USF Muma Business Review
A publication of the Muma College of Business | University of South Florida

Volume 6, Number 1	*Industry Analysis*	15 DECEMBER 2022

Informing Value: Complex Process Facility Digital Twins

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The organizational capability of a firm to create, integrate and maintain cyber versions of complex physical systems known as Digital Twins is a key enabler for joining the 4th Industrial Revolution. This article highlights the business case for firms in the petrochemical process industry to manage digital twins as valuable business assets based on academic and business literature, webcast and live presentations, and the professional experiences of the author. A digital twin maturity model is provided to differentiate how each level of data integration contributes to informing. Three digital twin asset valuation models are introduced to illustrate how digital twins can inform value in different contexts. Findings include how knowledge is generated from digital twins, and how an informing attribute of decision making referred to here as 'insight value' can be realized from maintaining digital twins over the full asset lifecycle. Many software applications and tools have become available for firms to adopt this innovative technology; however, integration with the diverse and often siloed systems that serve as data sources have been hampered by inconsistent data governance, data exchange requirements, and interface standards. This article, the first in a series of three, explores on-going efforts to mitigate this problem of practice as interest in application of this innovative technology reaches the tipping point where industry-wide adoption drives greater efficiency and improves decision making throughout the complex facility lifecycle.

> **Digital twins of complex facilities are on-ramps to the fourth industrial revolution, informing decisions with valuable insights throughout the asset lifecycle.**

Keywords: Digital Twin, 3D Model, Oil & Gas, Process Industry, Industry 4.0, Engineering Data, Complex Facility, Information Asset Lifecycle

Reflection requires a source of illumination. Mack looked in the mirror and saw nothing; then, he turned on a light. The instant Mack flipped the switch, he was informed by what he could see. The mirror was not Mack, but it really looked like him; it even moved like him. The mirror was valueless to Mack on the wall of a dark room, but with a light on, the reflection offered him instantaneous insight. The moment of observation allowed Mack to assess his readiness; it provided valuable real-time decision support. Mack may have been able to obtain this information in other ways, but this data source was available, economical, insightful, timely, and accurate. The mirror just needed Mack's support to fulfil its purpose.

Mack had decisions to make at work, too. As an information handover specialist at a large firm, he helped major capital project teams prepare documentation and data related to design, construction, operation, and maintenance of complex process facilities for transition to the operations organization. Mack had served in numerous information technology (IT) roles over the years. As his clients complained about IT's cost relative to its perceived value, Mack wondered if a more honest acronym for "IT" would be "iT." He felt that the strategic emphasis in IT in recent years was more on the "T" (technology) and not enough on the "i" (information). He also understood that most good decisions are made by looking carefully at the information; the technology is merely the means to access or deliver it. Like the light that illuminated Mack's mirror, firms should pursue an appropriate balance of focus between information and the technology required to do the illuminating. Just as too much light focused on a mirror would potentially compromise its capacity to inform value, excess technology for technology's sake could potentially create data overload, rendering the decision maker confused and frustrated.

As breakthrough information technologies are ushering in countless innovations every day, decision makers need ways to measure the extent that IT contributes to value in the form of insights i.e., 'insight value.' This industry analysis article focuses on how a rapidly emerging information technology is poised to revolutionize how petrochemical process industry (PcPI) facilities in the oil and gas (O&G) sector are managed and maintained throughout their lifecycle. So, Mack, the techno-skeptic, wants to know, "What is this innovative technology and is it worth the investment?" To answer these questions, this article begins with a summary of digital twin (DT) technology, highlights a few techno-trends leading to increased adoption of digital innovations in the O&G sector, and provides background proposing why it has taken the O&G sector so long to do so relative to its peers in other industries. Next, key stakeholders in the industry are identified, including how each of their roles may benefit from adoption of DT technology up and down the PcPI supply chain.

Following an in-depth background of the context of the problem of practice associated with DT technology is an outline of the methods for this research to analyze the problem and propose solutions. Next, the article introduces a framework for understanding how digital transformation may enable the value DT technology contributes to information assets and emphasizes how it can provide clarity to help navigate uncertainty, inform better decisions, optimize efficiency, foster greater productivity, and improve overall performance. Finally, a discussion of the application of a maturity model and use cases for how insight value can be assessed from three different perspectives is provided. The conclusion highlights the ways DT technology will help firms realize more profitable return on investment for legacy complex facility assets with better stewardship of the digital versions of those assets, well into their operational lifecycle.

Technology Summary: Origins of Digital Twins Concept

This research shows how the O&G sector has an opportunity to adapt to complexity in a way that facilitates the role firms in that sector must inevitably play in bringing about the 4th Industrial Revolution (also referred to as Industry 4.0). According Nurala et al. (2020) in the literature review they conducted for their empirical analysis of Industry 4.0 adoption in the manufacturing sector, a recent and rapid increase in internet technologies has disrupted and redefined product creation, formation, delivery, and service. The Industry 4.0 oriented organization leverages information and modern telecommunications technologies to achieve a "real-time digital transformation of all vertical and horizontal business processes, while fully integrating the total value creation and delivery systems" (Nurala et al., 2020, p. 698). Geoffrey Cann, a former Deloitte partner and business advisor to the O&G sector defines "digital" in terms of three building blocks: Data, Analytics, and Connectivity. "Something that is digital… has these three basic elements operating together in some configuration" (Cann & Goydan, 2019, p. 11). The transformation that O&G firms have struggled to fully embrace in the past is necessitated by the need to adapt their organizations to manage the torrent of data being generated by sensors, procurement, logistics, maintenance, surveillance, and operational systems embedded in complex facilities throughout the O&G value chain. Cann (2019) states, "While the digital wave of change has had only a modest effect on oil and gas to date, early adopters in other industries have been much more profoundly impacted" (Cann & Goydan, 2019, p. 19).

For example, at the dawn of the 21st century, the manufacturing industry began to pursue digital innovations that would transform how it would do business for the decades that followed. In 2002, Dr. Michael Grieves introduced the concept of "product lifecycle management" (Grieves & Vickers, 2017, p. 93). He proposed a model suggesting rapidly evolving modern computing technology would soon allow designers to create a virtual version of new products, minimizing the "information inefficiencies" (p. 102) that often plague new ideas. Those ideas may have even sounded good at the time, but the high cost of building physical prototypes for visualization and testing doomed many of them before they could get past the proposal stage. Grieves stated that reducing informing inefficiency manifested as a wasted "time, energy, material trade-off" (p. 102). Investment in virtual modeling at various phases of a product lifecycle would "have a major impact on reduction of wasted resources in the lifecycle of our systems. Preventing a catastrophe caused by undesirable emergent behavior that results in loss of life is… priceless" (p. 103).

Grieves' concept of designing, prototyping, and testing in the virtual space disrupted how products were created and brought to market. Any product improvement feedback from consumers could be rapidly integrated into the virtual versions, further reducing the cost, and speeding up the time to market in closer alignment with what customers want. As this approach gained traction throughout the early 2000s, more innovations were added to include predictive modeling, simulations, failure analysis, and an electronic platform for referencing lessons captured from prior iterations. By 2010, Grieves' colleague at NASA, John Vickers, coined the term 'digital twin' to refer to the virtual twinning of the physical domain as its adoption was driving innovation in the aerospace industry (Grieves & Vickers, 2017).

The evolution of the data foundations for digital twins began at the earliest stages of data collection and analysis with workers handling "data manually based on empirical experience" (Tao et al., 2018, p. 158). Human capacity for innovation increased as each stage of technology improved. For example, before the first industrial revolution, productivity improvements depended on human experience as the data source; information was collected manually, and storage typically depended on human memory. Data analysis was arbitrary, and data was primarily transferred verbally from one person to another. Data management was not possible in this scenario. As machines were introduced, humans interacted with machines, and each served as a data source. Data was still collected manually but eventually stored in written documents. Analysis of data took on a systematic nature and transferred via documents on various physical media. Human operators conducted data management in simple forms, such as cataloging, filing systems, shelves, libraries, etc. (Tao et al., 2018).

When the information age emerged in the latter half of the 20th century, humans, machines, computers, and information systems served as data sources (Tao et al., 2018). Collection of data was semi-automated and stored in databases of increasing complexity (2018). Analysis of data applied conventional algorithms, and data began to be transferred via digital files as a primary media rather than physical media (2018). Data management increased in complexity and was managed via sophisticated information systems (2018). As 'Big Data' has taken hold, data sources include machines, sensors, users, information systems, public data, and the results of complex automated data collection mechanisms (LaValle et al., 2011; Tao et al., 2018). Primary storage of data in the modern 'Big Data' environment is cloud-based rather than in a proprietarily hosted on-premises computer network (2018). Data is analyzed via complicated Big Data algorithms and transferred digitally via standardized digital file formats (2018). Data management is conducted by cloud services and artificial intelligence systems (2018). These evolutionary steps form the data foundation (LaValle et al., 2011) for the introduction of digital twins as a key enabling technology for innovation (Qi et al., 2021).

The Petrochemical Process Industry: Oil and Gas Sector

The modern PcPI consists of public and private firms that manage the technical aspects of complex facilities and infrastructure, including utility systems, pipelines, electrical power generation, gas compression systems, water treatment, oil, gas, water separation systems, lubricants, instrumentation systems, safety systems, product storage, waste management, transport systems, power distribution systems, chemical plants, refineries, blending facilities, energy production systems, drilling, subsea, mining, shipping, etc. (Hassani et al, 2017). Direct and indirect stakeholders of PcPI include anyone in need of economical energy, utilities, infrastructure, and chemical compounds necessary to support modern industrial human existence on planet earth.

The O&G sector of the PcPI delayed its shift to embrace digital transformation for nearly a decade compared to other technology dependent industries (Kohli & Johnson, 2011) due to complacency. That complacency stemmed from a period of record high commodity prices (USEIA, 2013) and ambitious global capital development projects that distracted most firms from heeding the warning signs that precipitated the oil price shock of 2014 (USEIA, 2014). By mid-2015, Ernst & Young estimated that at least $200 billion in capital projects had been cancelled or delayed (Bousso, 2015). Six months later, Wood McKensie Ltd. estimated that over $180 billion more had been delayed indefinitely world-wide, forcing industry consolidation, rationalization, and retraction (Stapczynski, 2016), further constraining the resources needed to invest in the ongoing digital transformation (Kohli & Johnson, 2011).

In 2019, Shell, Chevron, and BP, three of the four largest publicly traded global O&G sector companies, announced significant digital transformation initiatives (Beamer, 2019; Microsoft, 2019; Shell, 2020), promising to be leaner while encouraging employees and partners to embrace a digital mindset centered on agility and sustainability through what then promised to be an ongoing commodity price down cycle (USEIA, 2019). Complex facility investments grew last decade by 10% annually (AlixPartners, 2021); however, recent industry trends indicate a shift in capital investment in the future toward more carbon neutral energy sources (Goldthau et al., 2018) as several European based O&G firms have pledged to reduce emissions and pressure on U.S. based firms to follow their lead (BP, 2020; Crowley, 2020). Managing this transition to clean, sustainable operations demanded a deeper understanding of the technologies and resources necessary to transform energy production.

According to Baker (2019), to adapt to the challenges faced in the modern O&G sector, firms are beginning to forge close collaborative partnerships with experts in modelling, analytics, cloud computing, and artificial intelligence. He states, "digital twins will rapidly become standard for every new asset and a growing number of existing facilities" (Baker, 2019, p. 44). Baker believes owner operators who are willing to expose their complex facility assets to detailed data-gathering systems and integrating their virtual and physical assets as digital twins will find dramatic improvements stemming from this closed feedback loop boosting production, increasing asset life, maximizing efficiency, and ultimately improving safety (Baker, 2019).

Digital transformation finally reached the oil patch, and not a moment too soon. The digital infrastructure laid down throughout 2019 served as a foundation for business survival as the global COVID-19

Table 1. Digital Twin Benefits by Stakeholder Role

Stakeholder role(s)	Benefits from adopting full lifecycle management of digital twins
Complex facility project supplier; project engineering manager; design engineer/architect	**Virtual modeling of the future physical asset before bidding, buying, or building any aspect of the asset -- scheduling/planning of materials and manpower needed to fabricate, ship, construct, test, and start up a facility and its component systems**
Engineering data manager; 3D model application user; reality capture system user	**Provides accurate destination tool for getting maximum value out of 3D model investment by linking it to other data sources (process information, engineering asset register, internet of things, etc.)**
Procurement/construction contractor; Operations & maintenance engineer; Work package coordinator	**Better decisions from real-time linkage to procurement and logistics systems, maintenance management systems, spare parts inventory tracking/warehousing, geographic information systems, management of change database, asset integrity & reliability tracking systems, etc.**
Engineering information manager; Process safety information steward; information architect; MoC coordinator	**standard platform for consolidating information governance across systems to maximize enterprise value of shared content leveraging lessons learned and best practices, while integrating them to span traditional organizational silos – better modeling of site changes before they happen improves safety, reliability, minimizes downtime**
Training coordinator; Personnel recruiter; Safety orientation team leader; Personnel on board (POB) manager	**serves as a graphical visualization tool to foster simulations, training, conduct emergency response drills, predict potential points of failure, and expedite orientation of new personnel (particularly those that demand greater interactions with augmented, virtual and mixed reality platforms enabled by photo accurate digital twins).**

pandemic in early 2020 resulted in a majority of the industry's professional workforce out of traditional office buildings and into virtual "tele-work" digital environments, rapidly accelerating the pivot to online collaboration and information sharing (Rystad, 2020). Looking back on 2020, the International Energy Agency (IEA) specifically included "digital twins for [operations and maintenance]" as an example of sustainable development technology that "replaces hardware or labour with digital solutions" (International Energy Agency, 2021, p. 337). By the fourth quarter of 2020, production cuts and lower prices further reduced revenues in this sector resulting in higher pressure from the investment community for leaders in this industry to communicate how their firms planned to navigate what was becoming a more challenging economic and geopolitical landscape in 2021 and beyond (Dickson, 2020).

Stakeholders for digital twin adoption in the O&G sector

Numerous stakeholders are interested in understanding the contribution digital twin adoption can make to designing safer, more reliable facilities, improving decisions in all asset lifecycle phases, optimizing facility operations, and supporting a strong business case for on-going investment to usher in Industry 4.0 innovations and its promise of fully autonomous complex facilities. As shown in Table 1, stakeholders may benefit from adopting digital twins in different ways. Though some benefits realized are financial in nature (cost savings, return on investment, etc.), many benefits are intangible yet no less valuable to the overall organization.

Although the focus of this article is on the digital twins associated with complex O&G systems and facilities, many lessons may be applicable to other technical aspects of the process industry, including nuclear, geothermal, solar, desalinization, and water treatment plants. The complexity faced by leaders in this industry is compounded by the global geographic distribution of the supply chain for design, development, construction, and operational staffing of these facilities. Recent political and societal shifts toward fostering a more sustainable energy footprint is applying greater pressure on O&G firms to elevate the importance of corporate social responsibility that emphasizes innovative approaches to resolving the challenges of the energy equation (Biden, 2021). To meet many of these challenges, firms in the industry have embraced innovative digital technology (Hassani et al., 2017) and engaged in an ongoing digital transformation (Kohli & Johnson, 2011).

Background

As firms in the O&G sector transform, they strive to measure the value of Information as an Asset. In their qualitative study interviewing business managers about the barriers to effective deployment of information assets, Evans et al. (2012) quote a Chief Financial Officer, "We certainly struggle with it, and we don't bring it to the surface and give it the level of resources that it would need to get that value out. I think if we did understand the value then we'd change our thinking." (p. 167).

Rodgers (2007) echoes that senior managers struggle to grasp information value, but he does not fully explain why other than mentioning that executives have difficulty defining what aspects of information should be measured. Organizations often treat their information assets as a necessary maintenance cost, but they should, "regard data, information, and knowledge as their greatest assets and invest in their management accordingly" (Evans et al., 2012, p. 163). Although information is deemed critical to the firm's performance and a driver of competitive advantage, few studies provide more than anecdotal evidence for their opinions to explain why information is not better managed over its lifecycle.

Business journal articles, mass-media publications, and a recent book have been written exploring the field of "Infonomics," an emerging Information Management sub-discipline coined by Gartner business consultant and author Doug Laney. Laney (2017) suggests that firms should seek to get more out of their data than just "insights;" rather, they should seek what he calls "outsights" (p. 16). By proactively investing in information visualization assets such as digital twins, leaders can be intentionally forward looking, planning and anticipating where they are taking the organization. A holistic view of information enables decision makers to cast a vision for the future; this is information's true value (Laney, 2017).

From the researcher's professional experience, facilities engineering (FE) and operations personnel in the O&G sector are rarely given the opportunity to consider the origins of facility information. For example, content originating from 3D models and 'intelligent' design databases from capital facility projects have typically been handed over to operations as 2D rendered drawings, data sheets, piping and instrumentation diagrams, lists, or fact reports because the systems of record for storing and sharing that content were based on file format and storage using a physical file cabinet/library shelf metaphor. This approach constrained innovation as more interactive file sharing system complexity was simply not scalable to operational field locations in the pre-cloud storage platform era. As organizations gradually shifted to digital platforms, the challenge to remove redundant, obsolete, and trivial content overwhelmed migration systems and much of the legacy content was simply archived if it was not actively flagged for reference and retention. Systems of record for FE information are evolving to be more holistic, but the discipline and investment required to clean up decades of legacy content for existing facilities only adds to the difficulty of efficiently managing information for complex process facilities. That situation could influence the business case for adding yet another category of data to manage, such as digital twins.

The origins of a twin version of a complex physical system began during the Apollo Space program at NASA where they allocated resources that enabled design engineers to work with physical prototypes of a full-scale complex system or spacecraft. Like the modern O&G sector, the aerospace industry of the 1960s faced challenges where organizations worked with systems that were very expensive, often customized to the point that very few systems were alike, and due to their unique application to their environment, the systems rarely or, in some cases, had never been made before. Pressure to economize due to budgetary constraints as well as improvements in 3D design model technology made the use of a digital version of the physical asset possible (Grieves & Vickers, 2017).

In 2002, Michael Grieves introduced the concept of the lifecycle of a product in terms of its existence initially in a virtual space and later manifesting in a physical space when the design matured to the state where manufacture was possible (Grieves, 2019). His colleague John Vickers, NASA's chief technologist used the term Digital Twin in a NASA technology roadmap released in 2010 (Grieves & Vickers, 2017). The term has taken on buzzword status with several definitions, transformational promises, and misunderstandings. Nearly everyone using the term has a unique perspective for what it is and how it is applied to their situation. Grieves (2019) defines Digital Twin as:

[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 (pp. 176-177).

Although this definition includes other constructs, the use cases for this article are limited to the digital twins derived from photogrammetry or 3D models used in the operational context of O&G facilities. As described by Evans et al. (2019), early maturity level digital twins provide an on-ramp to developing the Industry 4.0 semi-autonomous and autonomous facilities of the future. Figure 1 is a maturity model de-

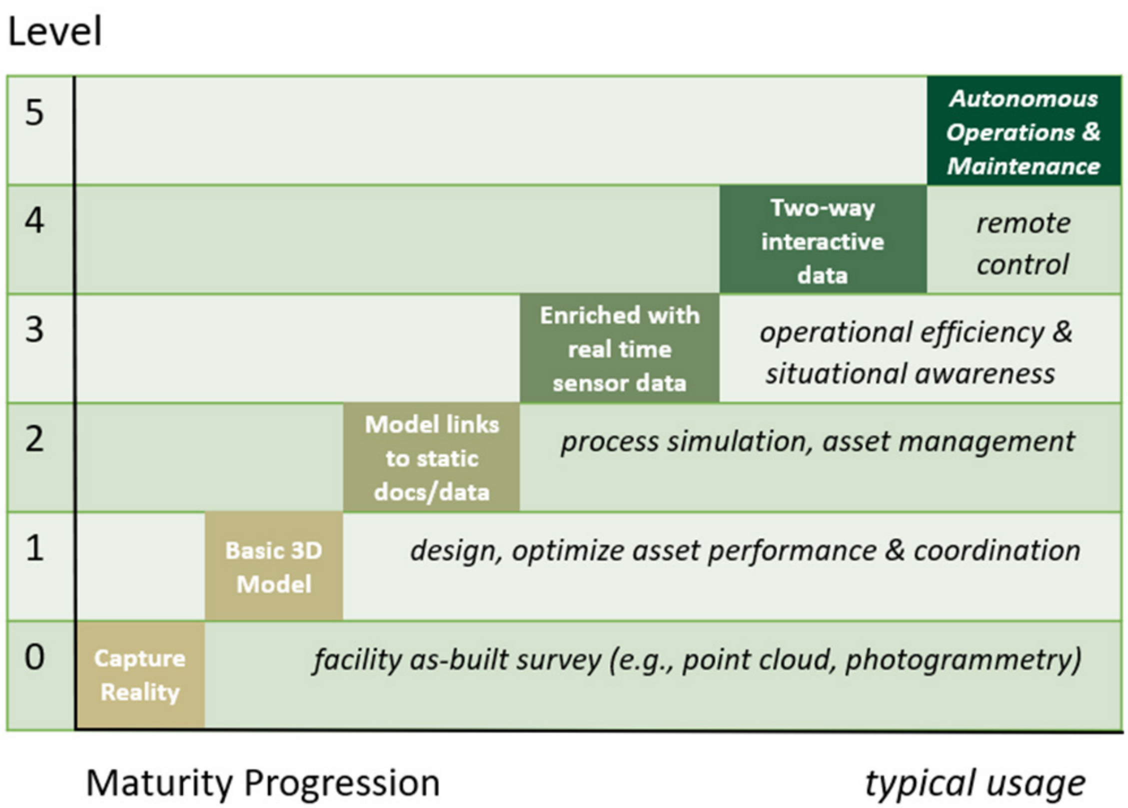

Figure 1. Digital Twin Maturity Model (Adapted from Evans et al., 2019)

veloped to help firms assess where the digital twins of their complex facility assets fit along an evolutionary continuum.

If we struggle to maintain our 3D model today, how will we be able to train an autonomous bot to manage it for us in the future? Development of organizational capability to maintain digital twins (DTs) is an evolutionary process that, for now, requires distinction in use cases between the need for basic block diagram/layout drawing graphics and full photo realism (Uitgebried Samenwerkingsverband Procesindustrie-Nederland [USPI-NL], 2020a). Valid use cases exist for each, and framing the discussion to understand one vs. the other is critical to being able to think clearly about how DTs can transform the way business, engineering, and operational decisions are made. For example, a foundation level 1 (basic 3D model) DT enables modeling, testing, improving, and validating compliance or accuracy in the virtual context before bringing the physical design into practical reality. In contrast, a photo or laser accurate level 0 twin must be linked to static asset data (level 2) to improve orientation, training, logistics planning and human to machine interactions or decisions, but that may not be possible until the physical version is built. Organizations must be intentional to progress their lower-level DTs to higher levels on the maturity model as shown in Figure 1.1 based on a DNV-GL (2020) "evolutionary stages" (p. 5) slide and Evans et al. (2019).

Literature Review Method

Reflecting on the challenges I faced as a subject matter expert in complex systems capital project handover to operations, I encountered a category of data, a hybrid between structured and unstructured data that merited further investigation. This hybrid was the semi-structured data contained in 3D design models and the so-called 'smart' instrumentation and electrical databases that were used as the source for designing process control of complex facility assets. Exploring terms associated with semi-structured data led to a realization that this was a potential area where the O&G sector seemed, as a whole, to be lagging in adoption at the time while other industries had made existential commitments to transform their strategies to leverage this innovative technology (Jones et al., 2020). Validating that assumption and determining how latent value might be exploited to influence greater adoption within this sector led to expanded searches for literature that illuminated this problem of practice (lagging adoption). This literature analysis also helped the researcher define the business case for better management of this hybrid category of business and technical data across all industries.

I began in early 2019 with an extensive literature review focused on understanding how O&G sector firms regard information as an asset, with a particular focus on engineering and technical design information that was typically part of the information handover to operations at the conclusion of a large capital project. I used the ABI/Inform Global database filtering on peer reviewed articles that contained keywords related to my research topic and soon realized that business, in general, and the O&G sector, in particular, had limited empirical evidence on this broad topic. I revisited that research several months later following a similar approach but expanded my Boolean searches via EBSCOHost to cast a wider net to detect whether any content had been missed or new research had been published in this domain. This later search also included articles written by industry experts outside of academia, such as Gartner or O&G sector consultancies.

When the phrase 'data is a company asset' found traction as a strategic theme in the O&G firm where I worked, I expanded my search criteria to try to better understand the categories of data that might be included in that primary digital imperative. I then subscribed to notifications from Gartner whenever they published new articles related to the data as an asset topic. Any content from both of those search efforts provided new keywords to consider and led to follow up search strings for recent articles via EBSCOHost or Google Scholar. Two research questions surfaced that inform the problem of practice:

Why is the Oil and Gas sector lagging in adoption of Industry 4.0 innovations?

What are the key value drivers that influence adoption of digital twins in the Oil and Gas sector?

Next, with these questions in mind, I scanned the resulting articles for any seminal academic authors of digital twin definitions or referenced articles of completed explorations of these topics. I then conducted new searches checking for peer reviewed content with a connection to the O&G sector or process industry, or generalizable findings associated with digital transformation, digital twin adoption, industry 4.0 innovations and analysis tools to track technical debt. Appendix 1.1 is a summary table of academic literature that met search criteria categorized by major themes included in the overall research activity for this article exploring the PcPI and the core problem of practice. It includes a 5-star ranking system used to code each article depending on how well the article content maps to the research questions and whether each provided useful insights representative of the industry, sector, or technical discipline under investigation in this line of inquiry.

As recommended by Yin (2018), to ensure external validity, I also referenced industry trade journals, government publications, regulatory requirements, conference proceedings, and academic and professional journal articles written about my research focus area: informing the insight value of digital twin lifecycle management and standardization. Several use cases and research themes were derived from analysis of archival data from Uitgebried Samenwerkingsverband Procesindustrie-Nederland (USPI-NL), a process industry standards organization consisting of members representing complex facility owner operators, engineering and procurement contractors, software vendors and suppliers (USPI-NL, 2020b).

Key Findings from literature review

Research Question 1: Why is the Oil and Gas sector lagging in adoption of Industry 4.0 innovations?

- The PcPI in general, and the O&G sector in particular have been lagging behind in adoption of Industry 4.0 related digital innovations over the past two decades (Kohli & Johnson, 2011; Jones et al., 2020; Wanasinghe et al., 2020; Ross et al., 2019; Reuters Events, 2020)
- From 2001~2014, the O&G sector experienced a protracted boom cycle diverting capital resources to complex facility development projects (U.S. Energy Information Administration [USEIA], 2013; 2014)
- The O&G sector is currently facing unprecedented uncertainty and pressure to transform how they conduct business (Stevens, 2016; EY, 2020; IEA, 2021; Dickson, 2020)

Research Question 2: What are the key value drivers that influence adoption of digital twins in the Oil and Gas sector?

- Information is a valuable business asset (Moody & Walsh, 1999; Evans et al., 2012)
- O&G sector is under pressure to become more carbon neutral requiring greater insights in sustainable operations (Goldthau et al., 2018)
- Digital Twins provide an efficient means to manage complex assets throughout their lifecycle (Grieves & Vickers, 2017)
- Digital Twins in O&G can be made more maintainable, sustainable with better standards (Cameron et al., 2018)
- Digital Twin value is evident when applied to Operations & Maintenance of existing complex process facilities (IEA, 2021)
- Digital Twin value can be realized at every level of across O&G organizations (Lheureux et al., 2020)
- Digital Twin adoption prepares firms for the transition to the workforce of the future (Schuster et al., 2015; Encinas et al., 2012).
- Digital Twin adoption and maturity increases intrinsic safety of complex systems (Evans et al., 2019)

Analysis

Finding 1: The Oil & Gas sector was lagging other industries in adoption of innovative digital technologies.

Diffusion S Curve

In his seminal work Diffusion of Innovation, Everett M. Rogers (2003) points out that his "S-shaped curve describes only cases of successful innovation in which an innovation spreads to almost all of the potential adopters in a social system" (p. 275). As a whole, the PcPI lagged the digital adoption curve as evidenced in the book Designed for Digital. Based on more than a decade of research on companies that had begun a digital transformation, not a single firm in the O&G sector was included as having committed to digital platforms (Ross et al., 2019). In late 2018, Dr. Jeanne W. Ross noted at a live teleconference that her core research findings in 2009 had not changed significantly in the ensuing nine years. Ross commented, "the only thing different now is the packaging" (Ross, 2018). As Ross and her research team prepared to publish their updated study, she admonished O&G sector business leaders to get on board as the tipping point was eminent and the modern tech-savvy workforce was demanding innovation and commitment to a digital-based organizational design (Ross, 2018).

Rogers (2003) highlights the consequences of innovation demand further as change agents tend to focus on positive benefits of adoption. Rogers (2003) also mentions that "consequences are often difficult to measure" (p. 470). Rogers' perception about difficulty of measuring innovation consequences aligns with the challenges that many industries have experienced in building a business case for adoption of digital twin technology. O&G firms, in particular, have lagged more than a decade behind the leaders in DT technology (the manufacturing industry). Following an upward trend in oil prices in 2016, "O&G companies appeared to shift away from cost cutting and resumed investment in innovation. The rapid digitalization associated with Industry 4.0 may have also contributed to the recent interest towards DT technologies" (Wanasinghe et al., 2020, p. 104,185).

Adoption of DT technology can take many different forms. A recent Gartner whitepaper describes three distinct types of DTs, and each has its own value proposition and trade-offs related to how it is developed and maintained. Specifically, "Discrete digital twins – [optimizes individual assets, personnel, and resources]," "Composite digital twins – [combines multiple discrete DTs and data within system or facility]," and "Digital twins of organizations – [maximizes value of a process throughout enterprise operations]" (Lheureux et al., 2020, p. 5). Each of these different forms of DTs enhances situational awareness and predictive capability of the system. When implemented as an enterprise decision support system, DTs also serve to improve decision quality at every level of the organization (Lheureux et al., 2020).

O&G firms' aspirations to adopt innovative digital technologies was evidenced in a recent survey conducted by EY (2020). O&G companies are seeking to "drive efficiency and productivity into operations, transforming how they operate and truly doing more with less" (EY, 2020, p. 1). The technical skills needed to support higher level DT technologies, such as virtual and/or augmented reality, artificial intelligence, internet of things, machine learning, remote monitoring, advanced analytics, and autonomous transport, are below where the respondents felt they must be to support sustained operations in the future. O&G sector firms are not only competing with other industries for personnel, but they are also retooling their existing workforce to meet these challenges. The importance of shifting from focusing on metrics associated with training completion to actively evaluating applied learning is key, according to an HR executive at an integrated oil company (EY, 2020). This observation demonstrates that lagging others in necessary technology adoption adds human resource constraints to the list of innovation diffusion "difficult to measure" consequences (Rogers, 2003, p. 470).

Though the evidence of the lagging adoption is real, the pressure is rising for PcPI to adapt to meet the challenges of the global energy transition that Dr. Fatih Birol, Executive Director of the IEA, contends is underway as he highlighted in the forward to IEA's "Energy Technology Perspectives 2020,"

[M]ore and more governments around the world are backing clean energy technologies as part of their economic recovery plans in response to the Covid-19 crisis… The private sector is also upping its game, with some oil and gas majors betting their futures on becoming lower carbon energy companies and top information technology companies putting increasing resources into renewables and energy storage" (IEA, 2021, p. 3).

In November 2020, Dr. Birol explained, "[the] digital world and energy world; they have just recently met. There are [currently] very few intersections that the digital world and energy world make use of each other…" (Reuters Events, 2020). He described the pivotal role policy makers and industry leaders need to play to bring about "…global energy digital transformations" (Reuters Events, 2020).

Finding 2: Knowledge generation and enterprise scale value from digital twins can be derived thousands of miles from the actual physical facility. However, the companies in the Oil & Gas sector often struggle to leverage their global scale when managing these valuable information assets.

S/W/O/T Analysis

According to the process industry standards organization (USPI-NL), O&G sector firms have traditionally not received or simply discarded design data during complex process facility handover to operations (USPI-NL, 2020a). I have experienced this phenomenon and seen it lead to lost opportunities (e.g., project cancellations), greater vulnerability to external threats (e.g., COVID-19, price volatility, supplier bankruptcy), and intrinsic weaknesses (e.g., limited organizational capability to maintain DTs). The main strength of most large firms in the O&G sector is their massive scale and global reach. Complex facility projects tend to involve partners with deep pockets and highly experienced technical and professional personnel. This strength taken to an extreme is also one of its greatest weaknesses. Large multinational integrated O&G companies could be illuminated by DTs in one region, yet in the dark in another. O&G firms tend to create silos where successes or failures are not intrinsically shared throughout the enterprise. Firms may treat each facility as a unique system with no insight value to other facilities. This treatment often creates an environment where valuable lessons are experienced and lost in the crowd rather than learned and incorporated into the corporate culture.

An opportunity for large firms in this sector is to leverage their scale and reach on major capital projects. Their massive scale often engenders a 'too big to fail' mindset among owner operators, partners, and investors. Complex process facility projects may span decades and cost several billion dollars once final investment decisions (FID) have been made. Mega projects tend to be funded to completion even if the economics no longer make sense or performance metrics fall short of the classic triple constraints of project management (schedule, budget, scope). Compromises have historically plagued mega projects with nearly 78% failing to achieve the promises of their FID budget/schedule projections (Merrow, 2012). O&G firms are rationalizing their portfolios given the effect of low margins on returns that is forcing much longer facility break even points. When large capital projects fail to deliver on their original FID, value is a serious threat to credibility and faith in the forecasting system. With greater flexibility regarding technology risk in their project execution methodology, those facilities could have paid off and far exceeded their design capacity if their design and contracting strategy had been more adaptable to technological innovations that become available after project contracts are signed and funded, representing an opportunity if they succeed in managing technology risk and a threat if they fail to do so.

Finding 3: Digital Twins of complex facilities in the O&G sector are a valuable business asset and should be maintained throughout the facility lifecycle to maximize the return on investment from that asset and ensure that its corresponding insight value is not degraded by neglect and lack of strategic consideration.

Information Asset Valuation

Moody and Walsh (1999) presented a paper at a conference that highlighted how valuation theories for intangible assets could be applied to information assets by accounting for the cost plus the benefits they bring during their lifecycle. The Digital Twin Asset Valuation Models that follow were generated as an abstraction derived from three of "the seven 'laws' of information" as proposed by Moody and Walsh (1999, p. 4). Specifically,

- DT asset (lifecycle) value increases with use
- DT asset (integrity) value increases with accuracy (data quality)
- DT asset (maturity) value increases with integration with other information

These models are generalized to illustrate how insight value can be assessed in conjunction with an incremental cost basis to track the interrelationship between dependent variables (V), such as lifecycle value (Figure 2), integrity value (Figure 3), and maturity value (Figure 4). In each figure, the estimated insight value (i) is influenced by differing incremental cost (c) bases; data asset (Figure 2), data quality (Figure 3), and data integration (Figure 4). The resulting graphs show how these variables track against one another, dependent upon the following:

- Asset lifecycle stage across the axis of time (Figure 2)
- Data quality level across the axis of improvement (Figure 3)
- Six maturity levels across the axis of DT integration progression (Figure 4)

The relative value depicted on each model is scaled to fit the range of V observation points across each axis. A decision threshold line is provided in each model to show the value state that must be reached before insight (i) from these assets can positively affect decisions.

In the Design asset lifecycle stage, the cost basis of building the digital twin, typically a 3D design model, is almost equal to its insight value to the contractor and project team but has little or no value to the operational context of the asset lifecycle because it is just a conceptual construct that could be many years away from its physical manifestation in its reality. During the Construction stage, insight value of the 3D model to the enterprise increases because it allows owner-operators to visualize what was previously an abstract idea, allowing them to begin planning for integrating it into their existing systems and processes. At this stage, the only cost is to keep it current with respect to changes occurring during the construction and commissioning activity; the lifecycle value roughly matches the incremental cost to maintain it.

As the asset enters the Operation stage, data asset costs remain steady as it is merely a maintenance

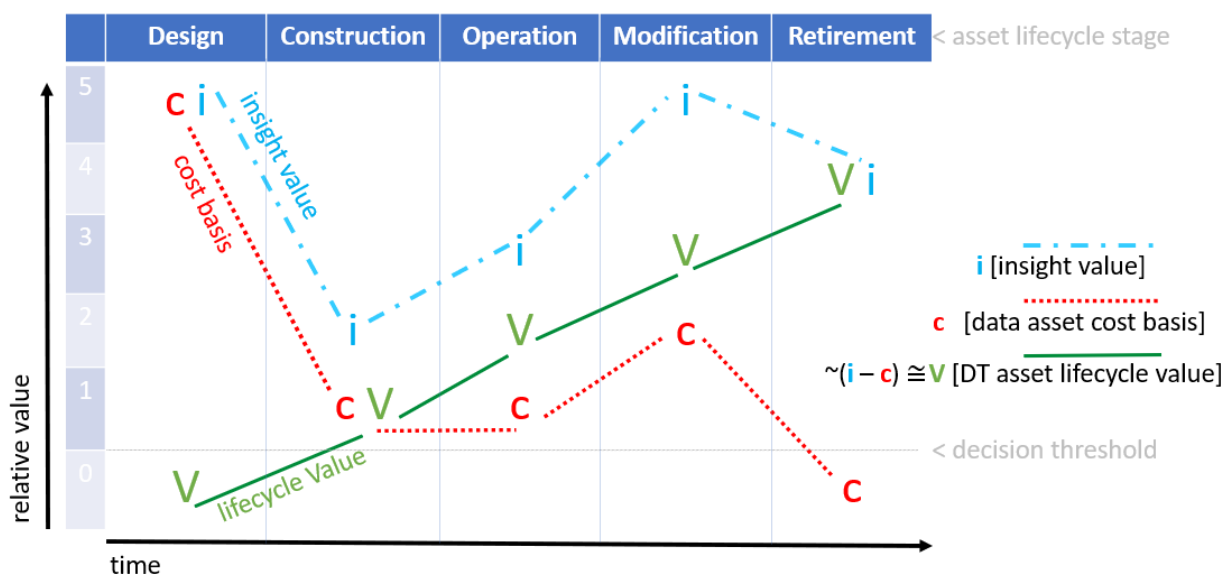

Figure 2. Digital Twin Asset Lifecycle Value Model (demonstrates how value increases with use)

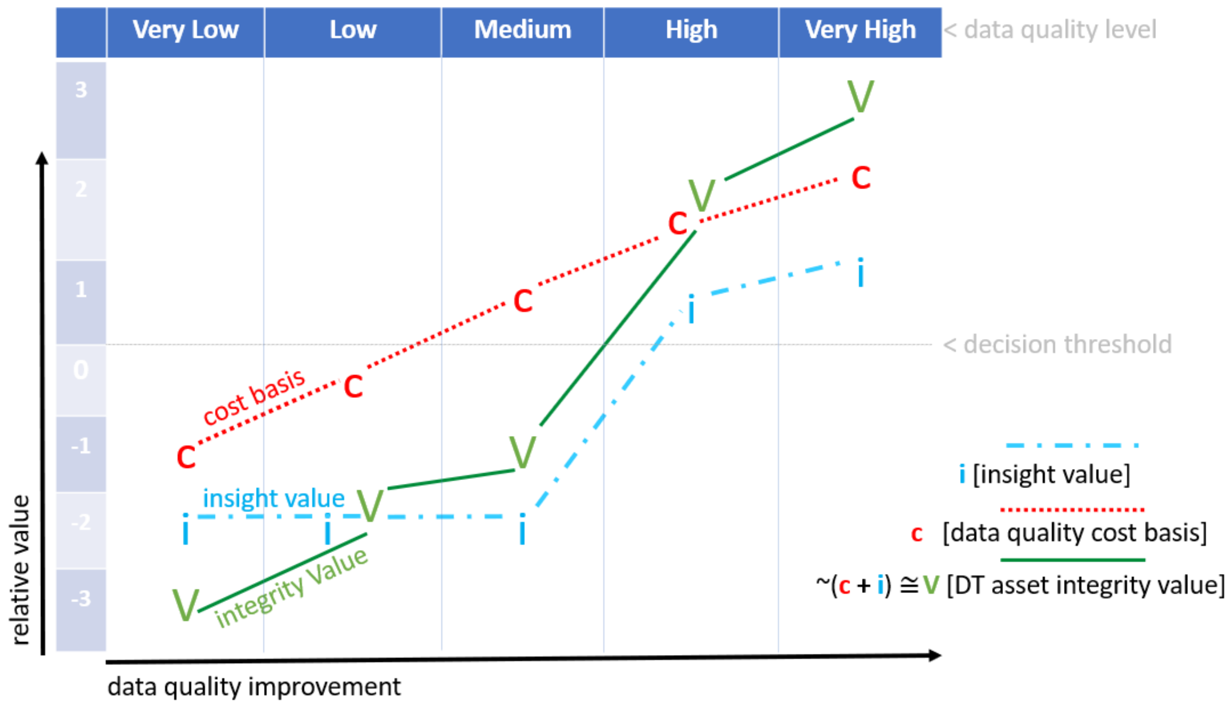

Figure 3. Digital Twin Asset Integrity Value Model (shows how value increases with accuracy)

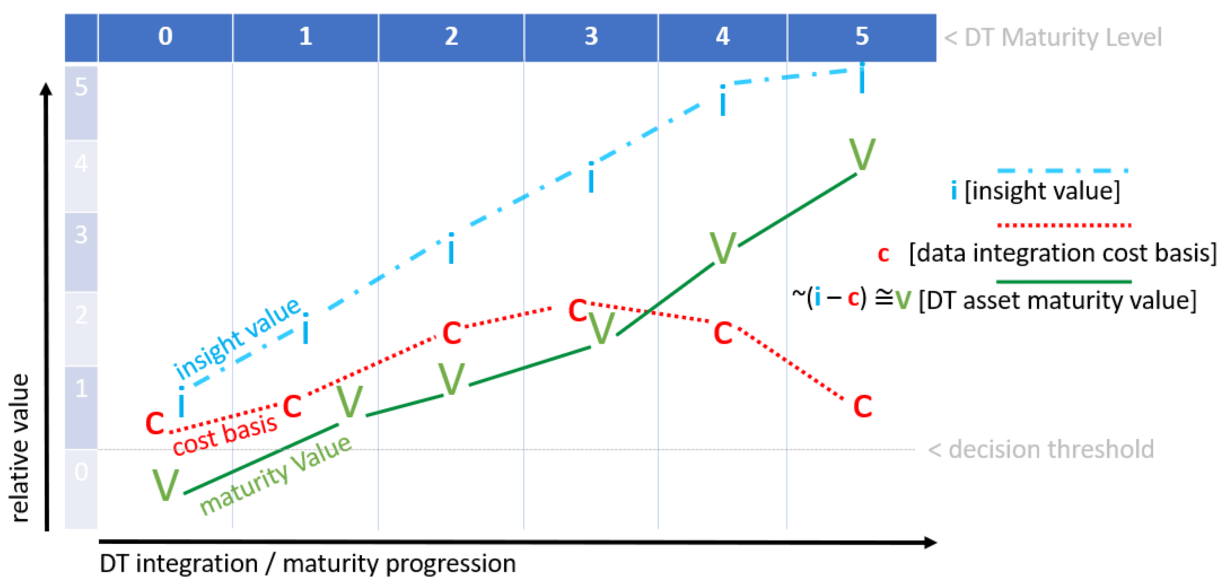

Figure 4. Digital Twin Asset Maturity Value Model (demonstrates how value increases with integration with other data)

function to keep it current with minor asset updates through the management of change process. In this stage, firms that have not maintained a 3D model may opt to expend resources to employ laser scanners to generate a point cloud or photogrammetry to create a digital model to reflect the built environment electronically (Collins et al., 2018). DT asset value increases in proportion to the amount of insight value the operations and extended enterprise gleans from the asset, depending on how much integration is taking place with other static or real time data sources.

In the Modification stage that typically accompanies major turnarounds or brownfield project enhancements, the costs rise due to the increase in updates to the core 3D model. However, the DT value jumps considerably due to the decisions that an accurate digital twin supports with predictive simulations of the current or future state, allowing engineering teams to optimize logistic material flow, concurrent processes, temporary process by-passes, and scheduling of work packages for completion. In the final stage of the asset lifecycle, the accurate DT has high informing and cumulative value at relatively little or no incremental cost as the asset undergoes Retirement.

Decisions related to work package planning, material movement, decommissioning, and decarbonizing systems are improved by an up-to-date digital version of the truth. It even continues to pay valuable dividends to stakeholders in other parts of the organization preparing for similar activities on other facilities as they can visualize lessons learned without having to physically visit the facility, even long after it has been taken out of service.

The difference in the calculation formula in Figure 3 is that cost is added to vs. subtracted from insight value because costs associated with improving data quality are considered more of a strategic investment in decision quality than a tactical operating expense. The track of digital twin asset integrity value illustrates how Very Low data quality for a DT renders its insight value less than useless because of the costs associated with the consequences of bad decisions based on bad data, or the cost of rework, second guessing, and accommodating uncertainty due to poor decision quality. At this state, actual costs to ensure the quality of data are deferred, allowing those resources to be allocated elsewhere, hence the negative cost basis. Overall negative DT asset integrity value is amplified because of the perception that it would be more economical to recreate the DT from scratch than try to mitigate the errors embedded in an untrusted virtual version of the physical asset. At the Low state, it may be cost neutral because there may be hope of mitigating the data quality to bring it above the decision threshold level of insight value for critical asset components.

The integrity value is better at the Medium data quality state, but it still reflects higher data quality management costs than perceived value, reinforcing management skepticism at this state. DT managers must emphasize the strategic value of investing in this asset, even though costs to do so greatly exceed the data's trustworthiness for informing decisions. Upon achieving the High data quality state, decision quality improves with insight value, and incremental costs start showing return on investment. However, there is a point where costs in the Very High data quality state cease to provide the same level of impact on insight value as timeliness of decisions may not be able to wait until all error or omission is removed from the system. The diminishing returns also appear more significantly when DT content management prioritizes data accuracy over data currency, particularly when the information is about non-critical system components, such as pipe supports, cable trays, and structural elements of complex facilities.

The premise that "information becomes more valuable when it can be compared and combined with other information" (Moody & Walsh, 1999, p. 8) is a perfect application of the justification for moving DT assets from lower levels on the maturity continuum to higher levels as illustrated in Figure 1. Since most O&G sector DTs of complex facilities appear to be at level 2 with some approaching level 3 (Marquardt-Tynan, 2021), any aspirations for more organizations to move their DTs to level 3 in the next few years must be met with the realization that there is fierce competition for operating expense resources in the current low oil price environment brought on by an oil supply glut and depressed global demand due to the on-going global COVID-19 pandemic (Dickson, 2020).

Geopolitical pressure to decarbonize the energy equation is rising as climate science continues to highlight the adverse effects of greenhouse gas emissions associated with most modern industrial activities (Goldthau et al., 2018). That reality further constrains available resources as O&G firms seek to invest in more sustainable alternatives to fossil fuel-based petrochemical products. Figure 4 reflects the benefits that may be gained by the natural reduction in incremental information integration costs as digital enabling technology infrastructure investments begin to pay off; analytical systems at higher levels of maturity are intrinsically designed for greater interoperability with open architecture while taking advantage of economical Platform-as-a-Service innovations. Similar to the DT asset lifecycle model, the insight value exceeds the cumulative maturity value, but more consistently correlated due to greater intentionality for positive growth along that axis than would naturally occur over a DT lifecycle without adoption of a maturity roadmap (as depicted in Figure 2).

Discussion

The findings above show how O&G firms have lagged their peers in other industries in adoption of digital technology but are rapidly working to catch up. Through digital transformation, O&G firms are reinventing how they are structured as well as shedding the traditional silos associated with upstream, midstream, and downstream business functions to focus on delivery of technological innovation through digital platforms across their enterprise (Lu et al., 2019). Also, the primary strength of O&G (its global scale and reach) has been weakened in the past by creation of information silos. A firm in this sector could distinguish itself by accelerating the intentional breaking of silos and leverage its scale to apply lessons learned from experiences at other facilities across the enterprise. In this way, the digital transformation provides a unique opportunity to change long standing cultural paradigms that have constrained the capacity for operational efficiency.

As O&G firms set out to improve capital project performance, they must also leverage their scale to capture the benefits of treating their information as a valuable business asset. Enterprise level intentional sharing, use, visualization, and integration of information assets can be the key to unlock the latent lessons from project failures and best practices that would otherwise be lost in information silos. Digital twins are no exception. As Gartner suggested, information meets the criteria to be considered an asset; however, it is not typically treated as one using current accounting methods, complicating how business leaders make decisions about their information (Laney, White, & Duncan, 2018). Often, leaders default to discarding what they do not understand or appreciate. This phenomenon may explain why 3D design models of complex facilities tend to rarely survive into the operational context. As the entry point for maturing DTs in Figure 1, 3D model lifecycle management suffers from short-sightedness at the O&G facility level at best and complete neglect at the enterprise level at worst.

USPI-NL initiated the Facility Lifecycle 3D Model Standards (FL3DMS) project when their consortium of process industry information management standards experts determined that the neglected state of 3D models of complex process facilities was a gap that needed to be closed and any aspiration of digital twins appeared 'dead on arrival' without driving to the root cause: failure to maintain the design data into the operational context (USPI-NL, 2020a). They quickly determined that having a data standard for the 3D model produces value pockets and exposes latent value pockets from greater information efficiency. Further insights derived from informal conversations with key stakeholders demonstrated that application of greater academic rigor on the business case for investment in maintenance of the 3D model throughout the facility lifecycle could enlighten the industry to a step change innovation in that it enables the aspiration of digital twins. However, this effort requires the corporate will for key decision makers of owner-operator organizations to prioritize investment in DTs, despite the localized optimization logic that tends to devalue design information based on ignorance regarding the consequences and opportunity costs of not maintaining or further integrating foundation level DTs, for example, 3D models linked to other operational systems (e.g., industrial internet of things, asset registers, sensors, real-time monitoring, remote control, process information, safety integrity level) (USPI-NL, 2021).

Any struggle to achieve anticipated operational efficiencies from the initial capital project proposal and design stage tends to create tension between project engineers and operations management personnel. Construction and start up may attribute the gaps to poor design, the design engineers may attribute them to contractor suppliers failing to execute the design intent, and operations is forced to evaluate personnel training, operating procedures, technical documentation, and maintenance strategy in a never-ending search for the root cause as to why they are unable to achieve optimal plant efficiency once they accept custody of the systems and processes. Also, given the relatively long complex facility project lifecycle, by the time physical facilities are built and installed, their basis of design and some of the technologies specified to track modifications throughout the construction and commissioning process may become obsolete.

Improving visibility of how digital twins could inform better decisions in the operational context should foster greater engagement between operations and project design teams. Earlier operational asset ownership of the digital twin during the project engineering design and execution phases may be a solution to mitigate these issues. If a project was to have to submit to operational Management of Change (MoC) processes, it would shift the paradigm that project work is discrete and independent from operational activities. In cases such as the recent turnaround activity on the Wheatstone Upstream platform completed in early 2018, large O&G firms can readily demonstrate the value of developing and maintaining digital twins while concurrent engineering and work package planning is underway (Chevron, 2021). This approach is particularly relevant during periods of relatively low O&G product prices when companies in this sector pursue more brownfield projects to extend the operational life or improve the efficiency of existing facilities. Fully integrated, well-maintained DTs provide a virtual laboratory to explore new and creative ways to maximize complex process facility efficiency.

Conclusions

The modern petrochemical process industry is rapidly waking up to the importance of preparing for Industry 4.0 and thus, recognizes the need to develop and maintain digital twins of complex facility assets. Large firms in the O&G sector face the challenge that the foundational elements to create digital twins have typically not been handed over to operations when the facilities were initially designed, constructed, and commissioned. This industry analysis article explores how understanding the business case for maintaining 3D design models in the operational context informs decision makers about this effective entry point for these firms to begin developing integrated digital twins. The researcher provides a digital twin maturity model (Figure 1.1) based on industry research explaining how these information assets serve as a bridge to attaining and maintaining fully autonomous facilities.

The literature regarding effective implementation of full lifecycle digital twins is limited (Jones et al., 2020) and requires greater exploration as the trends over the past three years demonstrate heightened academic and practitioner interest that portends engineering, information systems, and business schools will eventually produce graduates expecting digital twin technology tools to be as ubiquitous as a laptop or a mobile device is in the modern workplace.

The treatment of DT information as a valuable business asset is complicated by a general lack of appreciation of the value that quality information is to decision making. The researcher reflects upon an approach to assign relative value to informing decisions at various stages of the asset lifecycle (Figure 2), various levels of data quality (Figure 3), and various levels of digital twin maturity (Figure 4).

The process industry standards organization, USPI-NL, is actively coalescing key stakeholders around a standard to build the competency and governance guardrails to further reduce information inefficiencies (USPI-NL, 2020b). Subsequent studies in this series of three articles (as shown in Figure 5) include an empirical findings evaluation of recent efforts to implement digital twins at O&G firms and a design science research investigation of the business case for facility lifecycle investment in 3D models as a foundation for developing integrated digital twins using the elaborated Action Design Research (eADR) methodology (Mullarkey & Hevner, 2019).

The aspiration to develop the organizational capability necessary to adapt to an Industry 4.0 future requires investment in technological innovations and transformation of culture to proactively integrate information system assets with physical facility data throughout the asset lifecycle. Recent technological innovations in data aggregation (i.e., big data) and integration are fundamentally improving the human experience with cyber-physical systems (Tao et al., 2018) that enable the workforce to glean greater insight and improve decision quality (LaValle et al., 2011). Firms that invest in maintaining digital twins recognize benefits in productivity, process safety, and personnel training (Qi et al., 2021); also, they harness lessons learned from other use cases across an organization (Tao et al., 2018). The artist Claude Monet once proclaimed, “It’s on the strength of observation and reflection that one finds a way. So, we must dig and delve unceasingly” (Monet & Kendall, 2000, p. 20). Observations of current trends in the petrochemical process industry and reflections upon the academic literature reveal that effectively managing asset information value is a viable pathway to sustainability and profitable enterprise.

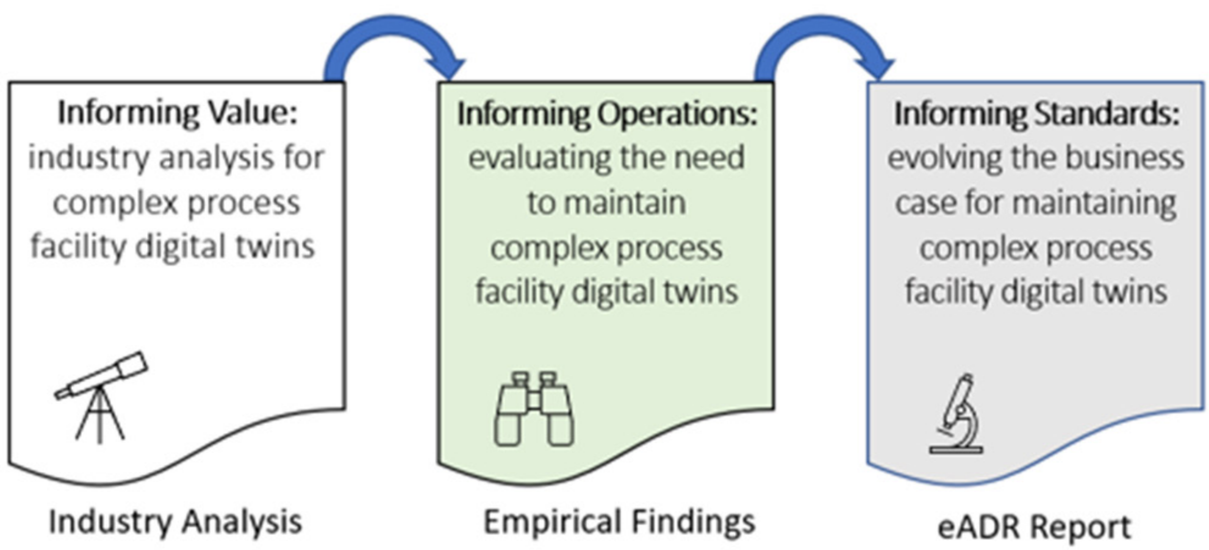

Figure 5. Research Trilogy Roadmap – Informing Complexity: the business case for managing digital twins of complex process facilities

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Review

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

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

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Appendix A: Matrix of Literature Selected for Industry Analysis by Theme

Theme	Author(s)	Title	Rating*
Digital Transformation	Love, Peter E. D.; Matthews, Jane	The 'how' of benefits management for digital technology: From engineering to asset management	★
Digital Transformation Adoption	Kohli, Rajiv; Johnson, Shawn	Digital Transformation in Latecomer Industries: CIO and CEO Leadership Lessons from Encana Oil & Gas (USA) I...	★★★★
Digital Transformation O&G	Fillinger, Sandra; Esche, Erik; Tolksdorf, ...	Data Exchange for Process Engineering – Challenges and Opportunities	★
Digital Transformation O&G	Hassani, Hossein; Silva, Emmanuel Siri...	The role of innovation and technology in sustaining the petroleum and petrochemical industry	★★★
Digital Twin Adoption	Heaton, James; Parlikad, Ajith K.	Asset Information Model to support the adoption of a Digital Twin: West Cambridge case study	★
Digital Twin Adoption	Qi, Qinglin; Tao, Fei; Hu, Tianliang; Anw...	Enabling technologies and tools for digital twin	★★★
Digital Twin Definition	Grieves, Michael; Vickers, John	Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems	★★★★
Digital Twin Definition	Jones, David; Snider, Chris; Nassehi, Ay...	Characterising the Digital Twin: A systematic literature review	★★★
Digital twin Definition	van der Valk, Hendrik; Haße, Hendrik; ...	A Taxonomy of Digital Twins	★★★
Digital Twin Development	Bickford, Jason; Van Bossuyt, Douglas L...	Operationalizing digital twins through model-based systems engineering methods	★★
Digital Twin Development	Han, Young-Soo; Lee, Jaejoon; Lee, Jun...	3D CAD data extraction and conversion for application of augmented/virtual reality to the construction of ship...	★
Digital Twin Development	Olivotti, Daniel; Dreyer, Sonja; Lebek, B...	Creating the foundation for digital twins in the manufacturing industry: an integrated installed base managem...	★★
Digital Twin Development	Stark, Rainer; Fresemann, Carina; Lindo...	Development and operation of Digital Twins for technical systems and services	★★
Digital Twin Development	Uhlemann, Thomas H. J.; Lehmann, Ch...	The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0	★★★★★
Digital Twin Development	Zhang, Lin; Zhou, Longfei; Horn, Berth...	Building a right digital twin with model engineering	★
Digital Twin Lifecycle	Errandonea, Itxaro; Beltrán, Sergio; Arriz...	Digital Twin for maintenance: A literature review	★★★
Digital Twin Lifecycle	Grieves, Michael	Virtually Intelligent Product Systems: Digital and Physical Twins	★★★★★
Digital Twin Lifecycle	Khan, Samir; Farnsworth, Michael; Mc...	On the requirements of digital twin-driven autonomous maintenance	★★★
Digital Twin Lifecycle	Macchi, Marco; Roda, Irene; Negri, Elisa...	Exploring the role of Digital Twin for Asset Lifecycle Management	★
Digital Twin O&G	Bevilacqua, Maurizio; Bottani, Eleonora;...	Digital Twin Reference Model Development to Prevent Operators' Risk in Process Plants	★
Digital Twin O&G	David B. Cameron, Arild Waaler, Tiina ...	Oil and Gas digital twins after twenty years. How can they be made sustainable, maintainable and useful?	★★★★
Digital Twin O&G	Min, Qingfei; Lu, Yangguang; Liu, Zhiy...	Machine Learning based Digital Twin Framework for Production Optimization in Petrochemical Industry	★★
Digital Twin O&G	Perno, M.; Hvam, L.; Haug, A.	Enablers and Barriers to the Implementation of Digital Twins in the Process Industry: A Systematic Literature Rev...	★★★
Digital Twin O&G	Wanasinghe, T. R.; Wroblewski, L.; Peter...	Digital Twin for the Oil and Gas Industry: Overview, Research Trends, Opportunities, and Challenges	★★★★★
Digital Twin Safety	Agnusdei, Giulio Paolo; Elia, Valerio; Gn...	A classification proposal of digital twin applications in the safety domain	★★
Digital Twin Safety	Lee, John; Cameron, Ian; Hassall, Maur...	Improving process safety: What roles for Digitalization and Industry 4.0?	★★★
Digital Twin Value	Greif, Toni; Stein, Nikolai; Flath, Christo...	Peeking into the void: Digital twins for construction site logistics	★★
Digital Twin Value	He, Rui; Chen, Guoming; Dong, Che; S...	Data-driven digital twin technology for optimized control in process systems	★★★
Digital Twin Value	Munir, Mustapha; Kiviniemi, Arto; Jone...	Business value of integrated BIM-based asset management	★★
Industry 4.0	Oztemel, Ercan; Samet, Gursev	Literature review of Industry 4.0 and related technologies	★★★★
Industry 4.0	Tao, Fei; Qi, Qinglin; Liu, Ang; Kusiak, A...	Data-driven smart manufacturing	★★
Industry 4.0 Adoption	Narula, Sanjiv; Prakash, Surya; Dwivedy,...	Industry 4.0 adoption key factors: an empirical study on manufacturing industry	★★★★
Industry 4.0 O&G	Fabio Di, Carlo; Giovanni, Mazzuto; Ma...	Retrofitting a Process Plant in an Industry 4.0 Perspective for Improving Safety and Maintenance Performance	★★
Industry 4.0 O&G	Lu, Hongfang; Guo, Lijun; Azimi, Moha...	Oil and Gas 4.0 era: A systematic review and outlook	★★★
Industry 4.0 Uncertainty	Magruk, Andrzej	Uncertainty In The Sphere Of The Industry 4.0 - Potential Areas To Research	★★★★★
Industry 4.0 Virtual Learning	Schuster, Katharina; Plumanns, Lana; G...	Preparing for Industry 4.0 – Testing Collaborative Virtual Learning Environments with Students and Professional ...	★★★★
Industry History	Aleklett, Kjell; Campbell, Colin	The Peak and Decline of World Oil and Gas Production	★
Industry History	Dannreuther, Roland; Ostrowski, Wojci...	Global Resources : Conflict and Cooperation	★
Industry History	Goldthau, Andreas; Keim, Martin; West...	The geopolitics of energy transformation : governing the shift: transformation dividends, systemic risks and ne...	★
Industry History	Hause, Matthew; Ashfield, Steve	The Oil and Gas Digital Engineering Journey	★★★
Industry History	Stevens, Paul	History of the International Oil Industry	★★★
Industry History	Stevens, Paul; Royal Institute of Internat...	International oil companies : the death of the old business model	★★
Industry History Economics	Baffes, John and Kose, M. Ayhan and O...	The Great Plunge in Oil Prices: Causes, Consequences, and Policy Responses	★
Industry History Economics	Baumeister, Christiane; Kilian, Lutz	Forty Years of Oil Price Fluctuations: Why the Price of Oil May Still Surprise Us	★
Industry History Economics	Mohaddes, Kamiar; Pesaran, M. Hashem	Oil prices and the global economy: Is it different this time around?	★★
Industry History Safety	Jian, Jiun-Yin; Miller, Gerry E.; Shah, Sahil	Preventing Human Error in Crane Operations: A Case Study of Organizational and Design Elements	★
Industry History Safety	Mason, Krystal L.; Retzer, Kyla D.; Hill, R...	Occupational fatalities during the oil and gas boom--United States, 2003-2013	★★
Industry History Safety	Woolfson, Charles	PREVENTABLE DISASTERS IN THE OFFSHORE OIL INDUSTRY: FROM PIPER ALPHA TO DEEPWATER HORIZON	★

Figure A1. Screen shot of table built in EndNote™ to depict Article ratings by theme*

Table A1. Core Themes and Subthemes from the Literature

Core Themes: (article count)	Sub Themes: (article count)
Digital Transformation (4)	Adoption (1); Oil & Gas (2)
Digital Twin (25)	Adoption (2); Definition (3); Development (6); Lifecycle (4); Oil & Gas (5); Safety (2); Value (3)
Industry 4.0 (7)	Adoption (1); Oil & Gas (2); Uncertainty (1); Virtual Learning (1)
PcPI History (12)	Economics (3); Safety (3)

*Subjective ratings of academic, peer reviewed articles/books assigned by the researcher indicate a combination of factors including fidelity, academic rigor, alignment with research objective, relevance, and currency. Articles assigned higher star ratings were more likely to be included as a reference.