		1	and done point clouds, maybe t
Photogrammetry/Point Cloud		1	big arguments is that technologies like photogrammetry here at SuperMajor is
Photogrammetry/Point Cloud		1	can pay a vendor to fly a drone around it and have an accurate 3D Picture of what I got."
Photogrammetry/Point Cloud		1	dated to point cloud from which you can make the model as you need, that is the way to go.
Photogrammetry/Point Cloud		1	e Aveva LFM that can integrate the 3D model and the laser scan

Figure A2. What Systems contain Digital Twin data at SuperMajor? Screen capture of QDA Minor analysis showing detailed text extracts by code for case 1

Appendix B – Comparative Analysis: SuperMajor Session vs. Kickoff Meeting with SMEs

This analysis includes screen captures from a spreadsheet generated with results extracted from QDA Miner code frequency reports of qualitative data analysis done using in vivo and descriptive coding to detect themes and categories that explore two research questions. Relative frequency of each code appearing is highlighted in green or blue according to each transcript's net results (SuperMajor/IMCOP Focus Group Session = Green, FL3DMS/External Kickoff Meeting = Blue). Figure B1 below provides a simple visual validation of whether the coded responses agreed with or contradicted the findings compared to one another. Following each graphic is a narrative describing the results.

Code	IMCOP	FL3DMS
RQ1: How do Oil & Gas industry experts perceive the need to maintain a digital twin of complex process facilities throughout the asset lifecycle?	23	46
RQ2: What insights can be acquired from examples of how 3D models of complex facilities are managed in the Oil & Gas sector after these assets are handed over to operations?	9	7

Figure B1. Frequency of Responses Related to Research Questions for Comparison

For RQ1, given the number of companies represented on the industry group discussion (FL3DMS), the relative number of mentions though higher is comparable to the number of mentions on the SuperMajor (IMCOP) session. For RQ2, given the diverse perspectives represented on the industry group discussion, the relative number of mentions though lower is comparable to the number of mentions on the individual firm session. This may be due to the team building/kickoff nature of the meeting, and less reflective of the actual perspectives of the parties represented on the video conference. As the FL3DMS call transcript was based on archival records, not facilitated by researchers with these questions in mind, it is interesting that these seven insights surfaced unprompted.

Given the number of companies represented on the industry group discussion, the relative number emphasizing of key stakeholders for 3D model maintenance though higher is comparable to the number of mentions on the individual firm session. As shown in Figure B2, operations is demonstrably important to both groups as the focus of both discussions was related to maintenance of digital twins throughout the facility lifecycle, the longest period being the operational phase. The project team as a 3D model stakeholder was mentioned almost as frequently for operations. This reinforces the premise that the project context is where the industry experts indicated has the most active use cases for digital twin content.

Code	IMCOP	FL3DMS
Operations	9	31
Project Phase	4	24
Vendors	2	7

Figure B2. Frequency selected key Stakeholders were mentioned

As shown in Figure B3, the industry group companies represented seemed to have a higher propensity to rely upon contractors to provide the OC to maintain the 3D models. SuperMajor's business units represented did however seem to support the premise that this is not a core skill for the operations engineering personnel within its organization thus mentioning it more often than supporting the 3D model in-house. There was agreement between the two transcripts on this metric where they both seemed to mention internal OC as less likely to maintain the 3D models than external parties. The Hybrid option had a very similar result, but the overall internal count reflected few instances where 3D models are currently being maintained and thus low OC within the firms represented to take on even a portion of the responsibility.

Code	IMCOP	FL3DMS
EPC Model Support	7	20
Owner Operator	6	9
Hybrid	1	3

Figure B3. Frequency with which the mode of Organizational Capability (OC) to maintain 3D models was mentioned

Ownership of the intellectual property of the 3D model itself was a question that was raised on the FL3DMS call as they pointed out that some contracts do not stipulate who owns the digital version of the physical asset prior to its completion. This contract strategy gap is particularly important in cases where transfer of custody of these electronic assets may not happen if the project never achieves final investment or the contract is cancelled. A comment on the IMCOP call from an expert was that a point cloud of a relatively new facility was generated for a proposed brownfield project but it was never passed to operations because the project was cancelled resulting in a loss of nearly $1.5 million in project expenditure on the point cloud capture, not including the international travel, visas, permitting and disruption to operations that took place while the survey was conducted. The potentially valuable insights from that project investment were never integrated into the operational environment.

Code	IMCOP	FL3DMS
Brownfield/MOC	5	3
Greenfield		8
Maintenance	3	2

Figure B4 Frequency the project type that would be a source of a 3D Model was mentioned

According to the SuperMajor experts, the source of a maintainable 3D model is more likely to be generated on a brownfield project (see Figure B4). This is primarily due to the lack of faith in the quality of a model that was never as built. The industry group on the FL3DMS meeting did not discuss brownfield situations very much during the session. Greenfield projects seem to be a popular source for maintainable 3D Models if the specifications and standards are put in place with the intention to maintain them. There is little harmony with the individual firm on this topic because they had no enterprise-wide specification for 3D model handover in 2019 when the discussion took place.

There was relative agreement between the groups that facility maintenance and turnaround activity may be a viable source for a maintainable 3D model. With more digitization of procurement systems, there were a few use cases with the visualization of procurement data that typically serves as the digital platform for computerized maintenance management systems (CMMS).

Code	IMCOP	FL3DMS
2-Front End Engineering Design	1	9
3-Detailed Design/Planning	5	19
4-Construction/Execution	6	2
5-Operate Asset	11	19
6-Asset Retirement	0	0

Figure B5. Frequency the Asset Lifecycle Phase where 3D Models are generated was mentioned

As shown in Figure B5., more of the industry group members mentioned Front End Engineering & Design (FEED) as the source of the 3D model content. This may be because of the makeup of the SuperMajor focus group not being as familiar with activity in the project phases given that they typically have not received the model from projects in the past. Detailed Design was mentioned several times as the source of the 3D Model and that harmonizes with the industry group's other responses. The fact that fewer in the industry group considered the model to be created during construction/execution stage could be more related to the backgrounds of the personnel on the call rather than the desired source of the model. Clearly, for both groups the Operate Asset phase was where the model type at the focus of the conversation would be generated given that models from legacy assets were either out of date or not handed over to operations after startup.

Neither group mentioned the need for a model in asset retirement, though it did come up in later discussions as a viable use case/value pocket because of the logistics and asset disposition for the "full lifecycle" including retirement. Of particular note based on a follow up conversation with an industry expert is the value a digital twin of a retired asset may have as an informing pathway when data is aggregated at the enterprise level. Higher order digital twins of existing and retired facilities can continue to contribute valuable lessons as source for historical data to help train an AI in conditions that may not exist in new facilities but are more likely to surface integrity and reliability risk factors in older assets as they begin to operate outside of original design parameters due to age or continuous use.

Code	IMCOP	FL3DMS
Cost Driver	18	1
Safety Improvement	2	2
Value Pocket	15	5
Visualization	5	15

Figure B6. Frequency the business case for investment in a digital twin was mentioned

As illustrated Figure B6, cost drivers for managing 3D models was a more important consideration to the business for the firm than for the industry at large. Safety improvement was equally important to both organizations. Identifying ways to derive value from the 3D model was a greater consideration to the firm than to the industry at large, though both considered it important. Though important to both, visualization of assets was less important to the SuperMajor than to the industry at large that focused on it more than any other consideration.

The industry group seemed to have more examples of photogrammetry/laser scan/point cloud-based models, though it was the second highest level of maturity for the individual firm (see Figure B7). The SuperMajor experts seemed to have much more focus on the 3D model as a standalone entity and a desire to maintain it, but the industry group that focused on standards for the 3D model saw it primarily as a bridge to higher levels of maturity. For SuperMajor, there were some examples where static data was integrated with the model via what they called the "company portal", but it was more the exception than the rule. The industry group indicated a greater interest in that as it was the second most discussed level of maturity.

The two transcripts seemed to agree that real-time sensor data was a meaningful aspiration, but it was slightly more so for SuperMajor than the industry group. SuperMajor experts mentioned only one instance of a fully interactive digital twin, while there were a few more examples in the industry group, but since there were more companies represented, this could be considered a comparable result (a slightly higher instance of this aspirational digital twin maturity level than SuperMajor). Neither group expressed an aspiration or

Code	IMCOP	FL3DMS
L0-Capture Reality	13	37
L1-Basic 3D Model	43	14
L2-Link to Static data	9	31
L3-Enriched with RT sensor data	5	3
L4-Two-Way interactive data	1	4
L5-Autonomous Facility	0	0

Figure B7. Frequency the Level of Digital Twin Maturity for the 3D Model was mentioned

Code	IMCOP	FL3DMS
Justification	0	5
Maintain Evergreen	4	1
Specifications	4	15
Standards	7	11

Figure B8. Frequency investment in OC to maintain Digital Twins were mentioned

plan to move into a fully autonomous facility environment during the discussion, though a later follow up discussion did reveal that there is at least one example within the companies represented in the industry organization that has already achieved autonomous operations.

Justifications for investment in OC was more important to the industry group than to SuperMajor experts (see Figure B8). The need to have the OC to maintain models after handover was slightly more important to SuperMajor than to the industry group. The transcript reveals that many firms represented by the industry group outsource most 3D model maintenance.

Specifications OC to maintain 3D Models was most important to the industry standards organization, though also moderately important to SuperMajor. This could be explained by the need for specifications when outsourcing OC. Standards were important to both, as it was the most frequently mentioned Digital capability for the individual firm and the second highest for the industry group. When combined, specifications and standards was the dominant theme related to investment priorities for maintaining digital twins.

Appendix C: Technical Debt Example: legacy hardcopy storage use cases at SuperMajor

The following photographs from the researcher's collection illustrate various use cases in the mid-2010's when 'SuperMajor' was beginning to challenge the need for physical storage of legacy project handover information that in many cases had already been captured in electronic form.

As shown in Figure C1, the top rack has pallets of boxed set of binders containing equipment manuals for a complex facility completed in 2003, these boxes were never opened, contents destroyed in 2016. A shipping invoice was attached to them showing they had been airfreighted and customs tariff paid at a total cost of $145,000 USD. Not pictured on the same shelf is a set of two pallets of boxes of maintenance manuals from another facility completed in 2009, also never opened. Book shelves of legacy equipment manuals dating back to 1980's stored in random order on opposite side of warehouse.

Figure C2 illustrates what happened when hard copy subsea scope documents went missing for nearly 3 years. They were found under a tarp on pallets onshore in an abandoned project laydown area while it was being cleared for demolition. Note the document binders on the left were at some point removed from the box they were in. The binders were piled directly on the pallet and were covered in mold, completely useless. This was the only hardcopy of the subsea work received for that facility. The aluminum box was later found containing fishing gear in a demobilized portable project office building that was also being razed to make room for a new drill pipe laydown area.

Figure C1. On-shore maintenance warehouse hard copy documentation storage.

Figure C2. On-shore laydown area, missing documentation discovered under tarp.

The following excerpts are from a hardcopy document hunt the researcher conducted offshore in 2012 at a facility completed in 2009. As shown in Figure C3, the dog-eared, marked-up bound document was a set of fab yard P&IDs from 2007. A spot check of the changes noted in this book found few were reflected in the final as built set saved in the onshore system of record for these documents. The justification was that these were for 'temporary MoCs' so they did not update the record versions.

The issue raised was that at least one of the temporary modifications included the introduction of sample points that were not removed and not part of the original pipe design and hydro-test specification. This finding was brought to the attention of the superintendent who ordered a complete audit of all facility PSI documentation modifications in preparation for an upcoming process hazard analysis.

Figure C4 is a clip showing documentation that was shipped with the facility when it left the fab yard that were stored floor to ceiling in the facility's recreation room. It was determined that the original facility 'library' was needed as office space, so the documents were stored "temporarily" in this recreation room but stayed there, unused for three years unsorted and not maintained. The bookshelves also compromised the crew's ability to access some of the recreation equipment.

This hardcopy data gathering effort helped the researcher recognize the risks associated with hard copy content being shipped to the facility. Rather than trusting the digital system of record, the operators had been conditioned to rely upon their own version of the truth. With rotational staff (28-days on/28-days off), this means that half the time, someone else was documenting a different version of the truth as changes took place and they may or may note share that insight with the person replacing them at the end of their rotation. This discovery and observations that this situation was not unique to this facility, region, or company led to the researcher's decade long quest to understand how to better manage information.

Figure C5 shows three rows of the second floor of on-shore base camp climate-controlled warehouse containing library of Facilities Engineering information dating back to 1960's. Note the metal containers on the left of each photo, those are special filing cabinets used to store full A1 size sheets of drawings hand-printed on vellum.

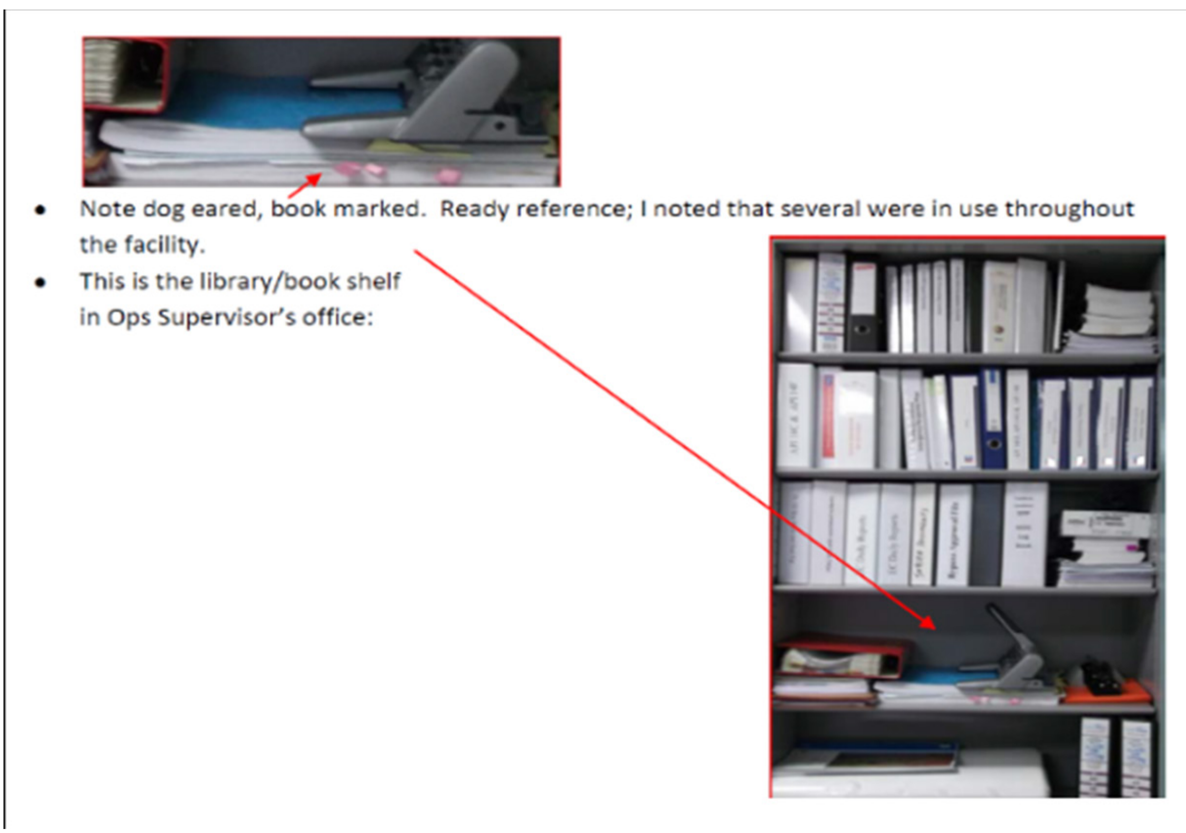

Figure C3. Documentation located in facility operations supervisor office.

Figure C4. Construction reference documents in recreation room.

Figure C5. On-shore Facilities Engineering documentation library.

Figure C6. Below the library.

Figure C7. Document Storage warehouse.

Below the grating piles of unfiled project handover documents stacked and miscellaneous boxes on the first floor as shown in Figure C6. Outside this warehouse, not pictured, was a row of ten (leaky) 20' steel containers filled with documents.

Figure C7 shows shelves of hardcopy file boxes located in a 70 million cubic foot section of a contract warehouse in the United States. It contains the archive of capital project documentation dating back to the 1930's from companies that it has acquired or merged with over the past century. Most of this content is slated to be digitized over the next few years. Current policy is to no longer receive content in hardcopy format. This location could be easily mistaken for the set used in the closing scene from the movie Raiders of the Lost Ark.