

Digital Twin Framework for Subsea Pipeline Monitoring and Integrity Management

Dulo Chukwuemeka Wegner
Inspection Engineer
Fugro

Itoya Moses
AI / Machine Learning
University of Benin

Ihiegbinam Onyekachi
Ezenwa
Energy Engineering
University of Hull

ABSTRACT

The protection of subsea pipelines is vital for the proper operation of offshore oil and gas infrastructure. However, their proximity to the oceans and the differing strains placed on the pipelines pose large obstacles for their monitoring and maintenance. Subsea pipelines, while crucial, are more complex than traditionally understood. Instead of observing their importance as snapshot assessments, more focus is required on the different avenues of deterioration, including disbandment, corrosion, and fatigue. To address these shortcomings, this research puts forward the use of digital engineering as a basis for subsea pipeline monitoring and integrity management systems. This would encompass active data control, real-time predictive analysis, and high-fidelity models. The digital twin is a system of virtual representations of physical infrastructures that are automatically updated with inspection and operation datasets. Essential parameters are ROV images, protected survey data, flow and pressure readings, temperature, and even the salinity and movement of the seabed. These datasets complement closed-based finite physical models for integration and trained analytic systems, which aim to project integrity forecasting and degradation process deterioration simulation. The inclusion of uncertain and probabilistic parameters with monitored material defect oscillations offers additional rigor to the model and allows for more informed risk decision analysis.

The ability for predictive reasoning is one of the innovative aspects of the framework with proactive integrity management and damage predictive analytics hotspot, inspection scheduling, and degradation life extension. Geographic information system (GIS) tools improve situational awareness with degradation and risk contour visualizations along pipeline routes. In the context of geospatial information systems (GIS), degradation-risk contour visualizations enhance operational situational awareness along pipeline routes and for pertinent surface and subsurface assets. Continuous monitoring and predictive models of subsea pipelines, along with the digital twin approach, shift integrity management from a reactive to a predictive and responsive framework. This shift to predictive adaptive management minimizes sudden failure, enhances regulatory compliance offshore, and reduces operational costs, all of which enhance the sustainable development of subsea energy infrastructure.

Keywords

Digital twin, Subsea pipeline, Integrity management, Pipeline monitoring, Real-time data, Predictive maintenance, ROV inspection, Corrosion assessment, Risk-based analysis, Data integration, Structural health monitoring, Environmental monitoring

1. INTRODUCTION

Subsea and deepwater pipelines remain a vital component for offshore oil, gas, and energy transport systems. They facilitate the transportation of hydrocarbons and increasingly hydrogen and carbon dioxide in the context of emerging low-carbon energy transitions (Peri and Tal, 2020; Mitchell *et al.*, 2021). These infrastructures span thousands of kilometers of seabed and operate in extreme conditions of deep water, sub-sea pressures, and toxic environments of seawater combined with shifting geotechnical conditions (Lin and Yang, 2020; Vijay Kumar, 2021). Because of their importance in the global energy supply chain and the environmental and operational stress factors, MacIntosh and others (2021) and Nelson and others (2021) observe that sub-sea pipelines require focused attention and critical management approaches. The breakdown of these systems leads to operational loss; however, it also enhances the risks of ecological threats to human life and the environment. This makes pipeline integrity a primary focus of offshore energy operators, regulators, and policymakers.

Integrity management is foundational for ends to be safe and sustainable when operating subsea pipelines (Yakoot *et al.*, 2021; Miller, 2021). It involves systematic processes to determine and deal with the risks of pipelines failing due to corrosion, fatigue, and damage from geohazards. Integrity management protects marine ecosystems, saves coastal people, and ensures compliance with hefty environmental and safety legislations by preventing leaks and ruptures (Suleiman *et al.*, 2019; Nkansah, 2020). The Deepwater Horizon and other infamous offshore accidents magnified the need to close the gap for missed proactive measures and the need for strengthened, resilient monitoring systems. With sustainability and corporate accountability being critical for the future, pipeline integrity management is both an unfortunate reality and an ethical necessity (Iqbal *et al.*, 2019; Hunsberger and Awâsis, 2019).

Monitoring and inspecting pipes have many aspects that can be integrated; however, most methods focus on precise aspects and deep-seated limitations. As reported by Zhang *et al.* (2019) and Chemisky *et al.* (2021), operators focus on prompt surveys done by ROVs, AUVs, and ILL. Current methods remain extremely resource-intensive and deploy snapshots, resulting in patches of situational understanding. In addition, monitoring systems that trigger alerts after surpassing critical thresholds employ a counterproductive and reactive approach towards monitoring (Zohrevand and Glässer, 2019; Rahouti *et al.*, 2021). Responses generated in such intervals are often either too slow, inadequate, or completely divorced from reality. Dealing with such circumstances in the future will require decision-making that transforms static systems, breaks simplistic defensive automatic alert modalities and thresholds, and develops customizable, integrated solutions for monitoring

in complex environments (SHARMA *et al.*, 2019; Ghosh *et al.*, 2019).

The use of digital twin technology is a case of paradigm-shifting innovation that directly addresses these gaps. Digital twins are dynamically updated virtual models of a physical asset intersecting with the real world through data received from multiple sensors, inspection devices, and monitoring systems of the asset and its context (Bécue *et al.* 2020; Singh *et al.* 2021). Digital twins operationalize data along with sophisticated simulations to enable real-time monitoring of the pipeline conditions, predictive forecasting of probable failures, and assist in decision-making via scenario modeling. Underwater digital twins, for instance, can combine inspection datasets and ROVs along with other imaging data, cathodic protection telemetry, and other physical parameters like temperature, seabed shifts, and marine growth activities (Stevens *et al.* 2021; Elijah *et al.* 2021). This helps estimate degradation rates and improve the effectiveness of maintenance resource allocation. More importantly, digital twin technology shifts the pipeline integrity management from a reactive to a proactive, data-driven approach, which increases asset reliability, reduces costs, and lessens the overall environmental footprint (Olaseni 2020; Adebisi *et al.* 2021).

The relevance of digital twin solutions is further bolstered by various domestic and international policy efforts seeking to prop up infrastructure resilience. In the United States, the Department of Energy (DOE) and the Department of Homeland Security (DHS) specifically describe the integration of advanced data analytics, machine learning, and simulation tools into the management of critical energy infrastructure as essential. These efforts underscore the importance of having systems that are robust and agile to evolving risks, including natural hazards, cyber-physical threats, and aging asset issues (Ross *et al.* 2019; Cesarec, 2020). By aligning digital twin frameworks with the DOE and DHS objectives, subsea pipeline monitoring systems can enhance the resilience and security of the energy infrastructure ecosystem. Further, the global policy drive toward energy transition and climate resilience also offers opportunities to digital twins for not only traditional hydrocarbon transport systems, but also for emerging subsea networks for hydrogen and CCUS products.

Within the context of offshore energy transport involving subsea pipelines, the essence of integrity management to avert failures with dire, unforeseen economic, environmental, and social implications cannot be overstated. While inspection methods do offer some information, the fact that they are done periodically and reactively creates gaps in the management of risk. Digital twin technology provides a significant innovation with its shift toward real-time continuous monitoring and predictive analytics, thus enabling more intelligent and resilient asset management. Its alignment with the DOE and DHS underscores its importance to the national energy security and resilience in the primary hydrocarbon networks as well as the future low-carbon energy systems (Ahmed and Engel, 2020; Johnson, 2020). This examines the digital twin subsea pipeline monitoring and integrity management framework, proposing new ways to sustain, protect and monitor offshore structures in response to shifting energy and environmental priorities.

2. METHODOLOGY

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology was applied to ensure transparency and rigor in developing the digital twin framework for subsea pipeline monitoring and integrity management. A structured search strategy was conducted

across multidisciplinary databases, including Scopus, Web of Science, IEEE Xplore, ScienceDirect, and SpringerLink, as well as key industry standards and guidelines from organizations such as DNV, API, and the U.S. Department of Energy and Department of Homeland Security, which focus on smart infrastructure resilience. Search terms combined keywords such as “digital twin,” “subsea pipeline,” “structural integrity,” “ROV inspection,” “marine environment monitoring,” and “predictive maintenance.” Boolean operators and truncation were employed to refine the search and capture variations of the terms.

Duplicate records were removed, and inclusion criteria were defined to select studies addressing digital twin applications, subsea pipeline monitoring, probabilistic reliability, machine learning for anomaly detection, or integration of inspection and environmental datasets into structural health models. Studies not related to subsea applications, those focusing exclusively on surface pipelines without a marine context, or those lacking methodological rigor were excluded. Both peer-reviewed journal articles and industry white papers were included to balance theoretical advances with practical industrial implementations.

The screening process involved a two-stage review. Initially, titles and abstracts were examined to exclude irrelevant works, followed by full-text reviews to confirm methodological relevance. Articles that met eligibility requirements were analyzed and coded into categories such as digital twin architecture, data fusion methods, inspection technologies (ROV, AUV, NDT), environmental parameter integration, and applications for resilience-driven integrity management. A PRISMA flow diagram documented the process, including records identified, screened, excluded, and finally included for synthesis.

Data extraction was performed systematically, collecting details on study objectives, methodologies, datasets, digital twin architectures, analytical models, and outcomes. Emphasis was placed on frameworks that integrated heterogeneous data sources such as inspection recordings, ROV imaging, and environmental parameters into unified digital environments. Special attention was given to studies aligning digital twin applications with resilience initiatives led by DOE and DHS, focusing on how these approaches enhance monitoring, predictive maintenance, and emergency response.

The synthesis combined qualitative and quantitative insights, highlighting key technological trends, limitations, and research gaps. Qualitative synthesis mapped the progression from traditional monitoring systems to advanced digital twin ecosystems, while quantitative comparisons examined performance improvements in predictive accuracy, maintenance efficiency, and failure probability reduction. The final integrated review informed the development of a digital twin framework that unifies inspection, environmental, and reliability modeling within a resilience-oriented decision support system

2.1 Conceptual Framework of the Digital Twin

The advent of digital twin technology represents a shift in approach to the monitoring and management of complex infrastructure systems. For example, within the framework of subsea pipelines, a digital twin describes a pipeline system whose physical attributes are captured in a virtual twin evolving in tandem in real-time and with attributed data. Unlike the models of the past, which fragmented systems in a single

moment, a digital twin is much more alive and reflects the changes in the operational dynamics, the stressors of the external environment, the condition of the asset, and the environment in which the asset operates (Rasheed *et al.*, 2020; Podskarbi and Knezevic, 2020). The digital twin is the first technology that integrates the physical structure of a subsea pipeline with the computational structure, creating a cyberspace. The twin not only visualizes the current state of the physical asset but also predicts its future performance and prescribes optimal remedial actions.

The digital twin of a subsea pipeline aims to achieve three basic objectives. First, a digital environment must be constructed whereby multi-source data are integrated and synthesized. Subsea pipelines are monitored through a variety of means, such as ROV imagery, cathodic protection surveys, ILI tools, and environmental monitoring systems. Each monitoring approach, despite having value, captures fragmented aspects of the pipeline's state. The digital twin framework amalgamates the heterogeneous data streams and datasets, reformatting them to produce a consistent, unified, and real-time view of the asset (NATIVI *et al.*, 2020; Lattanzi *et al.*, 2021). This integration enhances the understanding of the situation and allows for sophisticated analytics that exploit associations across numerous data domains.

The second objective concerns enabling the predictive modeling of degradation mechanisms. Corrosion, cyclic loading-induced fatigue, accumulations of marine growth, scouring, seabed movement, landslides, and corrosion fatigue all pose failure risks to subsea pipelines. Most monitoring systems only discover such mechanisms retrogressively and post-critical threshold transverses. A digital twin, in contrast, contains complex simulation models and probabilistic computation modules that can predict the degradation mechanisms under specific operational and environmental conditions. For instance, the twin forecasts corrosion growth, correlatively valuing the risks of the cathodic protection, seabed chemistry, and flow-induced vibration, and can remotely predict highlight sections of elevated risk. This predictive ability alters integrity management to focus on proactive risk avoidance strategies instead of reactive inspection-based responses (Falsetta *et al.*, 2020; Velmurugan and Dhingra, 2021).

Enabling maintenance and emergency planning decision support is the other focus area of the third objective of the digital twin framework. Relying on expert opinions and post-inspection reviews is the dominant approach when addressing pipeline integrity decision-making. This approach is often constrained by the available data and the amount of time required to process the data. This is during decision-making when the pipeline digital twin could offer several options the decision makers could choose from on the spot. Zhou *et al.* (2021) and Meierhofer *et al.* (2021) argue that a continuously updated digital twin would offer decision support and could imagine the impacts of and differentiate between various intervention strategies available for pipelines or other supported assets. This includes estimating how much coated repair is needed compared to how much cathodic protection adjustment is required or how much structural reinforcement is feasible in certain sections. In the case of sudden anomalies such as a pressure loss or a clam bed shift, a digital twin will rapidly conduct data analysis, locate where the defect could be, recommend rapid closure of the defect, and offer support on how to mitigate downtime to minimize risks, which would be detrimental to the environment or human life.

The life cycle of a digital twin for subsea pipelines starts at the conceptual framework and moves to prescriptive management. The first stage is design, where the initial digital twin gets constructed. It involves, for the first time to develop a physics-based or data-driven model geometry and model of the pipelines and their props, and allowing the environment to model its props and conditions to develop. It's time to incorporate the historical design parameter and other data, such as bathymetric surveys and soil structure interaction, to create a model of baseline representation. A digital twin is a static structure at first, but it directly aims to become dynamic by the time operational data is provided.

The second stage of the life cycle – operational phase – is characterized by the incessant ingestion of inspection and sensor data vis-à-vis distributed fiber optic sensors, acoustic monitoring systems, and cathodic protection sensors. These instruments transmit real-time data, such as strain, temperature, and electrical potential, on vibrations. ROV and AUV surveys also offer additional visual data on the coating, cracks, and marine growth. These data streams are incorporated within the twin, thereby updating and enhancing the twin's condition models of the twin and the pipeline. Due to this, the phase is dynamic and ensures that the digital twin maintains fidelity and is up to date with the physical system. The dynamic phase fully captures the system's information and state, which also includes changes that occur abruptly, as well as slow degradation (Madni *et al.* 2019, Minerva *et al.* 2020).

The predictive and prescriptive phases are part of the third stage. In the predictive phase, forecasting is done by incorporating cross analytics, machine learning, and finite element simulations. For example, the twin simulates the scenario where the seabed is eroded and how that would impact the stability of the pipeline, or increased tension of the content in the future energetic material, and how that would embrittle the material that it carries. These projections help the operators understand and identify the risks long before they could result in improper functioning of the system. In the prescriptive phase, the digital twin goes beyond prediction to provide actionable recommendations. It provides recommended maintenance schedules, repair techniques, and flow re-routing, seam-based simulation (Liu *et al.*, 2020; Dugan *et al.*, 2021). If the digital twin adds cost, safety, and environmental perspectives on the recommendations given, that would determine whether its role would be as a partner in decision-making or merely as a diagnosis.

This approach helps ensure that the digital twin transitions from a static model to a dynamic system that can learn and grow. It evolves from describing and assessing an issue to predicting and prescribing a solution, thereby establishing an ongoing cycle of interaction between the real and virtual worlds. This capability, which is a huge leap forward in subsea pipeline management, helps operators to lengthen asset life, conserve maintenance spending, and meet regulatory standards on environmental protection (Ho *et al.* 2020; Constantinis and Davies 2020).

The conceptual framework also addresses the strategic priorities of smart infrastructural resilience. With subsea pipelines increasingly carrying oil and gas, and also hydrogen and carbon dioxide for carbon capture and storage, the risks of potential new corrosion mechanisms need to be foreseen and countered. The digital twin is an effective and agile model that can handle both anticipated and unanticipated operational issues (Kousi *et al.* 2019; Erkoyuncu *et al.* 2020). Its merger of multi-source information, predictive insight, and multi-tiered operational decision-making serves the purpose of the U.S.

Department of Energy and the Department of Homeland Security, which advocate for an integrated, resilient, and data-centric approach to the management of pivotal energy assets.

A digital twin of subsea pipelines is a dynamic embodiment of a sophisticated model with a life cycle characterized by design, operation, predictive and prescriptive analytics, spanning deep integration of data, forecasting, and decision support. The digital twin transforms the fundamental underpinning of the subsea pipeline, integrity management by integrating diverse data streams, predicting degradation phenomena, and orchestrating timely corrective actions. It profoundly redefines subsea pipeline integrity understanding and management, providing a structuring principle for resilience and adaptability necessary for the safe and sustainable transportation of offshore energy, harmonious with the global system energy evolution (Valenturf *et al.* 2021, Arcangeletti *et al.* 2021).

2.2 Data Sources and Integration

The capacity for effective data integration and analysis is crucial to modern-day integrity management of subsea pipeline systems. As underscored by Agostinelli (2021), contemporary digital architectures like digital twins or machine-learning frameworks emphasize the importance of quality data streams refined into actionable insights to support timely and relevant decision-making. The data streams of interest split roughly along the lines of inspection data, ROV (remotely operated vehicle) data, environmental data, and the overarching data fusion layer that allows integration across different formats and modalities, as shown in Figure 1. The goal of this section is to delineate the different data categories and elucidate methods for their consolidation into unified pipeline monitoring systems.

The pipeline condition and integrity assessment rests on the cross-sectional integrity of the inspection recordings, more popularly known as the foundational datasets. The utility of non-destructive testing (NDT) methods in the quantification of degradations associated with the internal and external corrosion of structural components remains dominant. Ultrasonic thickness and magnetic flux measurements may provide the sought high-fidelity measurements of wall thinning, corrosion, and other external structural degradations chemically or mechanically influenced by the hydrocarbon mediums. Predictive and probabilistic risk models associated with the service life of any structure will be estimated from the primary NDT and quantitatively assessed against any of the probabilistic risk assessment frameworks.

Videos and images from Remotely Operated Vehicles (ROV) and divers augment the NDT process. Inspections made by divers are still essential for assets in shallow waters, where deep tactile touch and various types of direct intervention are available. The high definition and NDT-enabled ROV images expand the ability to inspect deep water pipelines where touch is unavailable. The ability to retrieve high-definition images and videos permits the assessment of the presence of dents, structural anomalies, and marine growth on the coating. The videos and still photographs provide qualitative information for the NDT results and reinforce the MDT approach by formulating a hypothetical situational relevance of the damage behind the recorded environmental settings (El Masri and Rakha, 2020; Gupta *et al.* 2021).

The balance of the information is obtained from the history of the undertaking, complemented by storing the information about various maintenance and repair logs. Such plans provide insights into past embedding, followed by the strategies and steps for repair, coating exchange, and the cathodic protection

reinstated. The reinforcement of the historical logs with the recent inspection results facilitates in construction of temporal degradation trajectories. These trajectories allow us to determine if the defects are recent or the consequences of a previously existing condition. The historical information permits enhancing the accuracy of reliability estimates and supports proof for the effectiveness of past strategies producing (Pettersen and Schulman 2019; Hund, L. and Schroeder 2020).

ROVs do most of the work when monitoring subsea pipelines for visual inspection because they complement it with real-time imaging of the pipelines and surrounding areas using high-resolution cameras and laser scanners. They also provide laser scanners and other imaging systems with the ability to recognize and classify defects such as corrosion, cracking, and biofouling with very little human oversight, thanks to sophisticated computer vision systems. They also allow for the recognition, and even automated recognition, of other sophisticated phenomena, thanks to the advances in imaging.

Robotic submersibles have integrated platforms that are also important for subsea imaging and include systems for optical and non-optical imaging. Non-optical imaging systems include systems for the acoustic visualization of the surrounding areas. Makes it possible to record acoustic signals for optical visualization and other subsea mapping techniques. Sonar profiling provides the capability for creating three-dimensional imaging systems of the seabed, and also for reconstructing, realigning, and even relocating submerged pipes. They allow for the recognition of geotechnical instability areas, changes in free spans, and burial depth with respect to position and range (Guigne and Blondel, 2019, and Anderson *et al.* 2019). These provide essential data that the computational fluid dynamics systems utilize when computing the maximum stress core from fluid pumping.

Payloads of ROVs often incorporate sensor packages specifically tailored to evaluate cathodic protection performance. By utilizing voltage and current mapping, it is possible to determine the distributions of electrochemical potential and to delineate the specific zones of underprotection and overprotection, which may accelerate the corrosion. These electrochemical measurements augment combined NDT-measured thickness data with a mechanistic approach to understanding the dynamics of corrosion. Therefore, the synthesis of images, acoustics, and cathodic protection data enables ROV surveys to serve as comprehensive diagnostics on the cathodic protection system of a subsea pipeline (Zhang *et al.*, 2019; Polagye *et al.*, 2020).

The integrity of the pipeline does not exist in isolation. Rather, it is intrinsically connected to the surrounding oceanographic and geohazard environment. Boundary conditions for both empirical and numerical approaches depend on oceanographic datasets. Current relative position, temperature, and salinity correlate in a complex fashion to corrosion rates, profiles of colonized marine organisms, and the mechanics of sediment dynamics. Data on the composition of the seabed help determine the stability of burial depth and vulnerability to scour in areas of active sediment mobility.

The action of water and air, among other forces, applies cyclic stresses to exposed spans of pipelines during storms and other severe weather, which accelerates fatigue damage. Thus, long-term records of water and weather are critical to estimating cumulative fatigue life and identifying elevated risk periods. Real-time weather data can be combined with historical records of storms to predict periods of high energy that could destabilize structures (Chen *et al.*, 2020; Temmer, 2021).

Geohazard datasets add another critical aspect to the available information for environmental monitoring. The majority of subsea pipelines cross areas prone to subsidence, slope failures, and seismicity. Geotechnical investigations and seismic hazard models quantify ground motion potential, fault activity, and soil shear strength to define geo-structural parameters. These geohazard components allow the dynamic risk modeling to include intrinsic decay mechanisms of the pipeline and the surrounding exogenous hazards of the subsea environment.

The collection of inspection, ROV, and environmental datasets examines the singular integration of the Constructed Layer of data, which serves as an interconnective digital structure. The data fusion layer becomes the architectural backbone of the integration as it combines disparate, concurrently collected sources into a single digital environment. The integration of unique formats and datasets that are proprietary standards, as well as those generated by different vendors, emphasizes the need for interoperability protocols.

The integration of datasets, which are neither glued nor rendered invisible through issues of compatibility, is effortlessly arranged due to the acceptance of open data standards (Avula, 2021; Trice *et al.*, 2021).

Standard pan data security laws and regulations are supplemented—open data standards are compliance mechanisms of the Department of Energy (DOE) and the Department of Homeland Security (DHS). The regulated data formats and defined reporting frameworks ensure the recurrence of data architecture across various projects, as well as the simplified inter-organizational collaborations for infrastructural resilience at the regional and national levels.

As part of the data fusion layer, GIS mapping is one of the most powerful tools available. GIS systems allow the spatial mapping of pipeline condition, inspection anomalies, ROV observations, and other georeferenced data within the context of the environment. This visualization augments awareness of the situation among operators and regulators, presenting a clear way to pinpoint areas of deterioration, correlate clusters of defects with surrounding stressors, and focus maintenance efforts on time. GIS has added predictive models, and in such scenarios, it reflects different risks that can be enabled in real time for the operators and predictors of the environment (Mbuh *et al.*, 2020; Sethupathy, 2021).

Integration of various categories of data into a single seamless digital framework determines the success of the monitoring and integrity management of the subsea pipelines. The recordings of inspection provide a history and chronologically precise measurements of the pipelines. The ROV data allow monitoring of depth with a sensor's multi-modality package. These data sets associated with diving deeper into the ecosystem assist in understanding the various determinants of the dynamic pipeline degradation systems that occur in oceanographic and geohazard systems. The data fusion layer harmonizes these disparate inputs into an interoperable, classified, and georeferenced web framework. So, the geospatial context and the integration of various data streams facilitate better proactive maintenance and subsea energy infrastructure protection. The need for seamless data integration will reach new heights as elaborate systems expand in their geography.

2.3 Digital Twin Architecture

The digital twin's architecture for monitoring and managing the integrity of subsea pipelines is an example of a multi-layered system that synthesizes physical data capture with advanced

analytics and interactive visualization, secure storage, complex interactivity, and multi-level decision support. Each layer functions autonomously, *yet all* integrate into a cohesive system that reflects the underwater infrastructure's situational awareness and manages it proactively (Lehr *et al.*, 2019; Callcut *et al.*, 2021). These components can be reduced into five primary interconnected layers: physical, data, analytical, visualization, and decision support, as shown in Figure 2.

Monitoring hardware and devices, excerpted from the physical layer that the digital twin rests on, are used to gauge the subsea world and the operational states of the line. Through distributed silicon sensors along the pipe, the critical attributes of the line, such as pressure, temperature, strain, vibration, cathodic protection, and potential, are captured. These measurements seek to capture phenomena around gradual device degradation, such as corrosion and fatigue, along with critical events like leaks or coating failure. With fixed sensors and as part of the seamless collaboration with the AUVs as well as ROVs, there are periodic assessments where the line is inspected at high resolution using sonars and laser scanners, as well as advanced imaging. (Watson *et al* 2020, Whitt *et al* 2020) These aimed and designed devices allow for high-accuracy geometric and visual assessments of various pipe states, such as cracks, buckles, free spans, and the growing free-living marine. This collective data captures the health of the pipes and serves as the foundation for the digital twin, along with the seamless and continuous pipe health data harvested with high precision.

The data layer serves as the repository and processing center that facilitates the efficient management of massive and diverse datasets that the physical layer generates. Secure cloud data storage systems have virtually unlimited ability to store inspection images, sensor time series data, and environmental monitoring data. In order to decrease latency and increase resilience, edge computing nodes that are geographically located near offshore installations perform the first stages of processing raw data streams, multiplexing and filtering streams to remove noise, value normalization, and data file size reduction to increase efficiency in transferring data. This architecture allows actionable data to be available in near real-time and minimizes the need for expensive, bandwidth-intensive channels. Also, confidentiality and other access control measures protect the sensitive data pipelines against exposure to potential adverse cyber actions (Baladari, 2020; Owobu *et al.*, 2021). In this manner, the data layer economically provides the higher architecture layers with secure data.

The analytical layer comprises the intelligence core of the digital twin. It integrates statistical methods, machine learning, and simulations to give meaning to unprocessed data. There are probabilistic models of reliability that determine and quantify the potential for failure, corrosively, and fatiguing, or buckling under random and uncertain conditions. These models have random material property variation, environmental loadings, and inspection data of varying inspection systems as stochastic reliability bounds.

Machine learning tools improve the detection of anomalies by studying massive amounts of imagery obtained from ROV inspections. In the datasets annotated with defects, trained Deep Learning models automatically capture cracks, coating disbandment, or covered marine growth that go unnoticed by people. These systems proposed by Perez *et al.* (2019) and Protopapadakis *et al.* (2019) improve the accuracy of detection, shorten the time needed for the entire inspection, and provide uniformity across extensive datasets.

In addition, stochastic simulations help predict time-to-failure for varied operational and environmental conditions. For instance, Monte Carlo methods create probabilistic models of degradation curves, which enable operators to forecast expected failure timelines and predict confidence intervals. By incorporating stochastic simulations with probabilistic reliability and machine learning, the analytical layer predicts and prescribes management actions that propel integrity management above traditional inspection-centered models (Osho *et al.*, 2020; Ren, 2021).

The analytical layer's intricate findings are finally configured as visuals that decision-makers can understand. 3D and 4D interactive models show the subsea pipeline system vis-à-vis the geography and timelines, which then permits the operators to analyze in real time the degradation of the pipeline system, the strain distributions, and their environmental interactions. 4D time-enabled models also showcase the evolution of anomalies to provide advanced warnings about high-risk areas

Operators, regulators, and emergency responders, among other stakeholders, receive integrated and tailored information through augmented dashboards. Operators view dashboards that focus on performance, risk, and maintenance. Permitted users are provided with views that focus on regulatory compliance with safety and environmental policies. Dashboards for Emergency responders are rapid response dashboards that identify response anomalies and strategies and recommend actions. The dashboards increase situational awareness of each user group, and the dashboard layer 'visualization makes certain that the insights are actionable and relevant to the users' operational roles (Nadj *et al.*, 2020; Dixit *et al.*, 2020).

The pinnacle of the framework is the decision-support layer, which transforms the operational and strategic guidance that comes from the analytical insights and visualized outputs. One of the decision support functions is the optimization of maintenance scheduling, which enables users to intervene based on operational risk profiles, degradation forecasts, and resource availability. This approach to maintenance scheduling and resource allocation ensures minimum asset downtime and operational availability, avoiding unnecessary costs and extending asset lifetime.

The support that aligns critical infrastructure for compliance with the engineering criteria set by the U.S. Department of Energy and Department of Homeland Security is a real-time risk assessment. These assessments evaluate multi-hazard scenarios, including corrosion, geohazards, and operational anomalies, to comply with national resilience standards of critical infrastructure.

Furthermore, the decision-support layer assists in virtual failure event mapping for scenario testing. For instance, modeling the impacts of losing a coating, extreme weather, or seismic activities on the drones' ability to stabilize the pipeline. Such modeling scenarios help operators better anticipate responses, enhance strategies for response, and improve overall contingency planning. By engaging with the decision layer, the digital twin gets enhanced predictive analytics with prescriptive decision support to engage as an active contractor, driving the pipeline operations on safety, the environment, and operational durability.

As a system, the five layers of the digital twin architecture together constitute a digital twin system of interrelated and cohesive components where the physical ensures the generation of high-fidelity data, the data layer captures and

stream stores, the analytical layer provides the data with predictive elements, the layer of insights develops a clear narrative, and the decision support layer creates a balanced actionable layer. Implementation of these strategies improves the overall pipeline subsea operations reliability, with the addition of operational goals of the energy infrastructure to improve adaptability.

The subsea pipeline digital twin architecture integrates a wide-ranging sensing, computation, analysis, visualization, and decision-making framework. This integrated structure of multi-source data, modeling, and scenario testing allows operators to shift from a reactive integrity management posture to proactive resilience strategies (Sahu *et al.* 2021; Yitmen *et al.* 2021). This architecture, along with the Department of Energy (DOE) and Department of Homeland Security (DHS) initiatives, demonstrates how pivots are essential to protecting energy infrastructure from offshore threats and persistent and evolving risks

2.4 Advantages of the Digital Twin Framework

The ability to closely monitor complicated offshore energy infrastructure has outpaced conventional frameworks for digitally monitoring it. Advanced digitally immersive environments are emerging as potential solutions to monitor and manage subsea pipeline integrity, integrating geo-spatial/contextual augmented reality immersive insight with predictive behavioral models and complex analytics (Enemosah, 2019; Wanasinghe *et al.*, 2021). Through the use of predictive analytics, augmented reality, multi-layered data streams, immersive complex models, and immersive forecasts available from digital twins, critical subsea assets can be closely monitored, and the decision support system can be revised dynamically to adapt to changing environments, as shown in Table 1. The effectiveness of the system can be analyzed from two sources: monitoring system effectiveness and system infrastructure resilience.

Table 1: Advantages of the Digital Twin Framework

Category	Key Features / Advantages	Impact / Benefits
Over Traditional Monitoring	- Transition from reactive to predictive maintenance. - Reduction in unplanned downtime and inspection costs - Enhanced visibility into inaccessible subsea environments.	- Optimizes maintenance scheduling and resource allocation.- Minimizes operational disruptions and associated costs.- Enables continuous monitoring of assets that are difficult or unsafe to access physically.
Resilience Benefits	- Proactive adaptation to DOE & DHS resilience targets. - Improved emergency preparedness through simulated response	- Supports compliance with resilience and safety regulations. - Improves readiness for extreme events or system failures. - Reduces the likelihood and impact of

	scenarios. - Strengthened public and environmental safety by minimizing catastrophic failure risks.	environmental incidents, enhancing overall asset reliability.
--	--	---

A main advantage of digital twins is the ability to change the integrity management approach from reactive to predictive maintenance. Classic methods of monitoring subsea pipelines rely on the periodic inspections performed by remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), or inline inspection (ILI) tools. These methods generate useful information, albeit at infrequent intervals, thus resulting in periods of information blackouts with regard to the asset's status. Conversely, operators tend to notice corrosion fatigue after it has already caused serious damage. However, the digital twin, by integrating sensor data, inspection inputs, and other information, allows the creation of predictive models to estimate the future value of the asset. As a result, operators are able to identify risks and take measures to prevent failures from occurring. The digital twin model also allows maintenance to change from a reactive approach, where a company is forced to manually handle problems, to a predictive approach that eliminates the chance of failures.

Beyond predictive abilities, the digital twin framework significantly reduces both the costs of unplanned downtime and the costs associated with inspections. Inspections that are conducted offshore are particularly resource-demanding, requiring the use of specialized vessels, equipment, and personnel. Moreover, unplanned downtime that is a result of unanticipated pipeline failures poses a significant financial burden in terms of the loss of production and the costs associated with emergency repairs. Through the use of digital twins, disruptions of this nature can be minimized through the optimization of maintenance schedules and prioritization of interventions using data-driven risk assessments (Savolainen and Urbani, 2021; Bazmohammadi *et al.*, 2021). It also manages to ensure that all inspection and maintenance activities are carried out at the necessary times by simulating the degradation mechanisms and predicting the possible points of failure. This risk-based strategy minimizes the number of inspections conducted without reason while also ensuring that resources expended are adequate in volume, hence reducing costs while improving the reliability.

Another key advantage is enhanced visibility into subsea environments that are fundamentally challenging to access. Conventional monitoring is limited to the fundamental operational parameters that characterize deep water activities, such as strong currents, poor visibility, and high pressure. These parameters negatively affect the quality and temporal frequency of observation performed during inspections. The creation and use of digital twins alleviate these constraints by integrating a diverse array of sensing and inspection data into a unified persistent model that provides operational context in real time. Dynamic 3D and 4D visualizations let operators virtually move around storage areas and pipeline networks, examine the real-time condition of pipelines, and track and forecast deterioration as well as assess potential risk areas beyond the reach of human inspection. Enhanced visibility in these instances greatly increases the confidence of the operators and decisions that can be made, as well as the level of

situational awareness, which surpasses anything developed beyond the conventional mediums of operational context.

In addition to exceeding conventional monitoring, the digital twin framework provides resilience advantages that further the strategic goals of the U.S. Department of Energy (DOE) and the Department of Homeland Security (DHS). These agencies focus on protecting critical infrastructure resilience from both natural and anthropogenic hazards. Digital twins assist with these objectives by supporting proactive responses to threats and environmental pressures. The framework relies on constant revisions and simulative model constructions to anticipate and mitigate threats and operational safety and identify system vulnerabilities, ensuring operational resilience of subsea pipeline networks to future geo-climatic threats such as climate-induced instability of the seabed, extreme weather, and increased transport of alternative energy carriers like hydrogen and carbon dioxide.

The system similarly augments concern for emergency preparedness by running simulated scenarios. Most conventional contingency plans map out the guidelines in the case of subsea failures. In this case, digital twins allow operators to conduct virtual drills by simulating scenarios, such as coating failures, leak initiations, and even seismic movements on the seabed. These virtual drills reflect on how failures may propagate, the operational consequences of such failures, and the most effective different counter-intervention strategies. Digital twins facilitate the equipped emergency response teams by providing real-time situational awareness, which in turn, lowers response times and improves coordination and mitigation to unforeseen consequences.

Perhaps most importantly, the digital twin framework enhances public and environmental safety by mitigating the risks of catastrophic failures. Subsea pipeline incidents can cause considerable damage to the environment, such as the destruction of marine ecosystems and large-scale hydrocarbon spills, with long-term repercussions for coastal ecosystems and communities. These incidents pose substantial reputational and regulatory liability risks for operators as well. Digital twins, through the means of predictive monitoring and emergency response, are able to drastically decrease the chances of such incidents occurring. Their capability to model the effects of these incidents on the environment helps with regulatory approvals and assists in meeting global sustainability aims. Digital twins thus enhance not only the technical resilience of offshore energy systems but also the social license to operate of these systems.

All in all, the digital twin framework is of transformative importance in subsea pipeline integrity management, as it provides the framework for predictive, risk-based maintenance as opposed to the reactive, costly traditional limitations of monitoring. In addition, it aids in achieving organizational and national resilience by minimizing societal risks and improved environmental preparedness. As the offshore energy sector evolves, it is the adoption of digital twins which will be instrumental in the balancing of economic efficiency, environmental responsibility, and public trust (Wanasinghe *et al.*, 2020; Borowski, 2021).

The digital twin framework provides predictive maintenance, improved visibility, maintenance and operational resilience, cost optimization, and enhanced visibility value adds for multifaceted benefits for subsea pipeline management. It also fulfills its capacity to borderlessly adapt to DOE and DHS resilience targets, improving emergency preparedness and minimizing the protective costs for human and environmental

safety. It, therefore, becomes the backbone of contemporary offshore energy infrastructure. Digital twins simplify integrity management and, by connecting the physical and digital worlds, advance the safe, resilient, and sustainable operation of deep-sea facilities.

2.5 Practical Implications for Stakeholders

The incorporation of inspection data, ROV monitoring, environmental parameters, and data fusion technologies into the management of subsea pipeline integrity systems shapes a paradigm shift for multiple, diverse stakeholders. These include asset managers and operators who autonomously oversee the performance of the infrastructure on a daily basis, regulators who ensure safety and compliance, technological innovators, and policymakers who guarantee the resilience of the national energy supply. Each group has their own unique, yet interrelated advantages stemming from the adoption of these data-centric, digital twin-enabled methodologies, underscoring the holistic advantages of integrated monitoring systems (Fuller *et al.*, 2020; Mèda *et al.*, 2021).

The asset managers and operators stand to benefit most from predictive capacity stemming from integrated data systems. The primary assumption is and, to some degree, still remains, that maintenance is a function of the passage of time. Unpredictive maintenance approaches rely on rigid schedules and reactive responses to failures, both of which carry substantial inefficiencies. The integrated outputs from ROVs and environmental datasets to assess pipeline health in motion is far more valuable on the foresight and predictive capacity.

Alongside project management, finance is also a key component of project management. The maintenance budget for subsea pipelines is among the largest operational budget items in offshore oil and gas and renewable energy ventures. Through data-centric models, oil operators can focus on high-value, high-risk, and cost-effective maintenance and repair, thereby avoiding needless inspections and premature component replacements. The information concerning maintenance on the actual condition of the pipeline, assists with cost management with the ability to predict maintenance degradation patterns. Unplanned downtimes can also help mitigate failures in production and in turn improve profitability and the stability in the supply chain.

Safety also supports the business case for these technologies. Stopping monumental failures by taking action before losing control of the cracks, corrosion, and other hazards is protective of the oil business. It also supports the reputation of the organization by lowering the environmental concerns and the operational impacts of leaking hydrocarbons to the environment. The reputation is also supported by the help of the ESG disclosure reputation capital, which investors now underpin the value of any business.

For regulatory bodies, streamlined data sets allow for simplification in the compliance monitoring program. Complete and consolidated subsea operations are frequently undermined by unstandardized practices of monitoring, reporting, and data-logging submissions from operators (Gordon *et al.*, 2019; Bayliss *et al.*, 2021). The DOE and DHS standardization with respect to framework borders as sectorial DOEs use a common tongue in reporting for the oil and gas sector.

This also allows regulators to benchmark performance and examine compliance with safety and environmental standards, and conduct self-contained risk evaluations. They can use data layers that are geospatially mapped out to visualize entire

networks and cross sections rather than receiving localized reports. This ability improves oversight and allows for more informed regulatory choices. A good example is applying greater scrutiny to geohazard zones or modifying cathodic protection in corrosion zones.

Trust is enhanced through greater transparency. The energy infrastructure context is especially telling since there are dire societal and environmental impacts from any failures. Easy access to information that's been digitized and made standardized promotes the need for public accountability while also reinforcing accountability.

Subsidiary pipeline monitoring is made easier with the use of digital technology, thus presenting new chances for entrepreneurs in AI, robotics, and sensor technology. For example, ROV makers can create more marketable systems by outfitting their systems with high-def cameras, sonar profilers, and electrolyte sensors. There's a rising need for sensor systems that are compact, autonomous, self-propelled, and low energy asking as the need for restricted monitoring.

For technology vendors, the last frontier is represented by artificial intelligence (AI) and machine learning. Tools that automate defect recognition using computer vision replace the highly manual task of reviewing inspection videos, and predictive modeling tools integrate diverse datasets to anticipate various degradation trajectories. Such vendors are, therefore, strategically positioned to offer partners in the management of assets a Software as a Service (SaaS) solution that integrates with physical inspection hardware, which are the fundamentals of some asset management systems (Mäder, 2021; Silver and Sundvall, 2021).

The need for integration of disparate sources of data fuels the need for collaboration across technology boundaries. Data Fusion Layers: Different levels of data analysis performed in a data fusion system are described by various authors in different ways. Open standards and compliance agreements encourage a move from proprietary, siloed systems to flexible systems that are more interoperable and allow for deeper collaboration and greater technological advancement.

The policy implications of composite integrated monitoring systems are aligned with the objectives of national resilience. DOE and DHS focus on "smart infrastructure" as fundamental to energy security and note that subsea pipelines for fossil fuels and renewables are vital to the supply chain. Adopting data-based systems of resilience in infrastructure, in line with the above-mentioned initiatives, provides rational, backed systems for promoting infrastructure reliability.

The fragmented datasets remain a barrier to resilience planning at a systems level. Policy makers would have to remain tethered to isolated assets. Agencies would have to cope with analyzing the performance of regional networks in a fragmented manner and then allocate systemically. This fragmented funnel view remains a prerequisite to resolving cross-boundary cascading risks that might stem from extreme weather or seismic events.

In addition to the above to the other policies that DOE and DHS enforce, encouraging the adoption of digital twins, AI-assisted diagnostics, and real-time monitoring of the environment would embody a policy image of innovation-enhanced resilience. These other policies would work to meet a niche in providing leadership to the protection and resilience of critical infrastructure. There also appears to be the emergence of synergies with climate and oceanographic context policy folds as the usefulness of predicting and dampening adverse

environmental impacts continues to rise (Shrestha & Dhakal, 2019; Booth *et al.*, 2020).

The practical application of integrated data and monitoring frameworks goes well beyond stakeholder and partner boundaries. Under predictive maintenance, asset managers and asset operators enjoy substantially higher safety and cost efficiency. Regulators procure means for unobscured compliance. Robotics, sensors, and AI technology suppliers find niches for R&D work. Policy makers support smart infrastructure policies that enhance national resilience. These converging interests demonstrate that monitoring of subsea pipelines is more than a merely technical problem; it is a multi-faceted problem confined within operational, regulatory, technological, and policy boundaries. The growing global dependence on subsea infrastructure, coupled with collaborative access to integrated data frameworks, will make such data indispensable for safety, sustainability, and resilience..

2.6 Future Directions

The growth of digital twin systems for tracking and managing the integrity of subsea pipelines is becoming revolutionary. Although current frameworks exhibit the potential of amalgamating inspection records with ROVs and environmental data, future iterations are poised to expand this functionality. New promising avenues are the deployment of AUVs with sophisticated sensor networks, integration with real-time weather forecasting, blockchain data verification, cross-asset digital twin networks, and the creation of uniform standards for cross-border digital twinning of national infrastructure projects, as shown in Figure 3 (Jain *et al.*, 2021; Ahuja *et al.*, 2021). Collectively, these developments will not only improve the dependability of operations but also foster a more resilient and transparent infrastructure.

The AUVs are expected to augment the spatial and temporal extensiveness of subsea surveillance. Unlike ROVs tethered to a control console, AUVs can accomplish programmed missions, thus enabling the far-reaching continuous monitoring of subsea pipelines. With modular payloads, AUVs equipped with high-resolution sonar, cathodic protection sensors, and analyzers for the constituents of water within pipelines can provide critical information on early-stage degradation mechanisms over wide regions.

The use of AUVs for monitoring activities does make the use of manned vessels less frequent and expensive. Built for the future, AUV swarms promise to revolutionize AUV monitoring through near-continuous, real-time streaming of integrated data to digital twins. This operates within a paradigm shift that displaces a reliance on episodic inspection campaigns to episodic, or near-continuous, condition awareness for predictive modeling, thus greatly increasing the integrity management model's fidelity.

The integrity of an underwater pipeline can be affected by several multifaceted oceanographic conditions, such as underwater currents and varying temperatures, along with disturbances such as storms. Most digital twin models of today center on a locked and periodically refreshed matrix of data with little else. This does not enable them to detect sudden threats or respond to them. Certainly, future frameworks will increase their incorporation of real-time models of oceanographic forecasting built around satellite data, buoy networks, and sophisticated numerical modeling of hydrodynamic forces.

The model shifts the monitoring condition assessment from merely static condition assessment to more dynamic monitoring. For instance, digital twins capable of simulating pipeline sections under stress can be instituted for stress reduction mitigation through changing valve states for predictable high-energy storms or automated shutdown mechanisms. Such advances will thus enhance confidence that the environmental monitoring models integrated with condition data can be relied on to transform digital twin models from monitoring to active decision support models.

Operators and regulators are increasingly concerned with maintaining data integrity and authenticity as the volume of monitoring data increases. One potential solution is the application of blockchain technology, which records data from the specifics of the inspection and maintenance transactions of sensors and ledger records on immutable distributed ledgers. Each ledger in the blockchain can be secured using cryptographic methods, rendering any form of alteration or deletion of results impossible.

With blockchain technology, regulators can address longstanding issues with compliance tracking using verified and transparent data trails. Operators and regulators have fewer disputes regarding inspection outcomes and the subsequent audits, which improves operator confidence in the audit. In the future, the frameworks could be integrated with smart contracts, which, by exceeding defined thresholds, can automatically trigger regulatory workflows or alerts for maintenance (Khan *et al.*, 2021; Ajuwon *et al.*, 2021). This reinforces the automated and decentralized ecosystem for subsea pipeline integrity management.

This also shifts the focus from individual assets like pipelines, which is the current application of digital twin technology, to ecosystems of cross-asset integrations with multiple subsea and offshore elements. The interconnecting and interconnected pipelines, production platforms, subsea manifolds, and even offshore wind power cables form an integrated system. A degradation event in one component generates vulnerabilities across the system.

Integration of different assets' digital twins allows operators and regulators to analyze performance from multiple angles. For example, the seabed instability located around a pipeline might also endanger the adjacent power export cables to offshore wind farms. Cross-asset ecosystems facilitate coordinated risk assessments, shared data, and maintained strategy optimization across divergent energies. This integration supports the increasing tendency of hybrid offshore energy developments with coexisting oil, gas, and renewables.

The next and last of the crucial frontiers for future directions involves the integration of digital twin protocol standardization toward the DOE and DHS. Right now, the absence of standard data sets, interoperability instructions, and corresponding performance regulations stifles collaboration across siloed domains. In the absence of alignment, digital twins run the risk of becoming fragmented, vendor-oriented solutions.

Once standardization of digital twin protocols is achieved, operators and operators, tech developers, and regulators will all be able to plug their data seamlessly into national structural resilience plans. This will also lower the 'regulatory drag' by setting standards that are predictable and easy to follow for tech sanctions. More than just pipelines, this will be able to facilitate the convergence layering with other core energy infrastructures, establishing a national digital spine for smart resilience infrastructures.

The growth and convergence of digital technologies is set to transform the management and monitoring of subsea pipelines. Persistent coverage will be enabled by sensor networks deployed on autonomous underwater vehicles, and real-time oceanographic forecasting models will support proactive responses to evolving threats (Hwang *et al.*, 2019; Shi and Zhou, 2020). Blockchain will preserve the compliance and data integrity, cross-silo digital twins will provide cross-system insights, and the standardization of contacts across DOE and DHS initiatives will provide national-scale cross-domain interoperability. Collectively, these trends indicate fundamental energy networks will be protected by uninterrupted, transparent, and resilient monitoring, irrespective of growing operational and environmental complexities, as shown in Fig 3.

3. CONCLUSION

The digital twin framework incorporates state-of-the-art analytic capabilities to merge operational data streams with simulated dynamic insights for real-time subsea pipeline integrity supervision. Unlike conventional sequential, fragmented inspection and monitoring approaches, digital twins offer inspection and tracking systems with a Continuous Integrated Dynamic Representation (CIDR) of subsea assets. This enables robust analytics to assimilate inspection data, environmental data, and structural performance data in real-time to support robust, multi-faceted decision-making. Digital

twins allow for an adaptive monitoring framework, shifting the industry from reactive to proactive management.

The evolution of this model pivots around an integrated prospective approach to monitoring data streams for resilience. Predictive analytics embedded within the framework enables early pattern recognition and baseline assessments for corrosion, fatigue, and marine growth. Integrating inspection data, environmental sensor data, and simulations pivots monitoring from a snapshot in time to a dynamic, multi-variable assessment, then continuously adapts to changing oceanographic conditions. Resilience-oriented design frameworks align with DOE, DHS, and infrastructure's focus on post-hazard disruption systems with resilient, redundant, and adaptive structural dispositions.

Along with innovations in technology, digital twins have made a significant impact in safer management, lowering costs, and aligning infrastructure management with relevant policies of offshore structures. Digital twins also help in providing economic benefits, lowering inspection costs, and optimizing maintenance scheduling. Digital twins also help enhance emergency preparedness and risk mitigation, and improve public and environmental safety. All of these improve the digital twin's public value. The increasing complexity and interdependence of subsea energy systems make the digital twin the ideal framework for maintaining the DOE and DHS offshore operational policies with continuity and sustainability.

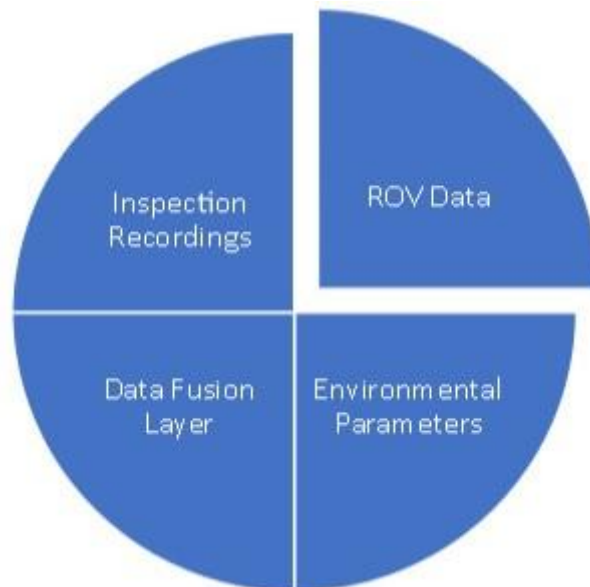


Fig 1: Data Sources and Integration

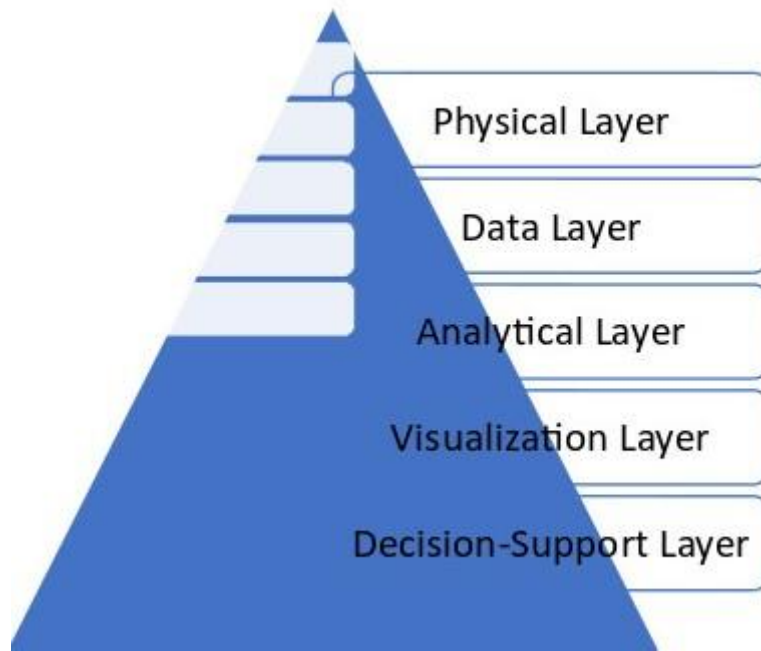


Fig 2: Digital Twin Architecture

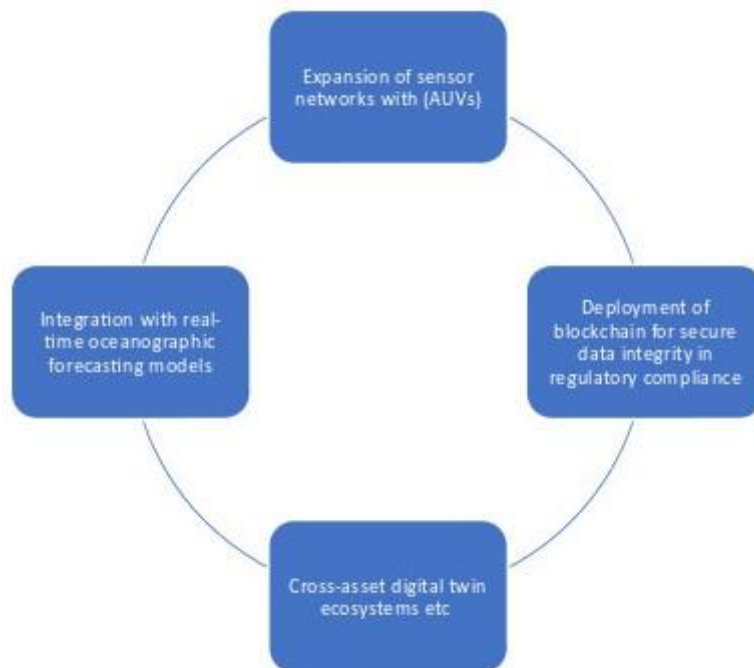


Fig 3: Future Directions

4. REFERENCES

- [1] Adebisi, B., Aigbedion, E., Ayorinde, O.B. and Onukwulu, E.C., 2021. A conceptual model for predictive asset integrity management using data analytics to enhance maintenance and reliability in oil & gas operations. *International Journal of Multidisciplinary Research and Growth Evaluation*, 2(1), pp.534-54.
- [2] Agostinelli, S., 2021. Actionable framework for city digital twin-enabled predictive maintenance and security management systems. *WIT Transactions Built Environment*, pp.223-233.
- [3] Ahmed, S. and Engel, R. eds., 2020. *Making US foreign policy work better for the middle class* (Vol. 23). Carnegie Endowment for International Peace.
- [4] Ahuja, N.J., Srikanth, P., Konstantinou, C. and Kaust, C.E.M.S.E., 2021. Blockchain and Autonomous Vehicles: Recent Advances and Future Directions. *Research. Gate*.
- [5] Ajuwon, A., Adewuyi, A., Nwangele, C.R. and Akintobi, A.O., 2021. Blockchain technology and its role in transforming financial services: The future of smart contracts in lending. *International Journal of Multidisciplinary Research and Growth Evaluation*, 2(2), pp.319-329.
- [6] Anderson, M.O., Hannington, M.D., McConachy, T.F., Jamieson, J.W., Anders, M., Wienkenjohann, H., Strauss,

- H., Hansteen, T. and Petersen, S., 2019. Mineralization and alteration of a modern seafloor massive sulfide deposit hosted in mafic volcanoclastic rocks. *Economic Geology*, 114(5), pp.857-896.
- [7] Arcangeletti, G., Aloigi, E., Baldoni, A., Branduardi, L., Castiglioni, F., Filippi, A., Leporini, M., Masi, O., Mercuri, A., Orselli, B. and Panico, P., 2021, September. Advancing Technologies for H2 and CO2 Offshore Transportation Enabling the Energy Transition: Design Challenges and Opportunities for Long Distance Pipeline Systems. In *Offshore Mediterranean Conference and Exhibition* (pp. OMC-2021). OMC.
- [8] Avula, R., 2021. Addressing barriers in data collection, transmission, and security to optimize data availability in healthcare systems for improved clinical decision-making and analytics. *Applied Research in Artificial Intelligence and Cloud Computing*, 4(1), pp.78-93.
- [9] Baladari, V., 2020. Adaptive Cybersecurity Strategies: Mitigating Cyber Threats and Protecting Data Privacy. *Journal of Scientific and Engineering Research*, 7(8), pp.279-288.
- [10] Bayliss, K., Mattioli, G. and Steinberger, J., 2021. Inequality, poverty and the privatization of essential services: A 'systems of provision' study of water, energy and local buses in the UK. *Competition & Change*, 25(3-4), pp.478-500.
- [11] Bazmohammadi, N., Madary, A., Vasquez, J.C., Mohammadi, H.B., Khan, B., Wu, Y. and Guerrero, J.M., 2021. Microgrid digital twins: Concepts, applications, and future trends. *IEEE Access*, 10, pp.2284-2302.
- [12] Bécue, A., Maia, E., Feeken, L., Borchers, P. and Praça, I., 2020. A new concept of digital twin supporting optimization and resilience of factories of the future. *Applied Sciences*, 10(13), p.4482.
- [13] Beloglazov, I.I., Petrov, P.A. and Bazhin, V.Y., 2020. The concept of digital twins for tech operator training simulator design for mining and processing industry. *chemical industries*, 18(19), pp.50-54.
- [14] Booth, L., Schueller, L.A., Scolobig, A. and Marx, S., 2020. Stakeholder solutions for building interdisciplinary and international synergies between climate change adaptation and disaster risk reduction. *International journal of disaster risk reduction*, 46, p.101616.
- [15] Borowski, P.F., 2021. Digitization, digital twins, blockchain, and industry 4.0 as elements of management process in enterprises in the energy sector. *Energies*, 14(7), p.1885.
- [16] Buck, J.J., Bainbridge, S.J., Burger, E.F., Kraberg, A.C., Casari, M., Casey, K.S., Darroch, L., Rio, J.D., Metfies, K., Delory, E. and Fischer, P.F., 2019. Ocean data product integration through innovation-the next level of data interoperability. *Frontiers in Marine Science*, 6, p.32.
- [17] Callcut, M., Cerceau Agliozzo, J.P., Varga, L. and McMillan, L., 2021. Digital twins in civil infrastructure systems. *Sustainability*, 13(20), p.11549.
- [18] Camelo, C., 2021. *Evaluation of the seismic response of gentle slopes in soft clay* (Doctoral dissertation, Tese de Doutorado em Engenharia Civil, Programa de Pós-Graduação em Geotecnia, Departamento de Geotecnia, Universidade Federal do Rio de Janeiro/UFRJ).
- [19] Carr, T.W., Balkovič, J., Dodds, P.E., Folberth, C., Fulajtar, E. and Skalsky, R., 2020. Uncertainties, sensitivities and robustness of simulated water erosion in an EPIC-based global-gridded crop model. *Biogeosciences Discussions*, 2020, pp.1-24.
- [20] Cesarec, I., 2020. Beyond physical threats: Cyber-attacks on critical infrastructure as a challenge of changing security environment—overview of cyber-security legislation and implementation in SEE countries. *Annals of Disaster Risk Sciences: ADRS*, 3(1), pp.0-0.
- [21] Chemisky, B., Menna, F., Nocerino, E. and Drap, P., 2021. Underwater survey for oil and gas industry: A review of close range optical methods. *Remote Sensing*, 13(14), p.2789.
- [22] Chen, J., Lange, T., Andjelkovic, M., Simevski, A. and Krstic, M., 2020. Prediction of solar particle events with SRAM-based soft error rate monitor and supervised machine learning. *Microelectronics Reliability*, 114, p.113799.
- [23] Constantinis, D. and Davies, P., 2020, October. Innovative asset integrity management to drive operational effectiveness. In *Offshore Technology Conference Asia* (p. D021S012R002). OTC.
- [24] Dixit, R.A., Hurst, S., Adams, K.T., Boxley, C., Lysen-Hendershot, K., Bennett, S.S., Booker, E. and Ratwani, R.M., 2020. Rapid development of visualization dashboards to enhance situation awareness of COVID-19 telehealth initiatives at a multihospital healthcare system. *Journal of the American Medical Informatics Association*, 27(9), pp.1456-1461.
- [25] Dugan, J., Mohagheghi, S. and Kroposki, B., 2021. Application of mobile energy storage for enhancing power grid resilience: A review. *Energies*, 14(20), p.6476.
- [26] El Masri, Y. and Rakha, T., 2020. A scoping review of non-destructive testing (NDT) techniques in building performance diagnostic inspections. *Construction and Building Materials*, 265, p.120542.
- [27] Elijah, O., Ling, P.A., Rahim, S.K.A., Geok, T.K., Arsad, A., Kadir, E.A., Abdurrahman, M., Junin, R., Agi, A. and Abdulfatah, M.Y., 2021. A survey on industry 4.0 for the oil and gas industry: Upstream sector. *IEEE Access*, 9, pp.144438-144468.
- [28] Enemosah, A., 2019. Implementing DevOps Pipelines to Accelerate Software Deployment in Oil and Gas Operational Technology Environments. *International Journal of Computer Applications Technology and Research*, 8(12), pp.501-515.
- [29] Erkoyuncu, J.A., del Amo, I.F., Ariansyah, D., Bulka, D. and Roy, R., 2020. A design framework for adaptive digital twins. *CIRP annals*, 69(1), pp.145-148.
- [30] Falsetta, A., Whiteley, E., Dickinson, C., Zhou, G. and Sundararaman, S., 2020, November. Utilizing Natural Frequency Monitoring and Machine Learning to Monitor and Predict Structural Integrity and Minimize the Cost of Fixed Offshore Platform Intervention. In *Abu Dhabi International Petroleum Exhibition and Conference* (p. D012S116R171). SPE.
- [31] Ferrara, P., Ricci Maccarini, G., Poloni, R., Campaci, R., Favaretto, M. and Grasso, T., 2020, January. Virtual Reality: New Concepts for Virtual Drilling Environment

- and Well Digital Twin. In *International Petroleum Technology Conference* (p. D031S058R002). IPTC.
- [32] Fuller, A., Fan, Z., Day, C. and Barlow, C., 2020. Digital twin: enabling technologies, challenges and open research. *IEEE access*, 8, pp.108952-108971.
- [33] Ghosh, A., Edwards, D.J., Hosseini, M.R., Al-Ameri, R., Abawajy, J. and Thwala, W.D., 2021. Real-time structural health monitoring for concrete beams: A cost-effective 'Industry 4.0'solution using piezo sensors. *International Journal of Building Pathology and Adaptation*, 39(2), pp.283-311.
- [34] Gordon, M.D., Morris, J.C. and Steinfeld, J., 2019. Deepwater or troubled water? Principal-Agent theory and performance-based contracting in the coast guard's deepwater modernization program. *International Journal of Public Administration*, 42(4), pp.298-309.
- [35] Guigné, J.Y. and Blondel, P., 2019. Acoustic Investigation of Complex Seabeds. *Underwater Technology*, 36(1), pp.12-12.
- [36] Gupta, R., Mitchell, D., Blanche, J., Harper, S., Tang, W., Pancholi, K., Baines, L., Bucknall, D.G. and Flynn, D., 2021. A review of sensing technologies for non-destructive evaluation of structural composite materials. *Journal of Composites Science*, 5(12), p.319.
- [37] Ho, M., El-Borgi, S., Patil, D. and Song, G., 2020. Inspection and monitoring systems subsea pipelines: A review paper. *Structural Health Monitoring*, 19(2), pp.606-645.
- [38] Hund, L. and Schroeder, B., 2020. A causal perspective on reliability assessment. *Reliability Engineering & System Safety*, 195, p.106678.
- [39] Hunsberger, C. and Awâsis, S., 2019. Energy justice and Canada's national energy board: a critical analysis of the line 9 pipeline decision. *Sustainability*, 11(3), p.783.
- [40] Hwang, J., Bose, N. and Fan, S., 2019. AUV adaptive sampling methods: A review. *Applied Sciences*, 9(15), p.3145.
- [41] Iqbal, H., Waheed, B., Haider, H., Tesfamariam, S. and Sadiq, R., 2019. Mapping safety culture attributes with integrity management program to achieve assessment goals: A framework for oil and gas pipelines industry. *Journal of safety research*, 68, pp.59-69.
- [42] Jain, S., Ahuja, N.J., Srikanth, P., Bhadane, K.V., Nagaiah, B., Kumar, A. and Konstantinou, C., 2021. Blockchain and autonomous vehicles: Recent advances and future directions. *IEEE Access*, 9, pp.130264-130328.
- [43] Johnson, A.F. ed., 2020. *Communications, Cyber Resilience, and the Future of the US Electric Power System: Proceedings of a Workshop*. National Academies Press.
- [44] Khan, S.N., Loukil, F., Ghedira-Guegan, C., Benkhelifa, E. and Bani-Hani, A., 2021. Blockchain smart contracts: Applications, challenges, and future trends. *Peer-to-peer Networking and Applications*, 14(5), pp.2901-2925.
- [45] Kousi, N., Gkournelos, C., Aivaliotis, S., Giannoulis, C., Michalos, G. and Makris, S., 2019. Digital twin for adaptation of robots' behavior in flexible robotic assembly lines. *Procedia manufacturing*, 28, pp.121-126.
- [46] Lambert, J., Bok, M. and Aziz, A., 2021, October. Integrating Underwater Data into GIS for Offshore Decommissioning in Bass Strait, Australia. In *SPE Asia Pacific Oil and Gas Conference and Exhibition* (p. D011S001R001). SPE.
- [47] Lattanzi, L., Raffaelli, R., Peruzzini, M. and Pellicciari, M., 2021. Digital twin for smart manufacturing: A review of concepts towards a practical industrial implementation. *International Journal of Computer Integrated Manufacturing*, 34(6), pp.567-597.
- [48] Lehr, W., Clark, D. and Bauer, S., 2019. Regulation when platforms are layered.
- [49] Lin, M. and Yang, C., 2020. Ocean observation technologies: A review. *Chinese Journal of Mechanical Engineering*, 33(1), p.32.
- [50] Liu, G., Jiang, T., Ollis, T.B., Li, X., Li, F. and Tomsovic, K., 2020. Resilient distribution system leveraging distributed generation and microgrids: A review. *IET Energy Systems Integration*, 2(4), pp.289-304.
- [51] MacIntosh, A., Dafforn, K., Penrose, B., Chariton, A. and Cresswell, T., 2021. Ecotoxicological effects of decommissioning offshore petroleum infrastructure: A systematic.
- [52] Mäder, G., 2021. Management of Software Assets: Challenges in Large Organizations.
- [53] Madni, A.M., Madni, C.C. and Lucero, S.D., 2019. Leveraging digital twin technology in model-based systems engineering. *Systems*, 7(1), p.7.
- [54] Mbuh, M., Metzger, P., Brandt, P., Fika, K. and Slinkey, M., 2020. Application of real-time GIS analytics to support spatial intelligent decision-making in the era of big data for smart cities. *EAI Endorsed Transactions on Smart Cities*, 4(9).
- [55] Mêda, P., Calvetti, D., Hjelseth, E. and Sousa, H., 2021. Incremental digital twin conceptualisations targeting data-driven circular construction. *Buildings*, 11(11), p.554.
- [56] Meierhofer, J., Schweiger, L., Lu, J., Züst, S., West, S., Stoll, O. and Kiritsis, D., 2021. Digital twin-enabled decision support services in industrial ecosystems. *Applied Sciences*, 11(23), p.11418.
- [57] Miller, D., 2021, December. How the API Standardization Program Helps Improve Public Perception of the Oil and Gas Industry. In *World Petroleum Congress* (p. D041S022R002). WPC.
- [58] Minerva, R., Lee, G.M. and Crespi, N., 2020. Digital twin in the IoT context: A survey on technical features, scenarios, and architectural models. *Proceedings of the IEEE*, 108(10), pp.1785-1824.
- [59] Mitchell, D., Blanche, J., Zaki, O., Roe, J., Kong, L., Harper, S., Robu, V., Lim, T. and Flynn, D., 2021. Symbiotic system of systems design for safe and resilient autonomous robotics in offshore wind farms. *IEEE Access*, 9, pp.141421-141452.
- [60] Nadj, M., Maedche, A. and Schieder, C., 2020. The effect of interactive analytical dashboard features on situation awareness and task performance. *Decision support systems*, 135, p.113322.
- [61] NATIVI, S., KOTSEV, A., SCUDO, P.,

- POGORZELSKA, K., VAKALIS, I., DALLA, B.A. and PEREGO, A., 2020. IoT 2.0 and the INTERNET of TRANSFORMATION (Web of Things and Digital Twins).
- [62] Nelson, J., Dyer, A.S., Romeo, L.F., Wenzlick, M.Z., Zaengle, D., Duran, R., Sabbatino, M., Wingo, P., Barkhurst, A.A., Rose, K. and Bauer, J., 2021. *Evaluating Offshore Infrastructure Integrity* (No. DOE/NETL-2021/2643). National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV, and Albany, OR (United States); Oak Ridge Inst. for Science and Education (ORISE), Albany, OR (United States); Theiss Research, La Jolla, CA (United States); Matric, Morgantown, WV (United States).
- [63] Nkansah, C., 2020. Environmental Risk Assessment of Drilling Waste Management Practices in Ghana's Oil and Gas Industry.
- [64] Olaseni, I.O., 2020. Digital Twin and BIM synergy for predictive maintenance in smart building engineering systems development. *World J Adv Res Rev*, 8(2), pp.406-21.
- [65] Osho, G.O., Omisola, J.O. and Shiyanbola, J.O., 2020. A Conceptual Framework for AI-Driven Predictive Optimization in Industrial Engineering: Leveraging Machine Learning for Smart Manufacturing Decisions. *Unknown Journal*.
- [66] Owobu, W.O., Abieba, O.A., Gbenle, P., Onoja, J.P., Daraojimba, A.I., Adepoju, A.H. and Ubamadu, B.C., 2021. Review of enterprise communication security architectures for improving confidentiality, integrity, and availability in digital workflows. *IRE Journals*, 5(5), pp.370-372.
- [67] Perez, H., Tah, J.H. and Mosavi, A., 2019. Deep learning for detecting building defects using convolutional neural networks. *Sensors*, 19(16), p.3556.
- [68] Peri, E. and Tal, A., 2020. A sustainable way forward for wind power: Assessing turbines' environmental impacts using a holistic GIS analysis. *Applied Energy*, 279, p.115829.
- [69] Pettersen, K.A. and Schulman, P.R., 2019. Drift, adaptation, resilience and reliability: toward an empirical clarification. *Safety science*, 117, pp.460-468.
- [70] Podskarbi, M. and Knezevic, D.J., 2020, May. Digital twin for operations-present applications and future digital thread. In *Offshore Technology Conference* (p. D031S037R006). OTC.
- [71] Polagye, B., Stewart, A., Joslin, J., Murphy, P., Cotter, E., Gibbs, P., Scott, M., Henkel, S. and Matzner, S., 2020. *An Intelligent Adaptable Monitoring Package. Final Report* (No. DOE-UW-0006788-1). Univ. of Washington, Seattle, WA (United States).
- [72] Protopapadakis, E., Voulodimos, A., Doulamis, A., Doulamis, N. and Stathaki, T., 2019. Automatic crack detection for tunnel inspection using deep learning and heuristic image post-processing. *Applied intelligence*, 49(7), pp.2793-2806.
- [73] Rahouti, M., Xiong, K., Ghani, N. and Shaikh, F., 2021. SYNGuard: Dynamic threshold-based SYN flood attack detection and mitigation in software-defined networks. *IET Networks*, 10(2), pp.76-87.
- [74] Rasheed, A., San, O. and Kvamsdal, T., 2020. Digital twin: Values, challenges and enablers from a modeling perspective. *IEEE access*, 8, pp.21980-22012.
- [75] Ren, Y., 2021. Optimizing predictive maintenance with machine learning for reliability improvement. *ASCE-asme journal of risk and uncertainty in engineering systems, part b: mechanical engineering*, 7(3), p.030801.
- [76] Ross, R., Pillitteri, V., Graubart, R., Bodeau, D. and McQuaid, R., 2019. *Developing cyber resilient systems: a systems security engineering approach* (No. NIST Special Publication (SP) 800-160 Vol. 2 (Draft)). National Institute of Standards and Technology.
- [77] Sahu, A., Mao, Z., Wlazlo, P., Huang, H., Davis, K., Goulart, A. and Zonouz, S., 2021. Multi-source multi-domain data fusion for cyberattack detection in power systems. *IEEE Access*, 9, pp.119118-119138.
- [78] Savolainen, J. and Urbani, M., 2021. Maintenance optimization for a multi-unit system with digital twin simulation: Example from the mining industry. *Journal of Intelligent Manufacturing*, 32(7), pp.1953-1973.
- [79] Sethupathy, U.K.A., 2021. Empowering Intelligent Decision-Making: Architecting Resilient Real-Time Data Platforms with Actionable Visual Dashboards.
- [80] SHARMA, A., ADEKUNLE, B.I., OGEAWUCHI, J.C., ABAYOMI, A.A. and ONIFADE, O., 2019. IoT-enabled Predictive Maintenance for Mechanical Systems: Innovations in Real-time Monitoring and Operational Excellence.
- [81] Shi, J. and Zhou, M., 2020. A data-driven intermittent online coverage path planning method for AUV-based bathymetric mapping. *Applied Sciences*, 10(19), p.6688.
- [82] Shrestha, S. and Dhakal, S., 2019. An assessment of potential synergies and trade-offs between climate mitigation and adaptation policies of Nepal. *Journal of Environmental Management*, 235, pp.535-545.
- [83] Silver, E. and Sundvall, A., 2021. Determine a company's Software as a Service potential. The development of a perspicuous investment analysis model from a venture capital perspective.
- [84] Singh, M., Fuenmayor, E., Hinchy, E.P., Qiao, Y., Murray, N. and Devine, D., 2021. Digital twin: Origin to future. *Applied System Innovation*, 4(2), p.36.
- [85] Stevens, B., Jolly, C. and Jolliffe, J., 2021. A new era of digitalisation for ocean sustainability?: Prospects, benefits, challenges.
- [86] Suleiman, R.M., Raimi, M.O. and Sawyerr, O.H., 2019. A deep dive into the review of national environmental standards and regulations enforcement agency (NESREA) act. *Suleiman Romoke Monsurat, Raimi Morufu Olalekan and Sawyerr Henry Olawale (2019) A Deep Dive into the Review of National Environmental Standards and Regulations Enforcement Agency (NESREA) Act. International Research Journal of Applied Sciences. pISSN*, pp.2663-5577.
- [87] Temmer, M., 2021. Space weather: The solar perspective: An update to Schwenn (2006). *Living Reviews in Solar Physics*, 18(1), p.4.
- [88] Trice, A., Robbins, C., Philip, N. and Rumsey, M., 2021. Challenges and opportunities for ocean data to advance

conservation and management. *Ocean Conservancy: Washington, DC, USA*.

- [89] Velenturf, A.P.M., Emery, A.R., Hodgson, D.M., Barlow, N.L.M., Mohtaj Khorasani, A.M., Van Alstine, J., Peterson, E.L., Piazzolo, S. and Thorp, M., 2021. Geoscience solutions for sustainable offshore wind development. *Earth Science, Systems and Society, I*(1), p.10042.
- [90] Velmurugan, R.S. and Dhingra, T., 2021. Asset Maintenance: A Primary Support Function. In *Asset Maintenance Management in Industry: A Comprehensive Guide to Strategies, Practices and Benchmarking* (pp. 1-21). Cham: Springer International Publishing.
- [91] Vijay Kumar, C., 2021. STRENGTHENING OF SUBMERGED PILES-Using Fibre Reinforced Polymer Materials.
- [92] Wanasinghe, T.R., Trinh, T., Nguyen, T., Gosine, R.G., James, L.A. and Warrian, P.J., 2021. Human centric digital transformation and operator 4.0 for the oil and gas industry. *Ieee Access*, 9, pp.113270-113291.
- [93] Wanasinghe, T.R., Wroblewski, L., Petersen, B.K., Gosine, R.G., James, L.A., De Silva, O., Mann, G.K. and Warrian, P.J., 2020. Digital twin for the oil and gas industry: Overview, research trends, opportunities, and challenges. *IEEE access*, 8, pp.104175-104197.
- [94] Watson, S., Duecker, D.A. and Groves, K., 2020. Localisation of unmanned underwater vehicles (UUVs) in complex and confined environments: A review. *Sensors*, 20(21), p.6203.
- [95] Whitt, C., Pearlman, J., Polagye, B., Caimi, F., Muller-Karger, F., Copping, A., Spence, H., Madhusudhana, S., Kirkwood, W., Grosjean, L. and Fiaz, B.M., 2020. Future vision for autonomous ocean observations. *Frontiers in Marine Science*, 7, p.697.
- [96] Yakoot, M.S., Elgibaly, A.A., Ragab, A.M. and Mahmoud, O., 2021. Well integrity management in mature fields: a state-of-the-art review on the system structure and maturity. *Journal of Petroleum Exploration and Production*, 11(4), pp.1833-1853.
- [97] Yitmen, I., Alizadehsalehi, S., Akiner, İ. and Akiner, M.E., 2021. An adapted model of cognitive digital twins for building lifecycle management. *Applied Sciences*, 11(9), p.4276.
- [98] Zhang, Y., Zheng, M., An, C., Seo, J.K., Pasqualino, I.P., Lim, F. and Duan, M., 2019. A review of the integrity management of subsea production systems: Inspection and monitoring methods. *Ships and offshore Structures*, 14(8), pp.789-803.
- [99] Zhou, C., Xu, J., Miller-Hooks, E., Zhou, W., Chen, C.H., Lee, L.H., Chew, E.P. and Li, H., 2021. Analytics with digital-twinning: A decision support system for maintaining a resilient port. *Decision Support Systems*, 143, p.113496.
- [100] Zohrevand, Z. and Glässer, U., 2019. Should i raise the red flag? A comprehensive survey of anomaly scoring methods toward mitigating false alarms. *arXiv preprint arXiv:1904.06646*.