# SPATIALLY ENABLED DIGITAL TWIN FRAMEWORK FOR THE FIELD DESIGN PROCESS OF OIL AND GAS PROJECTS

A Thesis submitted by

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For the award of

Master of Research

2024

# ABSTRACT

The field design phase is considered paramount in any oil and gas (O & G) project. However, during the field design phase, many projects still use traditional 2D plans to depict design information. Traditional 2D plans often fall short in effectively conveying design information due to limited visualisation, increased chance of errors, and inadequate workflows for stakeholder approvals. Consequently, land survey data model (LSDM) that store spatial data of infrastructure design inherit these constraints. Spatial digital twins (DTs), which combine digital twin concepts with spatial computing offer a virtual representation of real-world entities and processes in a 3D/4D environment, enhance visualisation, and accordingly, improve decision-making processes. However, digital twin developments are still relatively new in the scientific community, and consequently, existing DT frameworks need to be developed that accommodate land survey data models (LSDMs) to facilitate wider industry adoption, particularly in the context of the field design process of O & G projects. The aim of the study was to develop a spatially enabled digital twin framework for the field design process of O & G projects based on LSDM. To accomplish this aim, a widely accepted design science framework was utilised which was carried out through four stages: the foundation stage, design and development stage, demonstration stage, and evaluation stage. In the foundation stage, a literature review was conducted to explore the research problem and develop a conceptual framework that encompasses key components including data, standards, field design, users, and application. Following this, in the design and development stage, the system architecture of the framework, use case diagram, and sequence diagram were presented to illustrate the technical dimension of the framework. Further, a prototype was developed and successfully demonstrated through a case study approach in an area that lies on lot 2RP108045 and falls under the petroleum lease 229 under the Department of Resources, Queensland, Australia. The prototype was successfully able to visualise 2D and 3D spatial data and associated LSDM attribute information. The prototype was evaluated using the parameters stated by ISO/IEC 25010 and indicates its success within the defined study scope. This study provides a contribution towards Industrial Revolution 4.0, resulting in enhanced decision-making processes within the O & G industry and more effective management of energy resources.

# CERTIFICATION OF THESIS

I Sijan Bhandari declare that the Thesis entitled *Spatially Enabled Digital Twin Framework for Field Design Process of Oil and Gas Projects* is not more than 40,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes. The thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Date: 15 June 2024

Endorsed by:

Dr. Dev Raj Paudyal
Principal Supervisor

Dr. Sreeni Chadalavada
Associate Supervisor

Student and supervisors' signatures of endorsement are held at the University.

# ACKNOWLEDGEMENTS

I express my gratitude to numerous individuals whose unwavering support has played a pivotal role in materialising this thesis. My sincere appreciation to Dr. Dev Raj Paudyal, my principal supervisor, whose constant encouragement, and mentorship have been invaluable throughout this master journey. Your guidance has not only nurtured my research concepts but also imparted crucial lessons beyond academia, shaping me into a more adept researcher. I am immensely thankful for your respect towards my ideas and errors, and for instilling in me traits reflective of your commendable character. His wealth of knowledge in mine surveying, spatial data infrastructure, surveying, and spatial science, and research strategies has significantly aided in the timely completion of this dissertation. I am also equally indebted to Senior Lecturer Dr. Sreeni Chadalavada, my associate supervisor, whose motivation, insightful feedback, and analytical inquiries propelled me further on my Masters journey. His knowledge in research skills, oil, and gas, and in general civil engineering has immensely supported my research journey. His calm attitude will always remain in my heart as it has always encouraged me whenever I used to get worried about my research. Thank you very much for your support.

I extend my gratitude to my dear friend Rabina Twayana working as Research Associate, Geoinformatics Information Centre, Asian Institute of Technology, Thailand for her technical support. Her experience in Web-based GIS programming has immensely assisted me. Thank you very much for responding to my queries regarding WebGIS programming. I also extend my sincere appreciation to, Neil Severns (Director of DSQ Land Surveyors/Cadastral Surveyor) for managing approvals from the concerned authority to carry out the UAV survey on the case study area and allowing me to use DSQ surveying equipment including UAV. I can not forget my sincere thanks to my colleague Nick McNabb (GIS Consultant, DSQ Land Surveyors) for his immense support for the UAV survey and queries related to GIS in the context of the oil and gas project. My special thanks to Adam Tomlinson and Bruce Tjin (DSQ Site Supervisors, Chinchilla) for supporting me in local logistics during the UAV survey at the case study area. I am also thankful to other colleagues of DSQ Land Surveyors for their support and encouragement throughout this Masters study. I also would like to kindly thank Autodesk Inc. for allowing me to use their products (Civil 3D, Auto CAD Plant, and Navis Works) freely through the student access policy. My appreciation extends to Graduate Research School, University of Southern Queensland for accepting my research topic and allowing me to pursue a Master of Research (Surveying).

I would also like to convey my sincere gratitude to all Nepalese people living in Queensland who supported me during my stay in Australia. My Aunt Charu has been like my motherhood figure. I am grateful for her emotional encouragement during my Masters study. Additionally, my sincere appreciation to my brothers (Uri and Kanchi) for their brotherhood support throughout my master's journey. I also extend my gratitude to my friend Himal Thapa for his friendship throughout this study. I also would like to express my sincere gratitude to Prajwal Dai and Pallu Di for inviting me to their house during holidays. Thank you all for your social support during my study.

Last but not the least, my sincere appreciation goes to my parents (Sita and Kul Raj) and my one and only brother (Sakshyam) who remains a source of inspiration and courage for this study. Thank you, my family. Finally, I am done with my Masters research study.

# DEDICATION

*In Loving Memory of My Dear Maternal Grandfather and Grandmother.*

During this study, I lost my maternal Grandpa and Grandma. I can not explain in words how close I was to them. This thesis stands as a testament to the love, wisdom, and encouragement you bestowed upon me. With heartfelt remembrance, I dedicate this work to both of you, my eternal sources of inspiration.

Rest peacefully
Buba & Aama !!!

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# ABBREVIATIONS

| | |
|---|---|
| AEC | Architecture Engineering Construction |
| AI | Artificial Intelligence |
| APGA | Australian Pipelines and Gas Association |
| APIs | Application Programming Interfaces |
| ANZLIC | Australia New Zealand Land Information Council |
| AR | Augmented Reality |
| BIM | Building Information Modelling |
| CORS | Continuously Operating Reference Station |
| CSDILA | Centre for Spatial Data Infrastructures and Land Administration |
| CITA | Construction Information Technology Alliance |
| DT | Digital Twin |
| DTs | Digital Twins |
| DTC | Digital Twin Consortium |
| ER | Entity-Relationship |
| FOSS | Free and Open Source Software |
| GCP | Ground Control Point |
| GCQ | GasFields Commission Queensland |
| GIS | Geographic Information System |
| GLNG | Gladstone Liquefied Natural Gas |
| GNSS | Global Navigation Satellite Systems |
| IBIMA | International Business Information Management Association |
| IFC | Industry Foundation Class |
| ITDP | Institute for Transportation and Development Policy |
| IOGP | International Association of Oil and Gas Producers |
| IoT | Internet of Things |
| KML | Keyhole Markup Language |
| LAS | Land Administration System |
| NGP | Northern Gas Pipeline |
| NSW | New South Wales |
| O & G | Oil and Gas |
| OGC | Open Geospatial Consortium |

| | |
|---|---|
| PPE | Personal Protective Equipment |
| QLD | Queensland |
| RABC | Role Based Access Control |
| ROW | Right of Way |
| RTK | Real Time Kinematic |
| SBENRC | Sustainable Built Environment National Research Centre |
| SIS | Spatial Information System |
| SQL | Structured Query language |
| UAV | Unmanned Aerial Vehicle |
| UML | Unified Modelling Language |
| VIC | Victoria |
| VR | Virtual Reality |
| WFS | Web Feature Service |
| WGIC | World Geospatial Industry Council |
| WDRC | Western Downs Regional Council |

# CHAPTER 1: INTRODUCTION

## 1.1. Background to Research

The field design process in any oil and gas (O & G) project involves a series of activities for the successful development and operation of infrastructure (Sabri et al., 2015). According to the International Association of Oil and Gas Producers (IOGP), activities mostly depend on the infrastructure development protocols of the host country (IOGP, 2020). In the context of Australia, the field design process involves four key activities that include conceptual engineering design, detailed engineering design, approval of the design from various stakeholders, and finally archiving spatial data (X, Y, Z) of infrastructure designs into a central spatial information system (SIS) (APGA, 2022; Arrow Energy, 2013; Shell QGC, 2017; and West, 2011). The common infrastructures involved in field design include pipelines, roads, washdown, well pad infrastructures, utility features, culverts, fences, sumps, borrow pits, tanks, and processing facilities (GCQ, 2022). Further, conveying design information across multiple stakeholders in the field design process is crucial (West, 2011). The current practice of communicating design information to stakeholders is sharing spatial data of 2D plans through SIS (Arrow Energy, 2013). However, 2D design plans have limitations that are inherited in their spatial data, thereby causing challenges in visualising design information in SIS.

Digital Twin (DT) offers a detailed representation (3D, 4D) of processes, models, and entities thereby enhancing visualisation, analytics, and decision-making capabilities (Lee et al., 2018; Rajabifard et al., 2022; Sireesha et al., 2018). Realising the potential value of digital twins, the O & G sector has already commenced research and development for leveraging DT to enhance business operations (WGIC, 2022). However, a study conducted by Wanasinghe et al. (2020) outlines that the current developments in DT technology are in a very early stage for wider industry implementation. A study conducted by Elijah et al. (2021) suggested that current research initiatives on digital twins in the O & G industry are focused on developing theoretical and conceptual frameworks as well as exploring possible applications. Further, existing conceptual frameworks developed by research scholars as outlined in Appendix B could not be readily utilised in the field design process of the O & G project for storing and visualising the spatial data of infrastructure designs archived in SIS. This shortfall exists due to two key reasons. Firstly, existing frameworks have not accommodated the land survey data model (LSDM) tailored for the O & G sector. The LSDM is a geodatabase model developed by the IOGP, that enables the storage of spatial data of the infrastructure designs into the SIS of O & G projects (IOGP, 2022). Secondly, there is an absence of empirical studies that integrate the LSDM concept and spatially enabled digital twins in the context of the field design process for an O & G project. This integration is expected to enhance the visualisation of spatial data of infrastructure designs through 3D design models and DTs.

Therefore, this study has developed a conceptual framework for spatially enabled digital twins incorporating the industry-standard LSDM through a design science research approach. Further, a prototype was developed utilising the framework to assess its viability and it was demonstrated in a real-world scenario adopting a case study approach. Finally, a prototype was evaluated using the ISO/IEC 25010 model. This study significantly contributes to the advancement of the oil and gas sector and spatial science, facilitating more efficient and effective field design practices. This is achieved by leveraging the advantages of spatially enabled digital twin technology and the application of the LSDM.

## 1.2. Research Formulation

### *1.2.1.* Research Problem

Infrastructure designs play a pivotal role in the entire field design process (Adedeji & Samuel, 2013) and are also acknowledged as significant information for subsequent construction steps in the context of any O & G project (He et al., 2019). Accurate designs are crucial for effectively communicating infrastructure information among all the stakeholders which include engineers, ecologists, cultural heritage, geologists, and surveyors involved in the field design process (Santos, 2021). However, the current practice of communicating infrastructure design information is based on traditional 2D plans which are constrained in three key aspects (Eldeep et al., 2022; Santos, 2008; Sharafat et al., 2021). Firstly, stakeholders from non-engineering backgrounds often struggle to understand and visualise 2D plans during the design approval process, impacts their input. Secondly, depending solely on 2D plans increases the probability of design errors. Thirdly, the constraints imposed by traditional 2D plans result in workflow inefficiencies, contributes to delays in the review, approval, and management of designs. These constraints have serious implications.

For instance, during the design and construction of multistorey facilities and underground gathering network of O & G projects, the stakeholders from non-engineering found it very complex to interpret the 2D-based plans/maps which has adversely affected the efficiency of project execution (Sharafat et al., 2021). Similarly, design errors in construction projects add almost 16% of the initial project cost and delay the project duration by more than 50% (Wong et al., 2018). In addition to this, a study conducted by Eldeep et al. (2022) found that utilising a 3D model (such as BIM) significantly reduced the design duration by approximately 50% and immensely facilitated the design and construction process. Therefore, current 2D-based infrastructure design plans may not effectively support decision-making in the field design process.

Consequently, the above-mentioned limitations also extend to the spatial data of infrastructure designs stored in a central SIS used in the O & G project (Zhu, 2018). To address these constraints in SIS, the concept of a spatially enabled digital twin has emerged as a new paradigm in the spatial science discipline (Adreani et al., 2023). The spatially enabled digital twin is an emerging concept in the O & G industry (WGIC, 2022). However, existing DT frameworks in the O & G sectors are primarily associated with the manufacturing sector (Sireesha et al., 2018; Wanasinghe et al., 2020). Further, existing DT frameworks on the spatial science discipline are also focused on land administration, urban infrastructure, and the built environment (Aleksandrov et al., 2019; ANZLIC, 2019; Lu et al., 2020). Therefore, to fully utilise the advantages of digital twins in industry practice for the field design process for O & G projects, a spatially enabled digital twin framework should be developed considering the industry-standard model such as land survey data model (LSDM). The IOGP (2022) has directed that spatial data of infrastructure designs should be stored utilising the LSDM to ensure consistent spatial information management across O & G companies around the world. Therefore, the main research problem of this study was:

2D design plans have limitations, and these limitations are inherited in their spatial data, causing challenges in visualising design information stored in SIS. Spatially enabled digital twins would address this limitation. However, existing DT frameworks have not considered the industry-standard models such as LSDM, which are essential for storing spatial data of infrastructure designs during the field design process of the O & G project thereby impacting complete industry adoption.

### *1.2.2.* Research Aim

Based upon the above-mentioned research problem, the main aim of the study was:

To develop a spatially enabled digital twin framework accommodating the LSDM, which facilitates storing and visualising the spatial data of infrastructure designs in a virtual 3D environment, along with enabling the management of other crucial spatial information used during the field design process for O & G projects.

### *1.2.3.* Research Questions and Objectives

Two key research questions were formulated based on above research problem:

1. Can existing theoretical frameworks on DT be directly utilised in the field design process to store and visualise the spatial data of infrastructure designs based on the LSDM?

2. What is an appropriate approach for developing spatially enabled digital twin framework to store and visualise the spatial data of infrastructure designs and other associated spatial information?

To answer the above two research questions and achieve main aim of this study, following five objectives were formulated:

1. Review the DT concepts, existing frameworks, field design process, and LSDM for developing conceptual framework.

2. Develop conceptual framework of spatially enabled digital twin by encapsulating LSDM.

3. Utilise developed framework as a guiding principle for building a prototype to ensure framework viability.

4. Demonstrate the prototype for assessing its feasibility through case study approach.

5. Evaluate the prototype using ISO/IEC 25010 parameters.

## 1.3. Outline of Research Approach

In the domain of information science, design science framework is widely acknowledged in the development of artefacts (Johannesson & Perjons, 2021; Peffers et al., 2007). An artefact could be a model, construct, method or any instantiation (Johannesson & Perjons, 2021). Over time, the design science research approach has been adopted in various academic research/dissertations that are related to information science and systems (Atazadeh, 2017).

There are also research scholars who have adopted the design science approach in developing conceptual frameworks related to the DT, 3D GIS, and BIM paradigms. For instance, Kang et al. (2022) developed a conceptual framework for building a demolition waste management system in Hong Kong based on a design science approach that leverages digital twin technology. Similarly, Pan and Zhang (2021) developed the BIM-integrated digital twin framework for advanced construction project management through design science strategy. Similarly, Atazadeh (2017) utilised a design science methodological framework in his PhD dissertation that focussed on building a BIM framework for urban land administration. Kehily and Underwood (2015) discussed design science as an appropriate approach for their research in the field of BIM. In addition to this, Asghari (2022) completed his PhD dissertation in 3D spatial data validation using design science methodology. Therefore, this indicates that the design science approach is well acknowledged in the research community for developing conceptual frameworks related to information systems, digital twins, 3DGIS, and BIM. Hence, this study has also adopted a design science research framework to accomplish its aim and objectives. The adopted research design for this study is broken down into four key stages as illustrated in Figure 1.1.

### *1.3.1.* Foundation Stage

The foundation stage involves clarifying research problem through a systematic literature review (Shahidinejad et al., 2024). Initially, paper selection commenced by using digital twin and oil and gas as keywords across scientific digital libraries such as Scopus, Elsevier, IEEE Xplore, and MDPI. This initial screening yielded approximately 152 relevant articles, those papers which were published in other languages than English were excluded. Full access to some of these articles was obtained through various means such as Google Scholar, subscriptions to digital library and contacting authors. After removing duplicates, reading titles, key words, and abstracts, 108 articles were selected. Accordingly, after revision of these 108 articles, 38 articles were identified and deemed relevant.

### *1.3.2.* Design and Development Stage

The design stage includes four major activities. Firstly, the imagining and brainstorming approach of the germinal method (Johannesson & Perjons, 2021) was used to map out the relation between field design workflow, DT, and LSDM. Secondly, the rational decision-making model was utilised to select the ideas between customising existing frameworks or developing an entirely new framework. Thirdly, various diagrams were developed using Microsoft Visio tools that encompass components of the framework, use case diagrams, sequence diagrams, and system architectures. Fourthly, a prototype was developed using the agile methodology described by Molina & Pedreira (2019), which includes key four steps: requirement analysis, design, development, and deployment and testing.

### *1.3.3.* Demonstration Stage

The demonstration stage includes two key activities. Firstly, the selection of a case study area and demonstration of the prototype were carried out. The selected case study area is located on the property (2RP108045) in Queensland, Australia, chosen due to data accessibility. Similarly, a case of designing a new corridor was considered to demonstrate the developed prototype. A UAV survey was conducted to capture the required datasets for designing the corridor. Finally, 2D/3D models and associated spatial information were stored and visualised to assess the feasibility and applicability of the prototype.

### *1.3.4.* Evaluation Stage

The evaluation stage includes three key activities. Firstly, the context was analysed considering three factors: time, financial resources, and accessibility. Secondly, the goal and strategy were determined to confirm what needs to be evaluated. Thirdly, the prototype was assessed using eight criteria of ISO/IEC 25010, covering functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, and portability. Figure 1.1 illustrates the research approach which is broken down into four main stages.

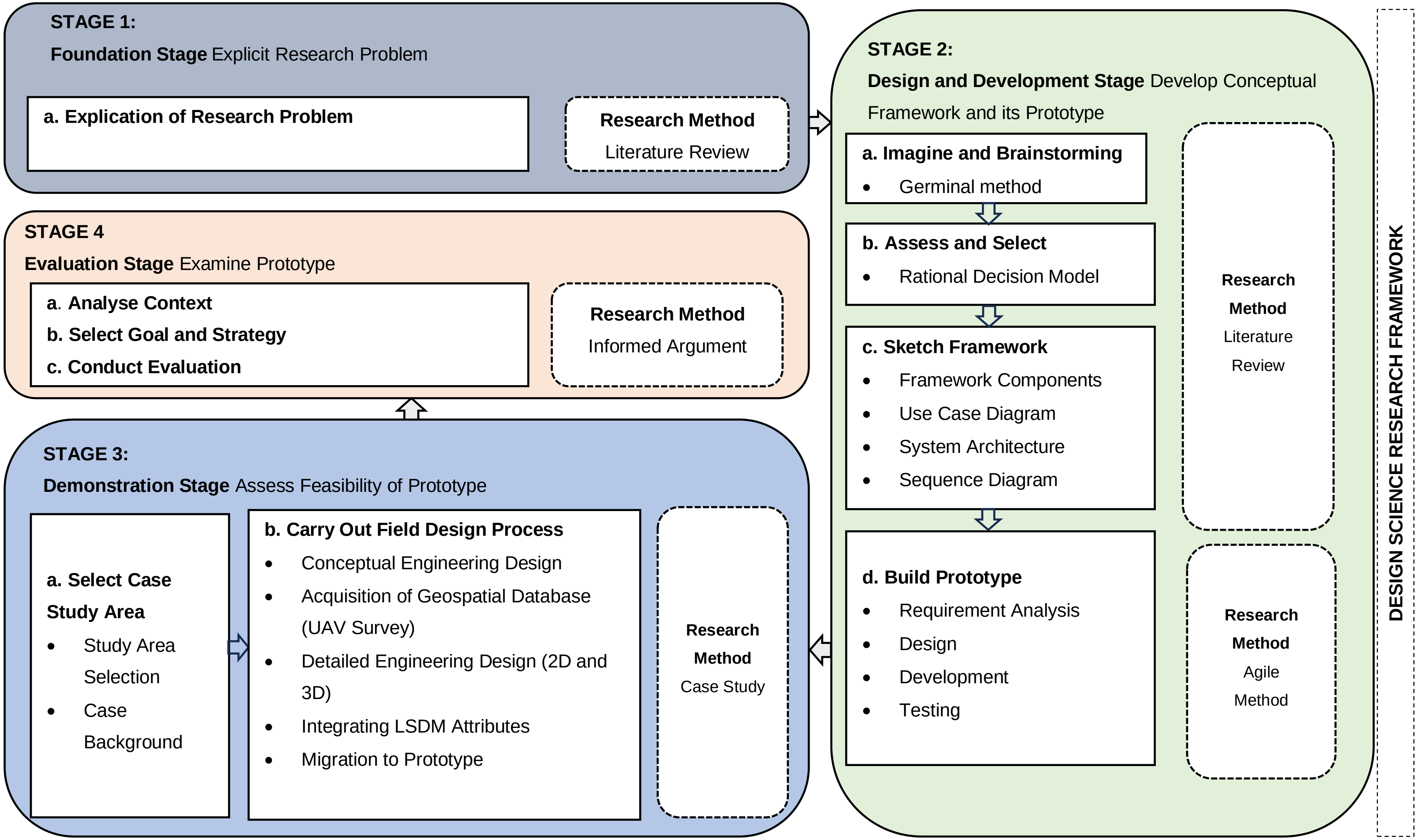



**Figure 1.1: Research Approach**

## 1.4. Structure and Outline of Thesis

This dissertation has been organised as illustrated in Figure 1.2. In total, six chapters have been presented to answer the research questions and objectives of the study.

Chapter One provides the foundation of this study, which includes background to the research, the research problem, the aim, and objectives. Following this, it outlines the summary of the research approach and the structure of the thesis. Finally, it presents the scope and limitations of the research.

Chapter Two describes the theoretical concepts of digital twin development. Further, it explores existing DT frameworks and identifies gaps within them. It also explains the typical workflow of field design O & G projects and outlines Australian practices. Following this, it provides an overview of LSDM. Finally, this chapter concludes by addressing the identified research gap.

Chapter Three illustrates the adopted research strategy and methods used to carry out this study. This chapter focuses on how design science has been adopted in this study to achieve the aim and objectives.

Chapter Four provides information about the developed framework and its associated diagrams. It demonstrates the components of the framework, including the use case diagram, system architectures, and sequence diagram. Further, it illustrates the prototype developed utilising the conceptual framework.

Chapter Five provides information about the case study conducted to assess the feasibility of the developed prototype. The chapter covers topics such as selected case study areas, case backgrounds, the UAV survey, conceptual engineering design, and detailed engineering design. Finally, this chapter discusses the migration of datasets to the prototype and provides information on its evaluation using ISO/IEC 25010 parameters.

Chapter Six highlights the research achievements and findings. Additionally, it delves into the significance of the research. The chapter concludes by providing insights into potential future research directions, specifically for scholars interested in spatial digital twin and 3D GIS studies, with a focus on the mining industry.

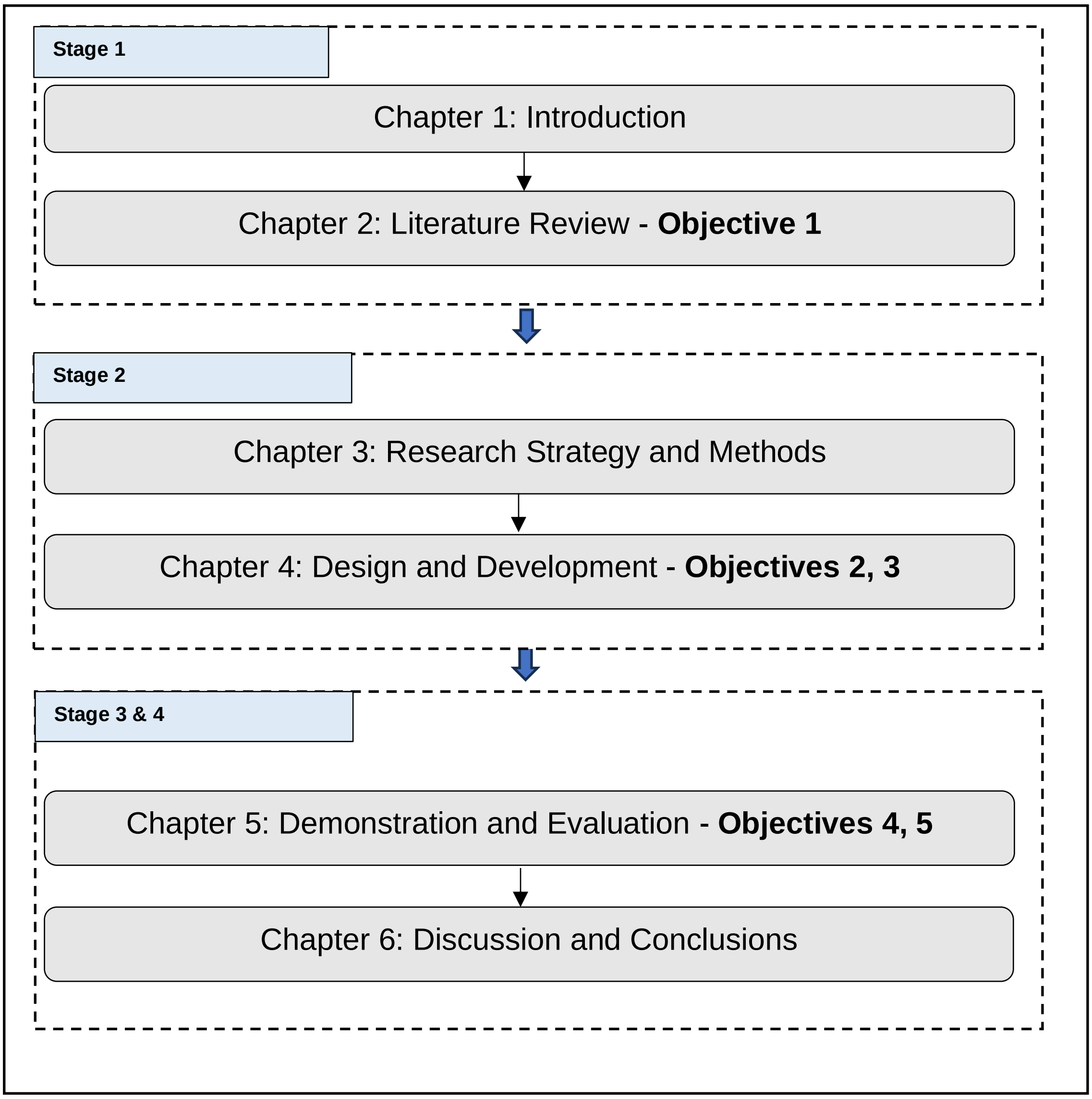



**Figure 1.2: Thesis Structure**

### 1.5. Scope and Limitation of Research

This study specifically focused on the onshore field design phase within the upstream sector of O & G projects. To substantiate the viability of the conceptual framework, a prototype was developed considering the study timeframe. Notably, the prototype was deployed on a localhost, incorporating essential functionalities that facilitate in storing and visualising 2D and 3D datasets based on the LSDM. The integration of LSDM attributes into the 3D models was achieved through manual XML scripting. Due to limitations in accessibility and time, the prototype was assessed using the ISO/IEC 25010 model evaluation parameters. In addition to this, due to time constraints and regulatory requirements, O & G stakeholders' inputs were not incorporated during the assessment. Furthermore, this study does not include the 4D component and is limited to 2D and 3D datasets. Although this prototype was assessed with working application (Digital Twin Victoria), there are geographical limitations, as the case study is conducted in a specific area of Queensland, Australia that may limit the generalisability of the findings to other geographical regions with different regulatory frameworks or infrastructures characteristics. It is also important to note that this study was conducted with a focus on the O & G sector of the Australian mining industry.

### 1.6. Chapter Summary

This chapter discussed the background to the research, the main research problem, the research questions, aim, and objectives. It also provided a rationale for the research problem. This chapter has also briefly discussed the adopted research framework in this study and justified why it was selected for this study. This chapter has also outlined the structure of the thesis and illustrated the scope and limitations of the study. Chapter Two delves into the literature review section that provides foundational background about the DT, field design process, and LSDM.

# CHAPTER 2: LITERATURE REVIEW

## 2.1. Introduction

The primary objective of this chapter is to explore concepts related to Digital Twins (DTs) and its existing frameworks, the field design process, and the land survey data model (LSDM). Section 2.2 introduces the concept of DT, while Section 2.3 discusses the current practices of DT in the O & G industry. Subsequently, Section 2.4 provides insights into spatially enabled DT. Further, Section 2.5 comprehensively investigates existing DT frameworks within the domains of spatial science, O & G industry, and construction and underground infrastructure sectors. Sections 2.6 and 2.7 provide information regarding the workflow of an O & G project, followed by an explanation of the typical field design process. Section 2.8 outlines the Australian practice of communicating design information by illustrating major O & G projects in the context of Australia. Following this, Section 2.9 presents an overview of the LSDM, and finally, the chapter concludes by highlighting the identified research gap.

## 2.2. DT Concept

### *2.2.1.* Definitions

The very first definition of the DT was used in the context of product lifecycle management in the early 2000s by a research scholar “Michael Grieves”, who stated “virtual representation of real-world that encompasses both entities and processes” (Grives, 2005) and changed over time and extended its applications into different disciplines. Similarly, Hagan (2015) defined DT as an “integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by digital thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin”. Over the last two decades, the definition of DT has been changed but the fundamental concept of the DT “3D virtual model” has remained constant.

A study carried out by Wanasinghe et al. (2020) suggested that DT should not be limited to 3D visualisation, and should also include data exchange between a physical asset and digital model, data analytics, and advanced 4D visualisation. A comprehensive review study carried out by Onaji et al. (2022) summarised twenty-two definitions of DT based on the existing literature, which is illustrated in Appendix A. Despite the lack of uniformity in definition and description, there is a similarity in key components of the DT: real-time interaction and the replication of physical asset functionalities in the virtual space. In 2020, Digital Twin Consortium (DTC) was formed as a global ecosystem, in which different working groups collaborated to drive consistency in terminology, system architecture, and interoperability of DT. The DTC has provided a generic and flexible definition of DT, which states “a virtual representation of real-world entities and processes, synchronised at a specified frequency and fidelity” (DTC, 2022). This definition incorporates Grieves’s fundamental concepts in DT including virtual representation, the real-world (both entities and processes), and the link between the virtual and real-world (Grives, 2005) that can be synchronised (Rajabifard et al., 2022). Later, this definition was used to define spatial DT by WGIC (2022) and serves as cornerstone for this study.

#### ***2.2.2.*** **DT Classification**

The plant twin and process twin are two major classifications of DT (Tao et al., 2019). The plant twin is a 3D virtual replica (3D model) that supports advanced visualisation, analytics, and simulation in the field of engineering, operations, and maintenance. In addition to this, plant twin plays a crucial role in providing training for emergency evacuation. For instance, with the help of plant twin, persons on site can navigate through VR applications. Additionally, the plant twin also supports the 3D design for conducting construction activities which aids effective decision-making.

Similarly, the process twin is the virtual replica of any event and systems that support examining the nature and capability of an asset. It also assists in finding the best optimal scenario, operating parameters, and safety procedures. Process twins are also used in the control systems of the O & G industry (Wanasinghe et al., 2020). Based on functionalities, Zborowski (2018) sorted DT into three additional categories: equipment level, system level, and plant level. Engineering design and modelling of the equipment are major elements of equipment-level DT (Wanasinghe et al., 2020). Similarly, system-level twins are aggregation of various equipment-level DTs whereas plant-level twins are a virtual replica of the overall plant which are constructed by integrating various system-level and equipment-level.

### *2.2.3.* DT Fundamental Components

In the field of research, various frameworks have been developed for the development of DT initiatives which are comprehensively discussed in Section 2.5. Among these frameworks, two widely recognised frameworks are the three and five framework components (Grives, 2005; Tao et al., 2019;) as illustrated in Figure 2.1 and Figure 2.2. The three framework components consist of physical space, virtual space, and connectors. Physical objects, models, sensors, and actuators are included in the physical space whereas advanced models in virtual space support data analytics and simulation acquired through physical space to determine the optimal control parameters (Grives, 2005).

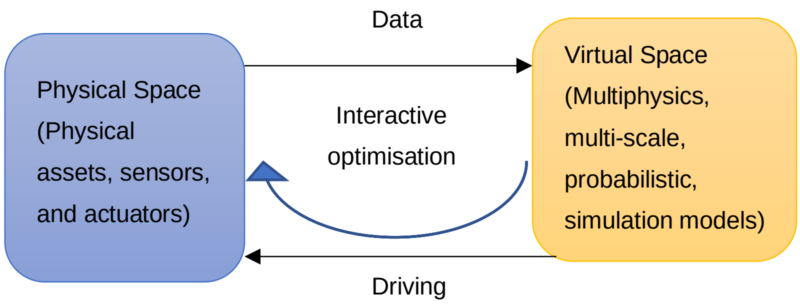



**Figure 2.2: Three Component Framework (Grives, 2005)**

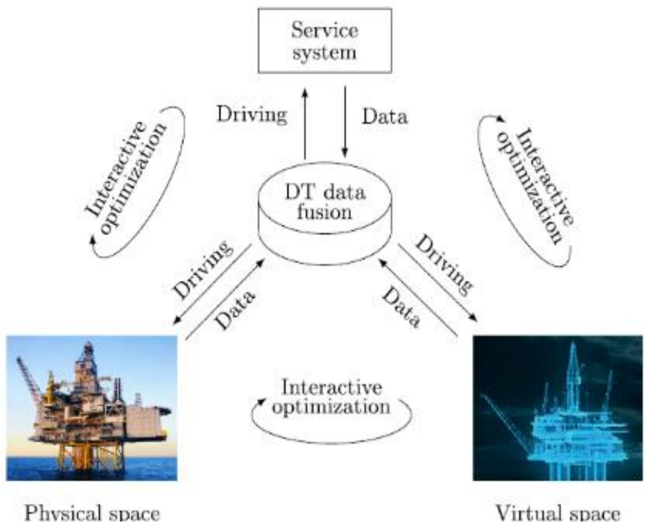



**Figure 2.1: Five Component Framework (Tao et al., 2019)**

Similarly, the five component framework consists of physical space, virtual space, connectors, DT data fusion, and system service (Tao et al., 2019). The attributes of the five component framework in physical space and virtual space are similar to the three component framework. The data fusion model serves as the connector between the physical space and virtual space, as well as the service systems. The components of the service systems encompass tools that support visualisation, quality, diagnostics, model calibration, algorithms, and various data services (Wanasinghe et al., 2020).

### *2.2.4.* Key Enabling Technologies for DT and Industry 4.0

The concept of "Industry 4.0" originated at the Hanover Fair, held in Germany in 2011 (Drath & Horch, 2014), marking the transition from Industry 3.0 to Industry 4.0 through leveraging digital technologies. Dalenogare et al. (2018) presented nine fundamental technologies in Industry 4.0 which are illustrated in Figure 2.3.

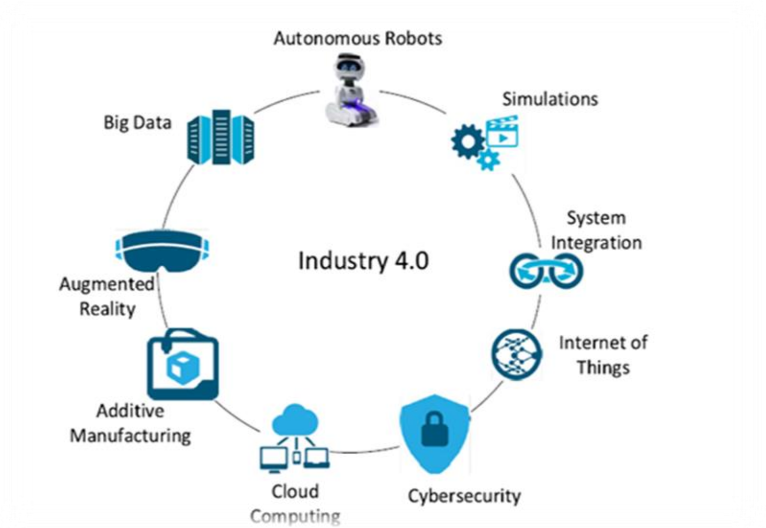



**Figure 2.3: Key Enabling Technologies (Dalenogare et al., 2018)**

Autonomous robots play a crucial role in O & G industry because they support incorporating and interacting with each other with a higher level of safety (Kamarul et al., 2016). Autonomous robots are an automatic system that "enables the use of control systems to handle different processes and machinery in the industry. Some of the advantages of industrial automation are cost reduction in wages and salaries, maintenance, increased productivity, less error and high quality, high flexibility, reduced turnaround time increased safety, and accurate information from data collection" (Elijah et al., 2021). A study carried out by Shukla and Karki (2016) explored the application of autonomous unmanned aerial systems on onshore sites for remote pipeline inspection, tank inspection, and automated gas sampling and are considered as pivotal autonomous robots. Further, unmanned aerial systems also aid in environmental monitoring, geophysical, topography surveys, security monitoring, equipment inventory/asset tracking, network communication (relays), and search and rescue missions (Elijah et al., 2021). Similarly, big data refers to multi-structured and unstructured datasets characterised by six major attributes which include volume, variety, velocity, veracity, value, and complexity. Within the O & G industry, big data is primarily utilised in exploration, drilling, and production (Pence, 2015).

Fundamentally, IoT is a technology that allows machine-to-machine communication across the network without interaction between humans and computers (Elijah et al., 2021). However, a study carried out by Flichy and Baudoin (2018) suggested that IIoT (Industrial IoT) is specifically an IoT technology advent in O & G industry to enhance operations and decline human interaction to ensure the highest level of security. In addition to this, Elijah et al. (2021) also illustrated the five major layers of the system architecture of IoT for the O & G industry which include the physical layer (sensors and actuators nodes to acquire data of the O & G equipment and facilities), the communication technology layer (connects physical layer with network layer using base station GPS, bluetooth, sigfox), the network layer (cloud computing blockchain technology for processing data), and the application layer (dissemination of the datasets through user reservoir management, hydraulic fractioning, seismic data processing, etc). Cloud computing is one of the fundamental technological components of Industry 4.0 because it offers various cloud-based services to the industry improving speed and efficiency and maximises business benefits to the industry. Perrons and Hems (2013) suggested different cloud computing services such as Google Computing Engine, Digital Ocean, Openshift, Dropbox, Zendesk, and DocuSign which can be useful in the O & G industry.

According to Frazier (2014), additive manufacturing is a procedure of constructing 3D models by stacking layer by layer. Further, additive manufacturing supports the production of complex geometries in the context of the O & G industry (Sireesha et al., 2018). Additionally, augmented reality is another component of the Industrial Revolution 4.0 that involves animation, 3D geometrics, and a virtual world that supports facility management in the O & G industry (Hou et al., 2014). In the context of the O & G industry, cyber security technologies support protection from black energy (Lee et al., 2018). Furthermore, system integration technology provides support to the O & G industry by integrating different facilities and improving the decision-making process. The major goal of system integration is the digitalisation of physical objects using acquired datasets from sensors and actuators (Jeschke et al., 2017). Simulation stands out as another pivotal technology in Industry 4.0, that supports the development, validation, and testing of various products within the O & G industry, primarily utilised throughout the product lifecycle (Rodic, 2017).

### 2.3. Current Practice of DT in O & G Industry

There are approximately ten application areas and enabling technologies of the DT in the oil and gas industry as demonstrated in Figure 2.4 (Wanasinghe et al., 2020). In application areas, the very first use of the DT concept is in asset monitoring and maintenance areas where the DT concept is widely utilised. Project planning and lifecycle management are the second-highest areas for utilising DT technology. Similarly, the third area to leverage DT is collaboration and knowledge sharing in the O & G industry. Further, drilling, virtual learning and training, offshore platforms, and infrastructure are at the fourth, fifth, and sixth levels of hierarchy respectively to leverage the DT concept. At the seventh level, the pipelines are the areas to implement DT. Finally, intelligent oilfields and virtual commissioning are the areas where the DT can be implemented in the O & G industry.

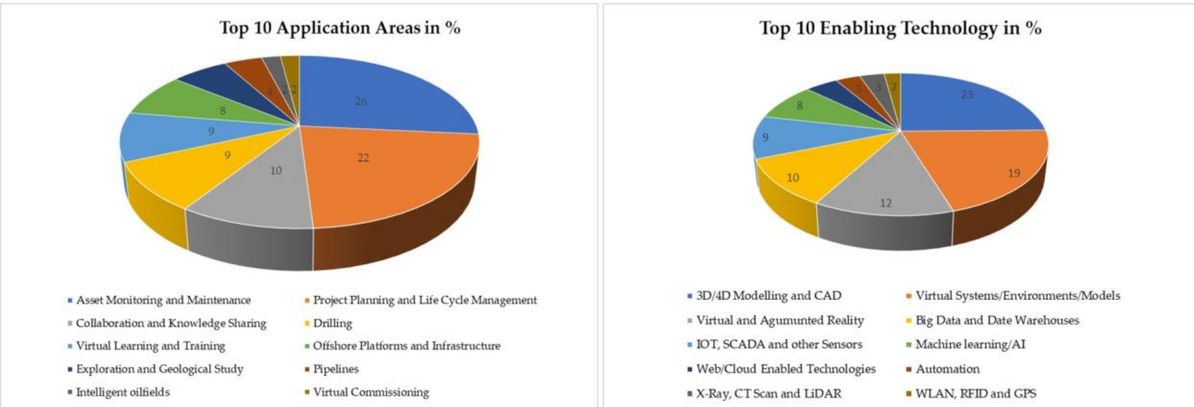



**Figure 2.4: DT Use in O & G Industry (Wanasinghe et al., 2020)**

3D/4D modelling and CAD are considered the topmost key enabling technology as illustrated in Figure 2.4. Similarly, virtual systems/environments/models are the second most enabling technology of DT. Virtual Reality (VR) and Augmented Reality (AR) are the third most enabling technologies in the oil and gas industry. Big data and warehouses are considered the fourth most enabling technology. The IoT and other sensors are the fifth most enabling technology in the oil and gas industry. The sixth, seventh, and eighth enabling technologies in the oil and gas industry are machine learning (ML), web/cloud-enabled technologies, and automation respectively. Interestingly, X-rays, CT scans and LiDAR are the ninth most enabling technologies. Finally, WLAN, RFID, and GPS are the tenth most enabling technologies in the oil and gas industry.

## 2.4. Spatially Enabled DT

### *2.4.1.* Spatial DT

Few research scholars have explored the applicability of the use of DT in the spatial industry. However, no explicit definition was stated in any existing literature until 2021. According to the policy report of WGIC (2022) spatial DT can be defined by the three parameters of definition, attributes, and benefits as illustrated in Figure 2.5.

A spatial DT is the virtual representation of real-world entities and processes by using positioning and dimensions to uplift the value, insight, and integrity of the virtual model which, in many instances, may be continuously updated at a synchronised frequency and fidelity (ANZLIC, 2019). Similarly, the parameters of the attribute state, "Whether implicitly or explicitly, most DT include in their virtual representations, the precise location and relative dimensions of elements included in their models" (WGIC, 2022). Additionally, spatial DTs enhance visualisation, facilitate faster interpretation, enable socioeconomic applications, and provide insights at a scale that outweighs the additional investment of a spatially accurate and positioned digital model of physical entities and processes" (ANZLIC, 2019).

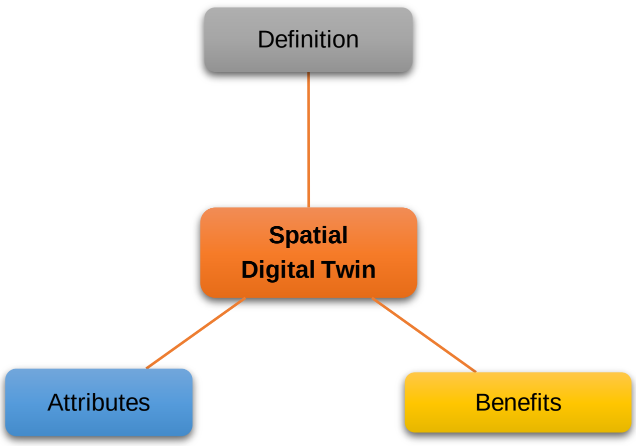



**Figure 2.5: Attributes of Spatial DT (WGIC, 2022)**

### *2.4.2.* Principles of Spatially Enabled DT

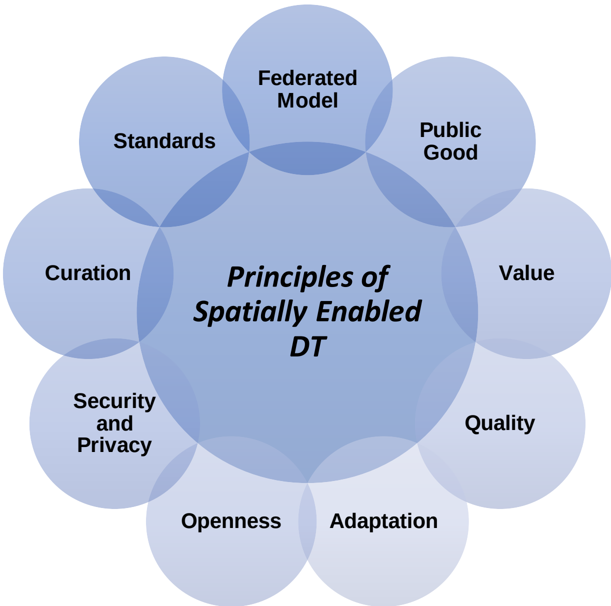



**Figure 2.6: Principles of Spatially Enabled DT (ANZLIC, 2019)**

In the context of Australia, ANZLIC (2019) developed nine principles for the spatially enabled digital twin as illustrated in Figure 2.6 and briefly discussed below.

- **Public Good**

DT should be utilised for the public good, and all non-confidential information across Australia should be made accessible to authenticated users.

- **Value**

The development of DT technology should add value to the Australian economy. All stakeholders: industry, academia, research centres, and government agencies, leverage this technology for sustainable management of built and natural environments.

- **Quality**

The datasets integrated into DTs system should be accurate and up-to-date so that users can always access reliable information.

- **Adaptation**

DT system should be developed in such a way that it is easy to adapt to the ongoing development of society and digital technologies.

- **Openness**

DT ecosystem should adhere to free and open-source principles as possible to fully implement them across every sector.

- **Security and Privacy**

The concept of role-based access control should be integrated into every DT system to ensure data integrity, data privacy, and data security.

- **Curation**

All data stored in the DT system should have explicit stewardship, standards, and policies to facilitate the development, maintenance, and accountable use of associated datasets.

- **Standards**

All stakeholders should be considered before designing DT standards to ensure interoperability, compatibility, and functionality.

- **Federated Model**

DT system should be developed based on a federated model to ensure the effective connection and sharing of data and services.

### *2.4.3.* Architecture of Spatially Enabled DT

Rajabifard et al. (2022) developed a system architecture as presented in Figure 2.7 for the spatially enabled digital twin. The key components of the architecture encompass 3D data management, live data management, real-time data stream, models, plugins, user management, and API management.

3D data management facilitates interactive 3D visualisation for effective decision-making. The main aim of 3D data management is to enable 3D visualisation, interaction, and analytics (Emmer et al., 2017). While comparing 2D and 3D data visualisation, 3D visualisation presents the real-world information more effectively (Han, 2023). However, the development of the 3D model of geospatial information is still considered a key challenge (Rajabifard et al., 2022). Similarly, live data management support in curating, managing, and analysing various real-time datasets available in different formats (Rajabifard et al., 2022). The real-time data can be acquired from different sources that including real-time traffic, weather forecasts, open street maps, and google maps (Faliagka et al., 2024). Further, this real-time data can be processed using the models/algorithms developed through artificial intelligence and machine learning techniques (Park et al., 2024).

Models and plugins are considered as the crucial components of spatially enabled digital twin architecture. According to Rajabifard et al. (2022), models are system-centric whereas plugins are user-centric. In addition, plugins are developed based on the specific problem (Chatley et al., 2003). The various AI models facilitate the processing of the datasets within the DT system that provides forecasted results (ANZLIC, 2019). Usually, AI models are developed using programming languages such  as Python, R, and java (Wynsberghe, 2021).

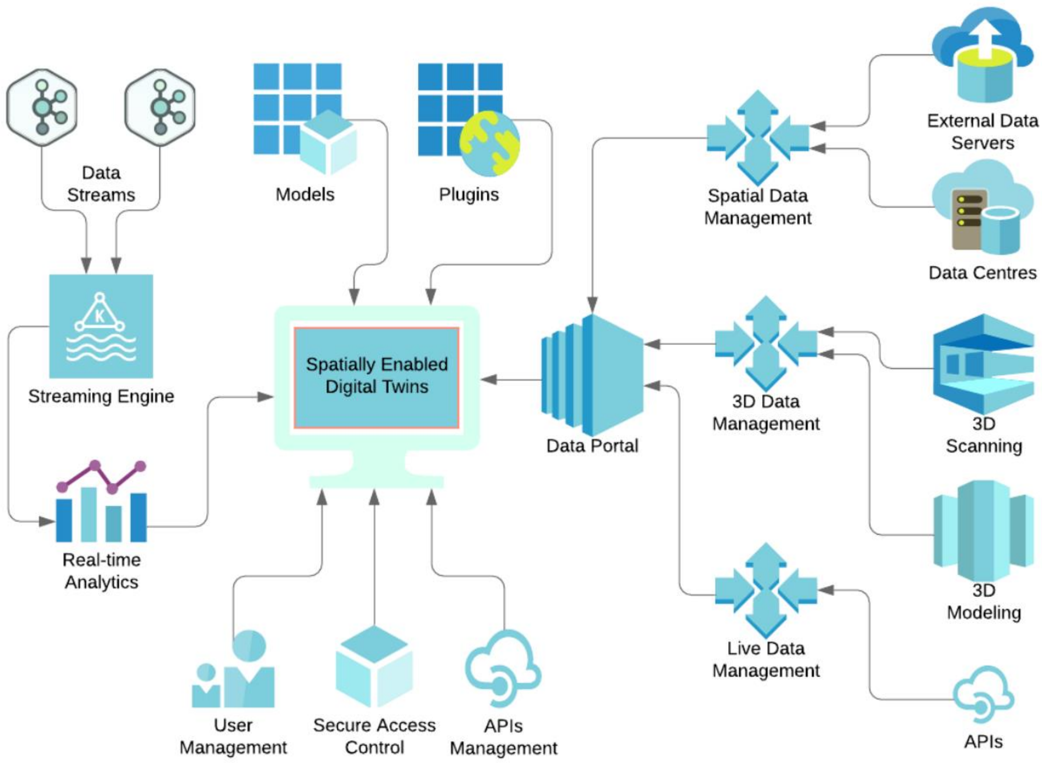



**Figure 2.7: Architecture of Spatially Enabled DT (Rajabifard et al., 2022)**

User management is another pivotal element of the architecture that allows diverse users to access the DT system (Rajabifard et al., 2022). The user management component enables different users to securely manage the datasets, models, and plugins. According to Rajabifard et al. (2022), the RBAC technique should be integrated into every spatially enabled digital twin framework. API management is another essential part of the architecture. According to Mathijssen et al. (2020), API management involves a sequential process that includes designing, publishing, and deploying the APIs that facilitate secure and effective data sharing into the DT system. Strong API management is pivotal in every DT system to securely manage all the datasets.

## 2.5. Existing DT Frameworks

The concept of DT is emerging in the scientific community. However, there are few significant contributions towards developing its conceptual framework. Through a systematic literature review, this study identified twenty-two models/conceptual frameworks/architectures categorised into three key domains that contribute to the development of DT initiatives. These domains encompass spatial science (SS), oil and gas (O & G), and others (O). Others comprise the areas of the mining industry, construction industry, and underground infrastructure sectors. The categorised DT frameworks are outlined in Appendix B and each framework's overview, strengths, and weaknesses are discussed below.

### *2.5.1.* DT Frameworks within the Spatial Science Discipline

A systematic literature review has identified nine frameworks in the SS discipline. In 2022, a comprehensive policy report was published by WGIC (2022) which introduced a conceptual framework for spatial DT. This framework incorporates four key facets: layer, application, standards, policies, and security. The layer facets are further categorised into the data layer, platform layer, and technology application layer. The various datasets that are considered in this framework comprise BIM, CAD, spatial data, non-technical data, and sensor data. Similarly, platform layers are divided into the visualisation layer, integration layer, data management layer, and user interface and service layer. Likewise, on the application layer, various DT user groups from planning and design, construction and monitoring, operations, decision-making, asset facilities, and disposal, have been included in this framework. This framework has contributed to the development of DT initiatives. It also serves as a theoretical DT model for industries that utilise spatial information and are eager to leverage DT technology in their business operations. However, for full implementation within the context of the O & G project, this framework needs further refinement and should be explicitly designed to align with the field design process of the O & G project, aimed at managing the spatial information.

Similarly, there are two DT frameworks developed with a focus on land administration. A highly acknowledged study conducted by Rajabifard et al. (2022) developed a spatially enabled DT system architecture that focused on the resilience infrastructure of urban settings. However, it was highlighted that this architecture could be modified and implemented across various industries. 3D data management, live data management, real-time data streaming, models, plugins, user management, and API management are key elements of the architecture. A detailed discussion of this architecture has already been presented in Section 2.4.3. This study has also demonstrated two use cases (3D cadastre interactive visualisation, query, manipulation, and 3D development envelope control for urban design) aligning with DT applications for urban land administration and 3D spatial planning. Nevertheless, this study is widely acknowledged in the research community, however, there is no empirical evidence of how it can be replicated or incorporated in the field design of O & G projects or in the mining industry.

Likewise, a study conducted by Broekhuizen (2021) as part of her Master's dissertation in 3D LAS demonstrates a system architecture that was developed by Cemellini (2018) based on open-source technologies. The architecture is composed of five components that contain client layer, network layer, server layer, and input layer. The client layer is based on the Cesium web application and Quantum GIS. The network layer connects the client and server layers through WFS protocols. Similarly, the server layer relies on PostgreSQL, GeoServer, and web servers. The key strength of this architecture is that it has utilised free and open-source technologies. Further, this empirical study has substantially contributed to the DT development initiatives and developed a methodology to integrate BIM and GIS concepts in a web-based 3D environment. However, the study only focused on the land administration paradigm.

The development of DT in the spatial science discipline can also be observed across the built environment and urban sectors. A widely recognised study was carried out by Lu et al. (2020) in the context of the management of information across various sectors of the city and buildings. This study developed a comprehensive system architecture of DT and validated it through a case study of the West Cambridge Campus. This study introduces a hierarchical architecture of DT operating at both building and city levels. The architecture comprises five layers: data acquisition, transmission, digital modelling, data/model integration, and service layers. This developed system architecture supports various services such as security and health management, transportation management, energy management, space utilisation, asset management, and environment management. Despite the high quality of the study in the context of the management of city infrastructure, there is no evidence of how it could be applied in the field design by integrating LSDM elements into O & G projects.

Similarly, another study conducted by Aleksandrov et al. (2019) focused on the development of a system architecture within the context of precinct information modelling (PIM). The system architecture consists of four integral layers. The first layer involves preprocessing steps crucial for structuring input data, encompassing tasks such as geometric cleaning, 3D representation creation, georeferencing, and attribute extraction. Following this, the second layer focuses on organising data and database structuring, serving as a central element by consolidating diverse spatial data into a unified modelling language (UML) data model, and establishing crucial connections among various data sources. The third layer acts as an interface, connecting the database to the frontend application, and enabling efficient querying, processing, and updates of structured data. Finally, the fourth layer, the frontend component, facilitates data visualisation and manipulation, empowering users to interact with the structured data effectively. This study also successfully validates the developed system architecture at the campus level (University of New South Wales, Australia) using a case study approach. However, it is important to note that the context of this study does not incorporate LSDM features. As a result, it remains uncertain whether the developed system architecture can be directly applied to the field design of O & G projects. Nevertheless, this study has made a significant contribution to DT initiatives and serves as a reference to integrate heterogeneous datasets, including building information systems (BIM), 3D GIS, and sensors within an open 3D web-based GIS system.

Further, a study carried out by Zhao et al. (2022) has also developed a conceptual framework for the application of DT technologies to revamp building operation and management (O & M) processes. The framework has presented five main architecture layers that include the DT preparation layer, DT acquisition layer, DT processing layer, DT transmission and modelling layer, DT model logic layer with intelligence tools, and

DT application/service layer. This conceptual framework has offered valuable insights regarding the management of heterogeneous information associated with building management data, QR codes, asset management data, real-time sensor data, and IoT devices. However, this extensive framework should be customised from the field design perspective before deploying seamlessly to the O & G project. Nevertheless, scholars of this study deserve great appreciation for their significant contribution to DT framework development.

Two notable empirical studies in the spatial science discipline have conducted specific case studies on 3D data conversion and data management respectively, contributing to DT initiatives. A study carried out by Chen et al. (2018) has gained recognition in the research community. It is a pioneering study that demonstrates an architectural solution to convert BIM datasets to 3D tiles in an open-source 3D Web GIS environment. This architectural solution offers a readily adapted approach for organisations that are seeking to enhance visualisation capabilities and utilise BIM data within an open-source 3D Web GIS environment. Although this solution focuses on BIM data visualisation, it falls short of fully addressing the requirements of an integrated system architecture that incorporates LSDM and the broader spatial information relevant to field design. Further, a study conducted by Colucci et al. (2021) has developed the conceptual model, logical model, and physical model of the database management system in integrating the BIM-GIS datasets using PgAdmin. However, this study is more focused on heritage information and does not consider the interactive system to manage the 3D BIM models. Nevertheless, this research has substantially added value to DT development and provides insights with empirical results regarding the integration of BIM and GIS in open-source environment which is crucial for developing any spatially enabled DT.

Despite all, a study conducted by Li et al. (2017) has developed an interactive web-based GIS system to manage spatial information associated with the oil and gas industry. This study has presented a three-layered system architecture that includes the data management layer, server layer, and client layer. The data management layer includes data layer, data access, and data storage in PostgreSQL. Further, the server layer consists of three modules: basic service, function, and control and these are further composed of many functionalities such as data transfer, base map, well location, visualisation, and request handling, among others. Finally, under the client layer, a visualisation interface is presented to interact with the associated user groups. It could be noticed that DT and LSDM concepts are not considered in the system architecture. However, it cannot be denied that this study has added significant value for acquiring knowledge on the management of geospatial information of the O & G projects.

### *2.5.2.* DT Frameworks on O & G Paradigm

In the context of the O & G industry, most of the DT frameworks have been developed for manufacturing sectors. From the systematic literature review, seven frameworks were identified in the O & G industry. A study carried out by Wanasinghe et al. (2020) demonstrated a few theoretical frameworks of DTs explicitly in the context of the oil and gas industry. The widely acknowledged five component frameworks developed by Parrott and Warshaw (2017) encompass sensors, data, integration, analytics, and actuators. Sensors and actuators operate within the physical space, whereas data and analytics occur within the virtual space. Integration technologies play a pivotal role in facilitating seamless communication between the physical and digital spaces. Communication interfaces serve as mediators linking sensor functionalities with integration functions, while edge security integrates necessary security protocols and encryption mechanisms to safeguard both the DT and sensor data from cyber threats. In this study, authors have mentioned that this framework can be directly applied to any sector of the O & G industry but there are not any existing empirical studies that could assess the viability of this framework in the spatial/field design sector of the O & G project. However, this study is considered a point of departure for DT research in the oil and gas industry because it comprehensively highlights the status of DT implementation in the O & G industry.

Similarly, Zhang and Sun (2021) developed a multi-scale framework for reservoir DT. The framework is based on three numerical methodologies: the Navier-Stokes schemes, Lattice Boltzmann Method (LBM) schemes, and Darcy schemes. The Navier-Stokes schemes represent widely used computational fluid dynamic methods in engineering calculations, particularly favoured for applications in single pores or in pipeline and facility settings. LBM schemes, functioning as a specialised discretisation of Navier-Stokes equations, offer ease in implementation and accommodate numerous models within the distribution function, making them highly popular for engineering computations. On the other hand, Darcy schemes are notably suitable for studying flow and transport in both representative element volume scale and field-scale porous media. From this, it can be certainly said that this framework has no relation to the spatial paradigm of the O & G project.

Further, a notable study done by Shen et al. (2021) developed the DT framework for predicting the production of the O & G. This framework integrates advanced technology across the various disciplines, combining physical and virtual entities with data. The physical layer integrates new information technology and virtual reality with IoT. Cloud-based storage forms the transmission and data layers. AI-driven analysis supports decision-making, while VR and AR enable visualisation. Data fusion is pivotal, incorporating real-time equipment status and historical data to enhance decision-making. This fusion enhances real-time accuracy and synchronisation between information and physical data, a key aspect during operational phases. The system integrates various facets of oil and gas production, including underground reservoirs, wellbore technology, surface production, and metering for gathering and transportation. By enabling real-time information exchange and bidirectional mapping between the physical and virtual production systems, it achieves comprehensive integration across the entire life cycle and elements of the industry. This includes the physical production system, virtual system, production design, optimisation, prediction, and the fusion of business data. However, this framework has not focused on the spatial science field and has not considered LSDM from a spatial information management perspective.

Similarly, another notable study has been conducted by Bevilacqua et al. (2020) that developed a DT reference model for risk control and prevention. The reference model comprises four primary layers: user space, DT, communication systems, and process industry physical space. The first layer of process industry physical space includes all physical industry resources such as products, personnel, equipment, material, process, environment, facility etc. The second layer communication system facilitates data transfer between the DT and plant elements, employing devices such as sensors and cameras. The third layer the DT manages data acquisition, visualisation, analysis for anomaly detection, and simulation of plant behaviour. It includes tools such as control and execution, simulation, anomaly detection and prediction, and a cloud server platform. The cloud server platform, a component of the DT, handles real-time data acquisition and visualisation through a cloud-based solution. Finally, the user space layer offers an interface for users, facilitating operational instructions, warning messages, and advanced services such as wearable systems for anomaly alerts and safety measures. However, there is no rationale for its feasibility in the field design process of the O & G project.

Likewise, a study carried out by Xiangdong et al. (2020) developed a system architecture to manage the O & G asset information. This architecture consists of four components that include: marginal layer, iass layer, pass layer, and saas layer. The marginal layer has IoT systems that encompass pipe, environment, fluid, and equipment. Likewise, facility management, resource management, and operation management along with fault recovery are all elements of the iass layer. Further, data analysis and simulation analysis are part of the pass layer. Finally, the saas layer delivers two services: pipeline asset management and equipment asset management. However, this architecture has not been empirically validated in real-world case studies and does not have any field design ingredients. In addition to this, this architecture is only focused on integrity management which indicates that system architecture could not fully facilitate the field design process.

Similarly, Lv et al. (2023) developed a system architecture for the DT technology (DTT) offshore oil and gas industry. There are four key layers in the architecture that includes: physical layer, data processing layer, data layer, and application layer. The physical layer encompasses the real-world entities including oil and gas assets. Furthermore, the data processing layer includes cross spatial data fusion model and calculation data model to process the raw acquired data from the physical space. Then, the data layer acts as a bridge between the data processing layer and the application layer. The data layer consists of components such as feature extraction, feature fusion, data transformation, and data reorganisation. Finally, the frontend layer (application) layer encompasses design, administration, and structural damage functionalities. This architecture has significantly contributed to DT framework development. However, it is focused on offshore O & G projects and lacks LSDM integration into its framework.

Regardless of the above, the study conducted by Konchenko et al. (2020) has illustrated the conceptual framework and validated it in the real world that focused on the virtual field design of the O & G project. The system architecture includes four key elements, such as: drone image processing application, backend system integration of public cloud stack and REST APIs, 3D immersive software, and an AR system. The drone processing application enables users to upload the UAV/aerial images and generate the orthomosaic. The backend system facilitates the users to extract the spatial information from the imageries. Further, 3D software facilitates users to experience a 3D virtual environment. Finally, the AR model supports the assessment of the conditions in a real time environment which ultimately supports users in planning maintenance. This architecture has been successfully deployed on field development examples to facilitate visualisation, seismic surveying, surface assets, surface, or seafloor. However, this architecture does not incorporate LSDM features to manage the spatial information which is considered pivotal in O & G directed by IOGP. In addition to this, this study is also focused on offshore operations only.

### *2.5.3.* **DT Frameworks on Others Paradigm**

The field design process of the O & G project is also interconnected with other disciplines such as the mining industry, construction industry, and underground infrastructure. Few remarkable frameworks have been developed in these sectors. The systematic literature review has identified six frameworks in these sectors.

A study carried out by El Bazi et al. (2023) developed the system architecture for the mining industry to manage the asset throughout its life cycle. This framework comprises two CPS layers: cyber and physical, along with three sublayers: data preprocessing, edge computing, and cloud. The physical layer involves collecting data from the open pit mine’s assets, including sensor readings, videos, staff records, etc. This data, often time series, undergoes specific processing tailored to its dynamic or static nature before being integrated into the DT. The cyber layer includes the data preprocessing sublayer, focusing on refining raw data for effective analytics. The subsequent edge computing sublayer operates close to data sources, enabling quick processing, reduced latency, and enhanced security. Meanwhile, the cloud sublayer, located at the top of the cyber layer, hosts the primary database, receiving data from lower layers for various applications such as predictive maintenance and process optimisation. Co-simulation services, operation data handling, and synchronisation services complement the framework, ensuring accurate representation and synchronisation between the physical and digital entities of the system. This framework would be one of the guiding frameworks for managing the asset information in every mining industry. However, for full implementation in the context of the field design process, further specific customisation is certainly required.

Similarly, Wang et al. (2023) have developed the DT model for managing safety information in coal mines. This study adopts a five-dimensional model as its foundational framework. This model comprises the physical entity, virtual entity, service system, twin data, and connection. A physical entity represents the real-world object under study and forms the basis for constructing the DT. The virtual entity is a high-fidelity digital simulation model of the physical entity, enabling real-time simulation, predictive analysis, and optimisation strategies for the service system while monitoring and regulating production processes. Service systems encompass various manufacturing systems supporting product manufacturing. DT encompasses all data related to physical entities, virtual entities, and service entities driving the DT through data integration. Lastly, connection serves as the essential linkage method among entities, services, and data, facilitating interconnection through sensors and data acquisition systems. Safety has been a key aspect in every mining industry and this architecture offers a significant contribution to obtaining complacency in safety by leveraging the DT concept. However, replicating this architecture for managing the spatial data of field designs in the field design process of the O & G project is not feasible.

Scholars have also explored DT frameworks for underground infrastructure including pipelines which are one of the pivotal infrastructures in the field design process. A study carried out by Shekargoftar et al. (2022) developed a pipeline operation and maintenance management system, an integrated framework, that streamlines the maintenance of gas utility pipelines. This framework integrates different technologies (BIM, GIS, and AR) to offer versatile functionalities. In this framework, commercial software applications were utilised to showcase how the framework can be practically implemented. Through a BIM plug-in, an AR application, and a cloud database, essential information related to gas utility pipelines such as construction details, GIS data, inspections, and repairs can be accessed directly on the existing 3D model. This study is highly acknowledged for integrating 2D and 3D datasets focusing on pipeline corridor design. However, the study is limited to mobile applications and does not incorporate LSDM.

A study conducted by Lee et al. (2023) has demonstrated an architectural workflow using open-source technologies to manage a DT spatial data model (DTS-DM). The system architecture initially acquires the original data of the underground utility tunnel model in IFC (.ifc) file format and then proceeds to convert it into DTS-DM model. This transformation facilitates user services. The service data are characterised by hierarchical file structures based on level of detail (LOD), spatial shape updates, and a database to store associated properties. Leveraging metadata (index structure) within the 3D tile arrangement, users can perform rapid, high-speed searches. Subsequently, they gain access to DT space services offered by the system. The architectural workflow demonstrated in this study could be a great reference for building spatially-enabled DT as it illustrates steps to manage numerous 3D datasets used for designing underground and above any infrastructure including pipelines. Nevertheless, the study focused solely on tunnel infrastructure without considering integration possibilities with other geodatabase models such as LSDM.

Similarly, a study carried out by Sharafat et al. (2021) also developed a BIM-GIS integration framework for underground utilities such as water, oil, gas, electricity, and telecommunications. This study suggests merging BIM and GIS frameworks to manage underground utility infrastructure effectively. It involves four layers: data source, processing, integrated BIM-GIS platform, and application. First, data on utility pipes is gathered using UAVs and GPR technology for surface and subsurface details. Then, the collected data is processed to create detailed models in BIM, adding extra information based on industry foundation class (IFC). Integration of BIM with GIS is performed using CityGML standard. The application layer holds key data for future design, construction, and maintenance tasks, supporting functions such as clash detection, design improvement, and facility management. The BIM-GIS framework developed by this study was successfully implemented in real-world utility infrastructure projects in different stages, including design, construction, and maintenance. Although this study provides a valuable example of integrating spatial information and field design information, it is important to note that it specifically focuses on the BIM GIS integration and does not directly incorporate LSDM features.

Further, there is another study carried out by Pan and Zhang (2021) to develop the architecture for DT for a BIM-enabled construction project. In this architecture, a UAV with LiDAR technology captures 3D data for real-time monitoring and transmits it to a BIM cloud for storage. Tools such as real-time and automated monitoring and control (RAAMAC) and IFC loggers analyse this data, generating insights for automated construction monitoring. These insights, combined with IoT data, create detailed virtual models used for simulations and data-driven management. The DT employs data mining to predict progress, identify bottlenecks, and optimise processes, offering timely feedback to managers. This setup allows for remote and efficient management of construction processes, integrating BIM, IoT, and data analysis techniques. This study has validated the use of UAVs in building DT for construction-related projects. However, it has not incorporated any feature classes of the LSDM in its architecture.

Therefore, from the above discussion, it is concluded that there have been significant contributions in building DT frameworks/architectures/models in the spatial science discipline, O & G, and underground infrastructure. These contributions have offered great value to the DT research community. However, existing DT frameworks lack the incorporation of the industry-standard data model such as LSDM and its implementation which is pivotal for storing spatial data of infrastructure designs during the field design phase of O & G projects. This absence will influence industry-wide adoption and implementation. Hence, the major aim of this study was to develop a spatially enabled DT conceptual framework integrating LSDM, allowing the storage and visualisation of spatial data of infrastructure design within a virtual 3D environment.

## 2.6. Overview of O & G Project

### *2.6.1.* Upstream

The fully integrated O & G industry primarily consists of three sections: upstream, midstream, and downstream (Leblanc, 2020). The exploration, appraisal, development, production, and abandonment are major life cycle stages of the oil and gas field (Ganat, 2020). Exploration is the key focus of the upstream section which involves seismic surveys to identify the potential sites for oil extraction to the surface (Millar & Dorling, 2020).

Similarly, the main objective of the appraisal stage is to investigate the volumes and attributes of oil and gas (Paulauskiene, 2017). In the development stage, the drilling equipment is installed, and gas is extracted through the production stage (Ovetska et al., 2021). In addition to this, activities such as design, commissioning, hook-up, and construction are crucial throughout the development stage. The production stage is mainly responsible for reservoir management, well tests and inspections, production optimisation, and many more (Santos et al., 2021). Finally, the abandonment of the well sites is conducted which involves removing the surface of equipment from well sites and environmental restoration (Paulauskiene, 2017). The generic lifecycle of the oil and gas field of the upstream section is illustrated in Figure 2.8.

### *2.6.2.* Midstream

The midstream acts as a bridge between upstream and downstream sectors. The major activities in the midstream are processing the oil and natural gas, storing, transporting, and distribution. In addition to this, midstream includes the pipeline infrastructure, and other transportation systems such as shipping services (Leblanc, 2020). The daily operation of the mid-stream includes transporting crude oil from the upstream sites to refineries or the downstream site.

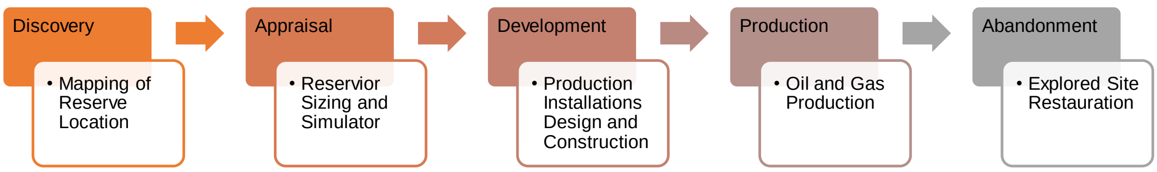



**Figure 2.8: Upstream Process (Santos et al., 2021)**

### *2.6.3.* Downstream

The downstream section primarily focuses on the marketing facet that includes oil refining, bulk terminal storage, retail and wholesale. Petrochemical plants, natural gas distributor outfits, oil refiners, and gas stations are the paramount assets of the downstream (Mette, 2021). Downstream oversees the distribution and converts to the final oil products. However, the crude oil is further refined into petrol, gasoline, fuel, and the final prepared products are distributed to retailers (Leblanc, 2020). In a nutshell, the downstream section of the O & G industry is involved in the management of the final oil products.

## 2.7. Field Design Process

The field design for any O & G project must adhere to the rules and regulations of the host country (IOGP, 2020). This phase involves the design of various infrastructures that include well infrastructure, rigs, access roads, gathering pipeline networks, and various other facilities such as utility features, culverts, pipeline tie-ins, fences, sumps, laydown areas, borrow pits, camps, tanks, and sewage treatment plants (IOGP, 2020; GCQ, 2022). Each O & G project has its own specific procedures and workflow and depends upon the nature of the project. Based on the information provided by Adedeji and Samuel (2013); IFTDP (2018); IOGP (2022); Lee et al. (2018); Mokhatab et al. (2014); Nouri (2016); Rahim et al. (2015); SBENRC (2017); Shell QGC (2017); Shen et al. (2021); VIVA Energy (2020); and West (2011), field design typically entails four key steps, conceptual engineering design, detailed engineering design, approval from various stakeholders, and finally storing the design spatial data into the central SIS of the oil and gas project based on LSDM. These four key activities are explained further.

### *2.7.1.* Conceptual Engineering Design

The conceptual engineering design is considered the initial phase in the design of infrastructure in any oil and gas project. Its primary objective is to develop and validate the feasibility of various alternatives (Paul et al., 2008). For instance, if there is a need to develop the road network or gathering network to connect well pads and existing road/gathering networks, different alternatives of road and gathering alignments are developed, and their feasibility needs to be assessed (Jemena, 2016). The conceptual engineering design mainly consists of five major activities which are explained further and illustrated in Figure 2.9.


**Figure 2.9: Key Activity in Conceptual Engineering Design (Paul et al., 2008; Jemena, 2016)**

- **Acquisition of Input Factors**

The first step is to acquire the various information (factors) that impact the design and construction of the infrastructures (Lee et al., 2018). Various information needs to be acquired from various stakeholders (Paul et al., 2008). In the context of Australia, stakeholders include ecologists, surveyors, cultural heritage officers, safety officers, and land access officers (Lochard Energy, 2022a). The information solely depends upon the nature of the project and its requirements. The key facet of information that should be covered include land sector, environment, design completeness, economics, safety policies, legislation, and acts (Senex Energy, 2022). After acquiring the factors, the engineering team proceeds with the identification of viable sites (Paul et al., 2008) which is explained further.

- **Identification of Viable Sites**

The main objective of this step is to identify the possible sites in the office for the proposed infrastructure to be designed (Mokhatab et al., 2014). The engineering department identifies the possible sites. Under the supervision of the lead design engineer, the engineering department mainly figures out the various alternatives for the sites (Paul et al., 2008). Historical aerial photographs, cadastral information, pipeline engineering specifications, road engineering specifications, reservoir engineering specification, and overall information acquired from various disciplines are considered while identifying viable sites (Mokhatab et al., 2014).

- **Selecting and Assigning Criteria**

This step is conducted once the design engineering team identifies possible sites for further design (Paul et al., 2008). Firstly, various criteria are prepared for the identified sites. The criteria are developed by the design engineering team in coordination with all relevant disciplines (West, 2011). Subsequently, the criteria are assigned to the identified sites, and weights are determined in consultation with members from other disciplines. For example, in the case of the gathering network, the design engineering team proposes various gathering alignments. Then, specific criteria (financial, environmental, design specifications, safety, etc). Once the criteria have been assigned, the engineering team further assesses and analyses them as explained in more detail in the following section.

- **Analysis of Criteria and Approval for Preliminary Design**

To finalise the viable sites among various alternatives, the engineering team conducts an analytical process by consulting with other stakeholders (Paul et al., 2008). In this analytical process, each alternative is compared from various perspectives: land acquisition, cultural heritage, safety, design, finances, and the environment (Arrow Energy, 2013). For example, in the context of a road network, various road alignments (A1, A2, A3, A4,…,An) are compared (ITDP, 2018) and the most suitable alignment is selected taking inputs from other departments. Each department provides opinions and arguments on the proposed site presented by engineeering department. Once representatives from all stakeholders are satisfied that the proposed site poses no constraints in any aspect, approval is granted for the preliminary design of the proposed infrastructure.

- **Preparation of Conceptual Engineering Design**

After selecting the feasible site for the proposed infrastructure whether it involves a road, gathering system, well pad, rigs, or plant facilities, the engineering team should prepare the preliminary design based on technical specifications (Paul et al., 2008). For example, the road network is developed in accordance with national/state design specifications, and gathering networks follow pipeline engineering specifications. Each infrastructure has its specifications for the preliminary design during the development of oil field sites (Lee et al., 2018). The primary output of the preliminary design is the plan/drawings/3D model and it depends upon the project requirements. Once the engineering department finalises the preliminary design, it should be sent to all departments for approval (Paul et al., 2008). If any departments are not satisfied with the preliminary design, amendments are made, and the design is resubmitted for approval. This iterative process continues until all stakeholders are happy with the preliminary design (Sabri et al., 2015). Once the preliminary design is approved by all disciplines, the engineering department sends the data to the spatial information management department for archival (Shell QGC, 2017).

### *2.7.2.* Detailed Engineering Design

This is the second step in the field design of any typical O & G project. The goal of the detailed engineering design process is to refine and communicate the preliminary design in a set of drawings/3D models, and specifications (Arrow Energy, 2013; ITDP, 2018; QLD Government, 2012; Sabri et al., 2015). The key steps of the detailed engineering design are presented in Figure 2.10.

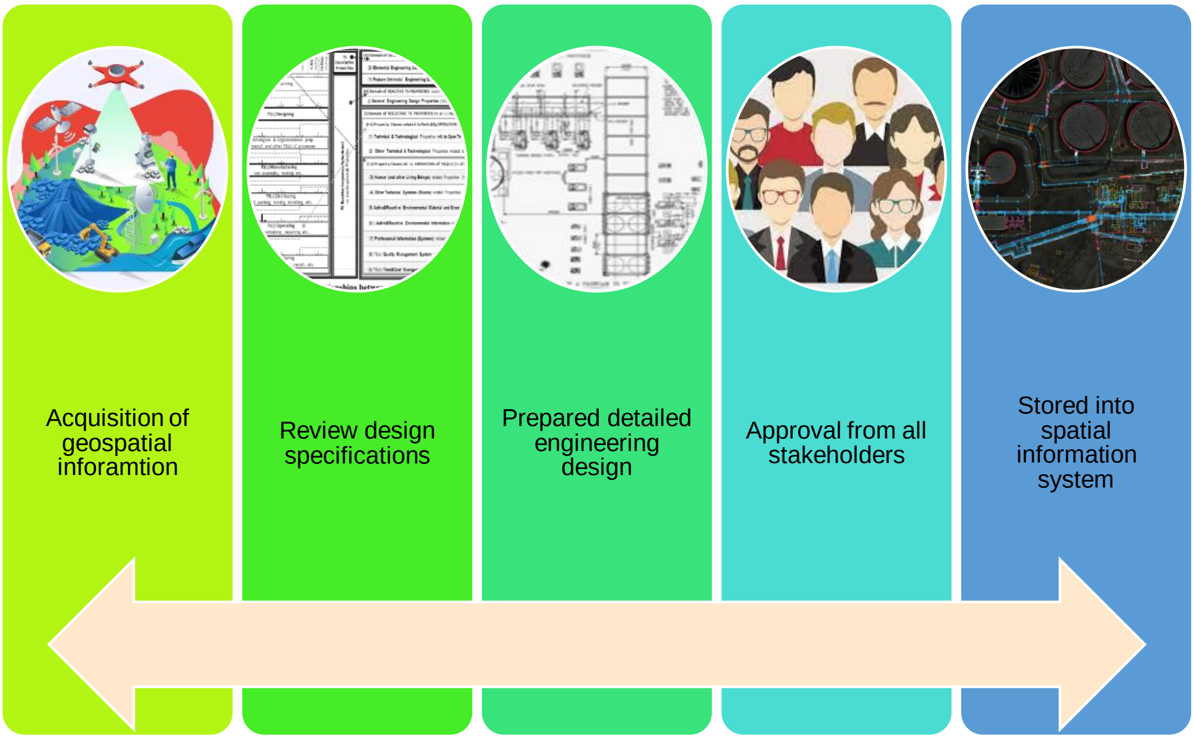



**Figure 2.10: Key Activity in Detailed Engineering Design (SBNRC, 2017; VIVA Energy, 2020; Shell QGC, 2017)**

- **Acquisition of Geospatial Information**

The primary aim of acquiring geospatial information is to gather on-site information to understand the existing surroundings. This is normally done through surveying activity (SBENRC, 2017; VIVA Energy, 2020). The choice of surveying and mapping techniques depends on the project; some may use the total station technique, while others might utilise the GNSS or UAV technique. It solely depends upon the project requirements (SBENRC, 2017). Once data are captured and processed, the surveying department should send the data to the spatial information management department for archival (Shell QGC, 2017). The surveying department always ensures that data has been captured precisely and meets project requirements (IOGP, 2022).

- **Review Design Specifications**

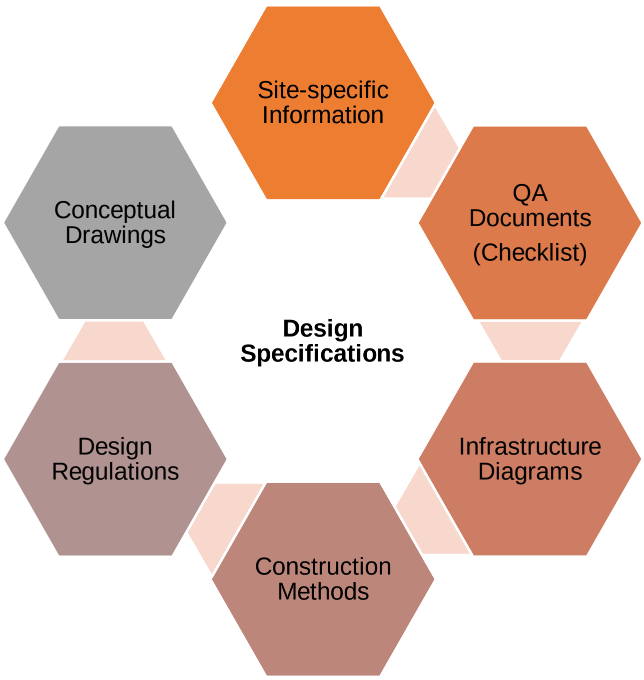



**Figure 2.11: Design Specifications (Srivastava & Takeidinne, 2012; West, 2011; Yi et al., 2019)**

The major objective of reviewing the design specification is to minimise the changes to the preliminary design stage (ITDP, 2018). The design specification varies from country to country or is project-specific and depends upon the host country's rules and regulations (IOGP, 2020). The key specifications of design are documented in the reports published by Srivastava & Takeidinne (2012); West (2011); Yi et al., (2019) and presented in Figure 2.11.

Site-specific information provides details about the unique characteristics of the location where the construction project will take place. This information includes geological, environmental, and logistical details (VIVA Energy, 2020). Similarly, conceptual drawings are early-stage visual representations of the project (Paul et al., 2008). Further, design regulations encompass local, regional, and federal standards that must be adhered to during the design and construction process (West, 2011). Moreover, construction methods outline the techniques and processes to be employed during the construction phase (Srivastava & Takeidinne, 2012). Infrastructure diagrams provide detailed representations of the layout and connections of various components in the construction project and QA checklists outline the criteria and standards that must be met to ensure the quality of the design (Paul et al., 2008; Yi et al., 2019).

- **Preparation of the Detailed Engineering Design**

The detailed engineering design phase is a pivotal activity where design engineering teams play a central role. This stage requires the preparation of a comprehensive set of detailed drawings/models, outlining layouts and levels, and setting out details for all infrastructure components (West, 2011). Each element of the conceptual engineering design undergoes a detailed design process to confirm that all necessary design procedures have been executed and design calculations are completed (ITDP, 2018; Srivastava & Takeidinne, 2012). In typical detailed engineering design, the initial step involves extracting existing background geospatial information from the SIS based on the project's scope and requirements (Shell QGC, 2017). Subsequently, the acquired surveying and mapping information is integrated into the design tool, such as AutoCAD (Paul et al., 2008). For access and gathering, 1D (linear linework) is designed, while for robust infrastructure, rigs, and facility building, 2D polygons/3D models are designed (West, 2011). It depends on the project requirements. The design process is fundamentally guided by conclusions from the review design step and information gathered during the surveying stage (SBENRC, 2017; West, 2011). Once the designs are completed, a design plan/model is prepared according to relevant cartographic rules and regulations specific to the project (Paul et al., 2008; Shell QGC, 2017). A checklist is then completed as part of the quality assurance (QA) process, rectifying any typos, and the final plan/model is prepared and sent to the stakeholders for further approval which is explained further (ITDP, 2018; Paul et al., 2008).

- **Approval From All Stakeholders**

This marks the final stage of the detailed engineering phase, aiming to secure approval from all relevant authorities for further field layout and construction (ITDP, 2018; Paul et al., 2008; VIVA Energy, 2020; West, 2011). Firstly, the design is distributed to all stakeholders, accompanied by relevant documents such as drawing/3D models and other associated information that includes Excel spreadsheets and reports which are attached to the reporting database (Arrow Energy, 2013; Jemena, 2016; VIVA Energy, 2020). The structure of this database is tailored to the specific project. Secondly, each relevant discipline conducts a thorough review of the detailed engineering design from their perspective (Paul et al., 2008). For instance, the environmental department assesses the impact of the designed infrastructure on environmental aspects, while the cultural heritage department evaluates its impact on existing cultural heritage sites. Upon approval from all disciplines, the spatial information management team receives and archives the database from the design engineering team (Shell QGC, 2017).

- **Archiving to Spatial Information System (SIS)**

Once all stakeholders involved in the field design process have reviewed and approved the detailed engineering design of the proposed infrastructure, the final crucial step involves migrating the spatial data of the infrastructure design into the SIS using LSDM (IOGP, 2022). This ensures that the precise geospatial information of the design of the infrastructure are stored for the further construction phase (Arrow Energy, 2019; IOGP, 2022; Shell QGC, 2017; VIVA Energy, 2020). Section 2.9 of this dissertation elaborates on LSDM, which serves as the industry-standard framework for managing spatial data during the field design phase.

## 2.8. Field Design in the Context of Australia

Section 2.7 discusses how a typical field design process operates in any O & G project. Subsequently, this section provides insights into the current practices of communicating design information related to the infrastructure involved in the field design process within the O & G projects in the context of Australia. The main purpose of reviewing the projects was to identify how design information of the relevant infrastructure was communicated within the project. The three major steps were carried out. Firstly, to explore these current practices, existing resources were examined. However, during the literature review, accessing specific field design information was challenging due to the limited availability of reports on the Internet. Consequently, twenty corporate reports were filtered out based on accessibility. Furthermore, among twenty reports, four were selected based on the available content regarding the field design aspect of O & G projects. The below sub-sections outline the four O & G projects that include the field design aspect.

### *2.8.1.* Jemena NGP Projects

The aim of this project is to establish a new underground natural gas pipeline extending approximately 622km, traversing the distance from Warrego in the Northern Territory to Mount Isa in Queensland (Jemena, 2018).

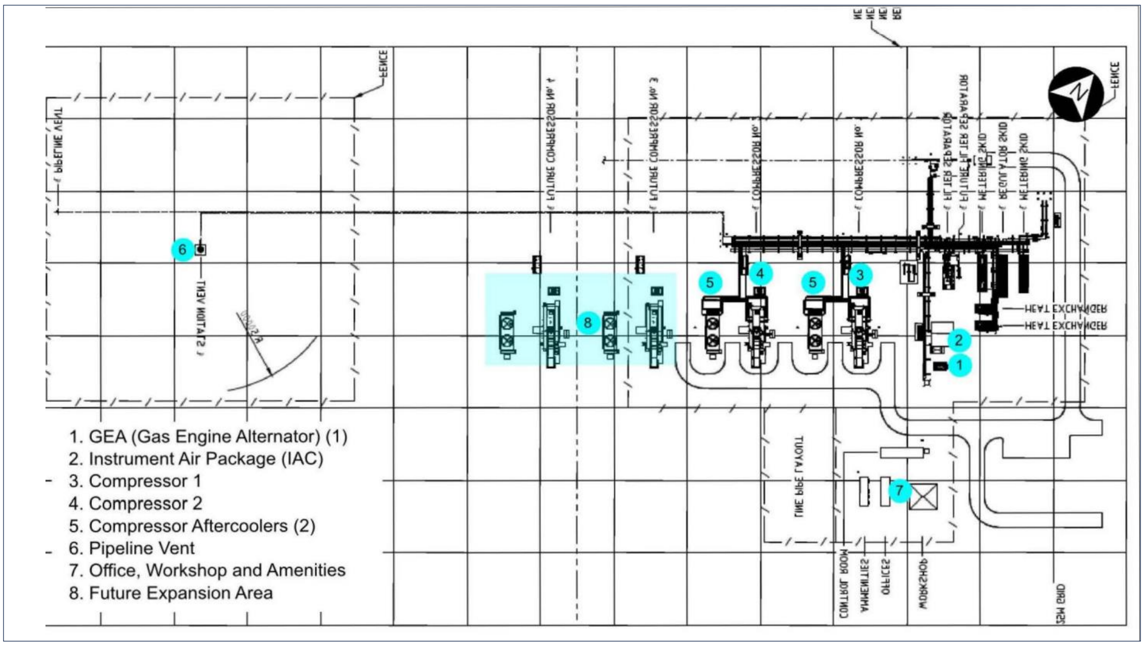



**Figure 2.12: 2D Plan of Compressor Station (Jemena, 2016)**

The key components of this project include the construction of a 323.9mm gas pipeline, a compressor station, three mainline valves, and five cathodic protection stations (Jemena, 2016). The construction infrastructure encompasses a 30m wide Right-of-Way (ROW), access tracks, and additional workspace for temporary facilities (Jemena, 2020). These pieces of infrastructure are essential for efficient gas transportation whereas compressor stations facilitate regulating pressure and mainline valves facilitate managing flow preventing pipeline corrosion (Jemena, 2018). After reviewing the report written by Jemena (2016), it was found that most of the infrastructure designed during the field design phase was communicated through 2D plans. For instance, the design of the compressor station was presented through a 2D plan, as illustrated in Figure 2.12. Furthermore, the design information of camp layout and pipeline alignment during the field design phase was also communicated through 2D plans. The key identified issue due to the use of the 2D plan was the illustration of complex design information associated with the compressor stations which is difficult to interpret for stakeholders from non-engineering backgrounds (Byun & Sohn, 2020).

### *2.8.2.* Santos GLNG Project

This project area is situated in Queensland, Australia, covering coal seam gas (CSG) fields from the southern region of Roma to Emerald (QLD Government, 2015). Within this project, a liquified natural gas (LNG) facility is also located on Curtis Island near the coastal city of Gladstone (Santos, 2009).

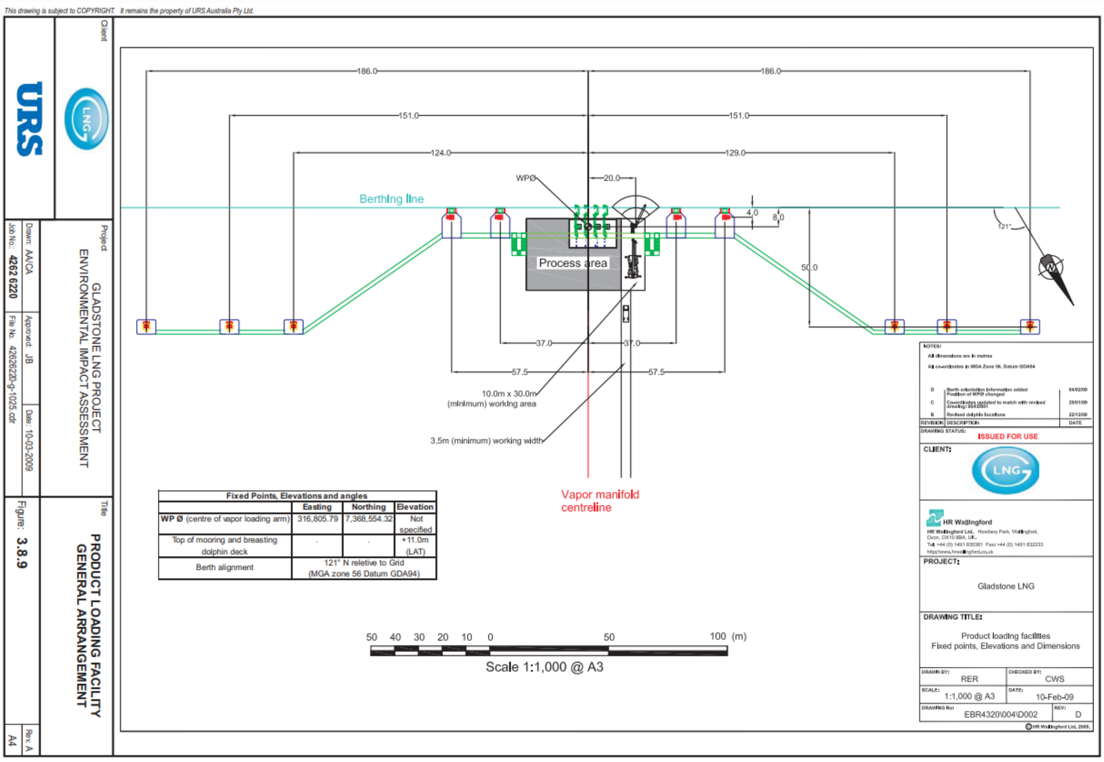



**Figure 2.13: 2D Plan of Facilities (QLD Government, 2015)**

The purpose of this facility is to connect the gas fields to the LNG facility through a gas transmission pipeline (QLD Government, 2014). The key infrastructure involved in this project includes 12 centralised compression and water treatment facilities, 150 nodal compressor stations, a 300mm pipeline, Right-of-Way (ROW), access tracks, pipe racks, and utilities (QLD Government, 2015). After reviewing the report published by Santos (2009), it was observed that most of the infrastructure design for this project was presented through 2D plans. Figure 2.13 illustrates one of the facilities of the project where the design information of the processing plant is depicted through a 2D plan, although spot height values are presented on the plan. The key identified issue through the use of the 2D plans was the high probability of design error through 2D design linework as discussed (Zhou et al., 2024).

### *2.8.3.* Arrow Bowen Gas Project

This project is located approximately 850 kilometres from Brisbane and 150 kilometres southwest of Mackay, Queensland (Arrow Energy, 2014). It comprises an estimated 6,625 production wells and associated coal seam gas infrastructure, with a predicted lifespan of approximately 40 years (QLD Government, 2014).

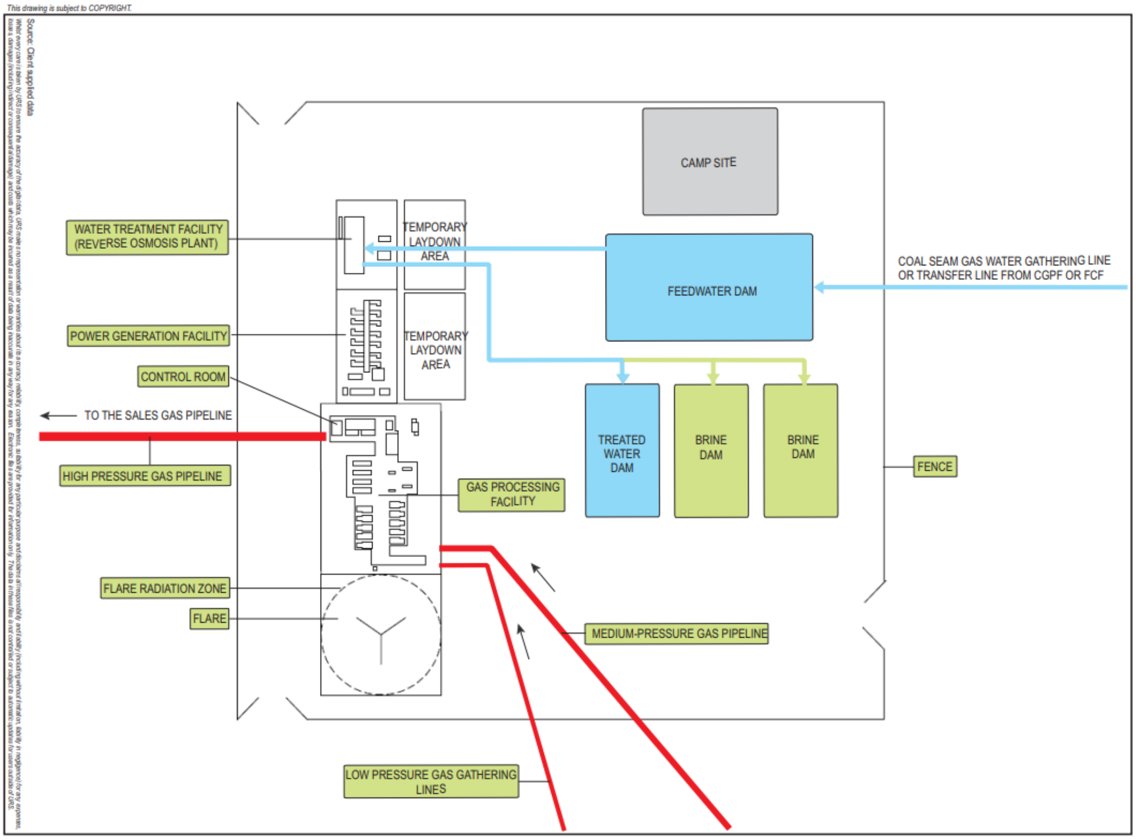



**Figure 2.14: 2D Plan of Processing Facility (Arrow Energy, 2014)**

It encompasses an area of 8,000 square kilometres and its operational scope includes key infrastructure components such as wells, pipelines, processing facilities, roads, a water treatment plant, personnel camps, and borrow pits (Arrow Energy, 2014). The report prepared by Arrow Energy (2014) does not contain comprehensive information about the infrastructure design, but it has provided a conceptual 2D plan of the processing facility. This plan is illustrated in Figure 2.14. The major infrastructure featured in this plan include a campsite, control room, water treatment facility, temporary laydown facility, gas processing facility, fence, and gathering line connecting to the processing facility. The key identified issue in this project was the illustration of the design information using conventional 2D plans which offer limited visualisation (Al-Rbeawi, 2023).

### *2.8.4.* HUGUS Project

The aim of this project is to increase underground gas storage capacity by utilising depleted gas from the Heytesbury field (Lochard Energy, 2022b). The development involves establishing a new wellsite to access three distinct fields: Mylor (PPL4), Fenton Creek (PPL4), and Tregony (PPL7) (Lochard Energy, 2022b).

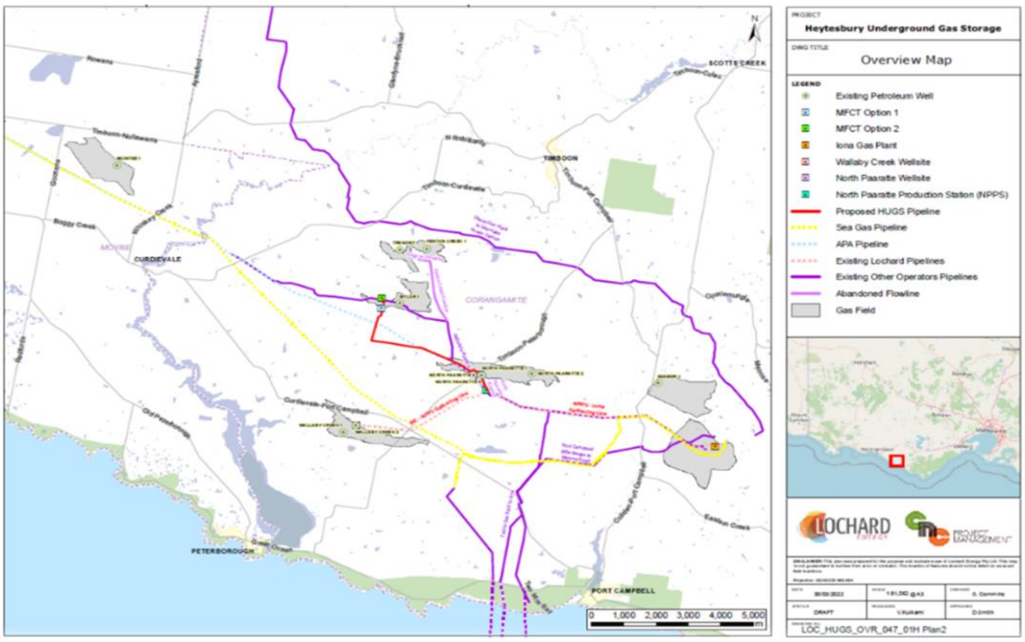



**Figure 2.15: 2D Plan of HUGUS Project (Lochard Energy, 2022b)**

The new well site facilitates improving operations by providing access to all three fields from a singular location, thereby optimising efficiency and resource utilisation. The pipeline corridor comprises a 5.5-6.5 km underground pipeline, with a nominal diameter ranging between 250 and 300 mm (Lochard Energy, 2023). The key infrastructure of this project includes Right-of-Way (ROW), underground pipelines, roads, fences, camps, and washdown facilities (Lochard Energy, 2022b). The report published by Lochard Energy (2022a) provides an overview of the project from an environmental assessment perspective. However, after reviewing the report, it was found that the design information was communicated through 2D plans. Figure 2.15 represents the polylines of the underground pipelines communicated through the 2D plans. The key identified issue was the use of the underground polyline information in a 2D plan which includes limited visualisation (Sharafat et al., 2021).

### *2.8.5.* Identified Practice on Projects

The above discussion highlights how 2D plans convey infrastructure design information across various O & G projects. In the Jemena (2016) report, the field design phase primarily utilised 2D plans for design communication. Similarly, the QLD Government (2015) project also relied on 2D plans for infrastructure design. The QLD Government (2015) report followed suit, with design information conveyed through 2D plans, including the conceptual plan of the tunnel site and a conceptual 2D plan of the processing facility as illustrated in Figure 2.13. These plans represent key infrastructure features such as the campsite, control room, water treatment facility, laydown facility, gas processing facility, fence, and gathering line connecting to the processing facility. Similarly, Arrow Energy's (2014) project also utilised the 2D plan to communicate the design of the processing facility. Furthermore, the Lochard Energy (2022b) report, focusing on environmental assessment, also utilised 2D plans to depict design information of the infrastructure associated with the project. The report includes Figure 2.15 which illustrates the linework of underground pipelines through 2D plans. Therefore, it should be noted that 2D plans are still in practice across multiple O & G projects for conveying infrastructure design information.

## 2.9. Land Survey Data Model

This model was developed by the Geomatics Committee of IOGP as demonstrated in Figure 2.16 (IOGP, 2022). The LSDM serves as a geodatabase data template and serves as a guiding principle of data dictionary for all the projects around the world for various purposes that incorporate infrastructure design, topographic surveys, geodetic networks, UAV/LiDAR operations, vegetation surveys, imagery sources, Right of Way (ROW) assessments, cultural data, geological studies, environmental surveys, and infrastructure monitoring (IOGP, 2022). LSDM is specifically tailored for contractors providing surveying and mapping support, and oil and gas companies managing onshore exploration licences, production facilities, and related infrastructure. IOGP (2022) advised that as part of utilising LSDM survey contractors should supply the geodatabase of the infrastructure design based on the LSDM geodatabase template. This approach minimises data replication and redundancy. Further, LSDM facilitates the storage of crucial geospatial and non-geospatial details within land-based survey activities for the design of any infrastructure. The details about the LSDM geodatabase classes are explained further.


**Figure 2.16: Land Survey Data Model (IOGP, 2022)**

### *2.9.1.* LSDM Classes

The LSDM geodatabase serves as the primary component of the GIS deliverable (IOGP, 2022). It is based on the LSDM template provided as part of this data model, with a structure comprising 54 objects organised into five feature datasets, outlined in Figure 2.17 (IOGP, 2022).

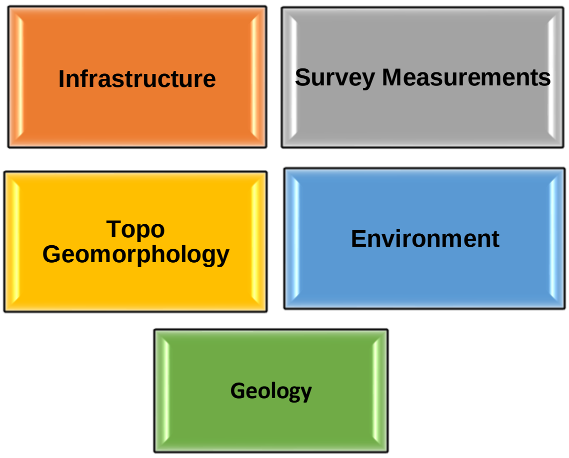



**Figure 2.17: LSDM Classes (IOGP, 2022)**

While the geodatabase template includes all feature datasets and classes, not every class may be relevant. For instance, a topographic survey may not involve high-resolution seismic equipment, thus not populating the geology class. Survey contractors are tasked with populating only the relevant feature classes and completing attribute tables for each utilised class. Different surveys (topographic, environmental, geotechnical, seismic, etc.) conducted over an area of interest gradually contribute data to various feature classes, building the comprehensive dataset outlined in the LSDM. The discussion of the five feature datasets is explained below.

- **Infrastructure**

The infrastructure dataset's primary goal is to record oil and gas company assets, such as production facilities, control buildings, transmission pipeline systems, engineering features, safety systems, on-site offices, and accommodations (IOGP, 2022). Additionally, it should encompass non-company infrastructure data; this involves public transport, utility routes (like roads, railways, and public rights of way), and utility lines such as electric, fibre optic, and domestic water lines (IOGP, 2022).

- **Survey Measurements**

The survey measurements class is associated with overseeing survey project management, data acquisition, charting, and processing data gathered from survey instruments (IOGP, 2022). Additionally, this class includes the documentation of features aligned with International Mine Action Standards (IMAS) and land release guidelines.

- **Topographic Geomorphology**

Topographic characterisation plays a pivotal role throughout the life cycle of an oil and gas facility, influencing aspects from access and planning to engineering, development, operations, and eventual decommissioning (IOGP, 2022). Topography relates to the elevation, terrain features, geographical delineation, and surface geomorphology of an area (IOGP, 2022). This dataset is designed to capture comprehensive information about the land's topographical attributes.

- **Environment**

Assessing the environmental aspects of an onshore area, conducted through processes like baseline studies, impact assessments, and ongoing monitoring, holds significant importance in managing oil and gas facilities (IOGP, 2022). This evaluation spans from the initial engineering and design stages to field development, ongoing operations, maintenance, and eventual decommissioning and retirement. This class encompasses a wide range of environmental factors, including the physical, biological, and chemical properties of the surroundings, covering aspects like soil composition, water quality, air attributes, fauna, flora, and more (IOGP, 2022).

- **Geology**

Geology features, often termed geohazard features, are critical in land surveys (IOGP, 2022). These surveys, such as shallow seismic or geohazard surveys, aim to identify subsurface features that could pose risks to drilling operations or the placement of infrastructure. This involves detecting potentially hazardous elements like shallow gas or liquids, unconsolidated soils, cavities, shallow fault lines, irregularities in bedrock, and boulders, among others. The primary objective is to pre-emptively identify and mitigate any potential risks to drilling or construction activities (IOGP, 2022).

### 2.10. Summary of Identified Research Gap

The literature review discussed in the preceding sections primarily focuses on three key aspects: the foundational elements of digital twins, existing digital twin frameworks/architectures/models, the field design process, and an overview of the LSDM. Section 1.2.1 of Chapter One highlights three significant limitations associated with using 2D design plans: ineffective visualisation, higher probability of design errors, and inefficient workflow. These limitations extend to the spatial data stored within the central SIS of O & G projects, presenting challenges that could be addressed by leveraging current state-of-the-art technology, specifically Digital Twin (DT). The literature review indicates that while digital twin technology is an emerging concept, its implementation in industry requires further development. Recent initiatives in digital twin development have primarily focused on enhancing smart manufacturing within the O & G sector. Similarly, digital twin development in spatial science predominantly revolves around urban land administration. However, existing digital twin models in the general construction, mining, and underground infrastructure sectors do not directly align with the LDSM requirements of the O & G project. Despite a thorough investigation of twenty-two frameworks, none of the existing research explores the integration of the LSDM into these digital twin frameworks. Similarly, the existing practice of communicating the design information in O & G projects on field design still relies on 2D plans as illustrated in the context of Australia through five projects in Section 2.8. Consequently, the primary research problem identified after the literature review was:

2D design plans have limitations and are inherited in their spatial data, thus causing challenges in visualising design information stored in SIS. Spatially enabled digital twins would address this limitation. However, existing DT frameworks have not considered the industry-standard model, LSDM which holds crucial significance in storing spatial data of infrastructure designs during the field design process of the O & G projects, thereby impacting complete industry adoption.

# CHAPTER 3: RESEARCH STRATEGY AND METHODS

## 3.1. Introduction

Chapter Two provides theoretical knowledge on the DT, field design, and LSDM which provides an understanding of their significance within the context of the study. A rationale has also been provided in Section 1.4 of Chapter One for selecting a design science framework for this study. This chapter explains two key aspects. Firstly, brief introduction about design science research framework. Secondly, it provides detailed information on five stages that encompasses foundation stage, define requirement, design and development stage, demonstration stage, and evaluation stage.

## 3.2. Research Strategies and Methods

Johannesson & Perjons (2021) defined research strategy as a comprehensive blueprint for conducting a research study, and guiding researchers in planning, executing, and monitoring their investigations. While a research strategy offers valuable direction, it is accompanied by research methods that provide detailed guidance for carrying out specific tasks within the study. Research methods delineate how data should be collected and analysed, encompassing techniques such as interviews, questionnaires, or statistical analyses (Johannesson & Perjons, 2021).

## 3.3. Design Science Research Framework

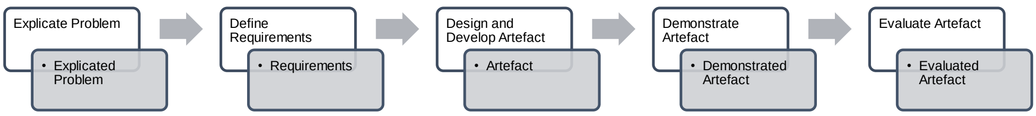



**Figure 3.1: Methodological Framework for Design Science Research (Johannesson & Perjons, 2021)**

Design science is the scientific study and creation of artefacts as they are developed and used by people with the goal of solving practical problems (Ahmad et al., 2013). In general, the design science research framework includes five major activities, explicating the problem, defining requirements, designing, and developing an artefact, demonstrating the artefact, and evaluating the artefact as demonstrated in Figure 3.1 (Johannesson & Perjons, 2021). The design science framework initiates by investigating and analysing the research problem, defined as the gap between theory and the current real-world situation. This entails three primary sub-activities: precise definition, positioning and justification, and finding the root cause of the research problem.

There are several approaches in the design science research paradigm that have been developed by numerous scholars (Ahmad et al., 2013; Blessing & Chakrabarti, 2009; Hevner et al., 2004; Johannesson & Perjons, 2021; Kuechler & Vaishnavi, 2008; Markus et al., 2017; Maung et al., 2011; Muntaheen, 2021; Peffers et al., 2007). The fundamental principle used for each is similar. However, this study has utilised the latest research framework developed by Johannesson & Perjons (2021).

### 3.4. Foundation Stage

The main objective of this stage was to explicate the problem. The research method for this stage is illustrated in Figure 3.2. The systematic literature review was conducted as illustrated in Figure 3.3

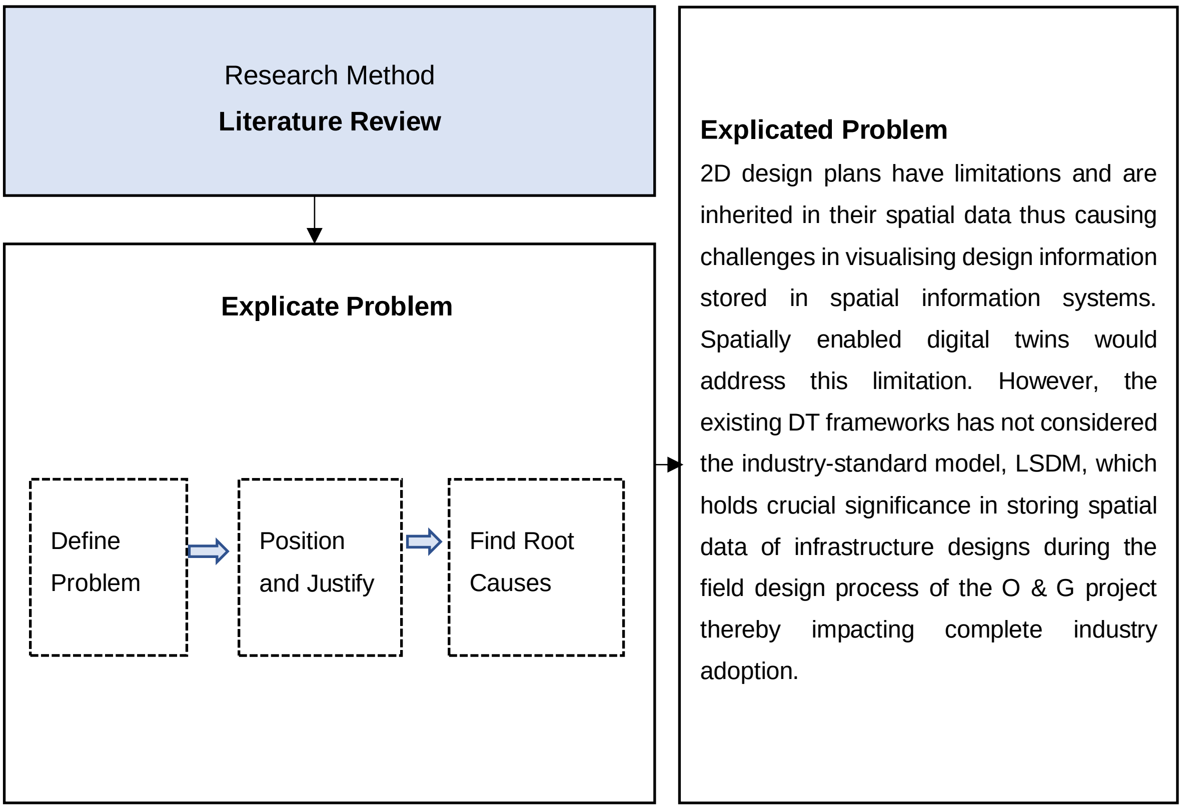



**Figure 3.2: Foundation Stage**

Firstly, guideline suggested by Kitchenham et al. (2013) for performing a systematic literature review (SLR) in software engineering was taken as a reference for the literature review process. The work carried out by Wanasinghe et al. (2020) was found valuable in the context of this research and taken as base. As illustrated in Figure 3.3, the paper selection was started using two keywords, digital twin and oil and gas on the scientific digital libraries, Scopus, Elsevier, IEEE Xplore, and MDPI. The initial keywords-based screening identified ap-proximately 152 relevant articles search within article title, abstract and keywords. Those papers which were published in other languages than English were excluded. Full access to some of these articles was obtained through various means such as Google Scholar, subscriptions to digital library and contacting authors. After removing duplicates, reading titles, key words, and abstracts, 108 articles were selected. Accordingly, after revision of these 108 articles, 38 articles were identified and deemed relevant. Finally, using a synthesis matrix tool developed on Excel spreadsheet, full texts articles were obtained, and profundity review was conducted.

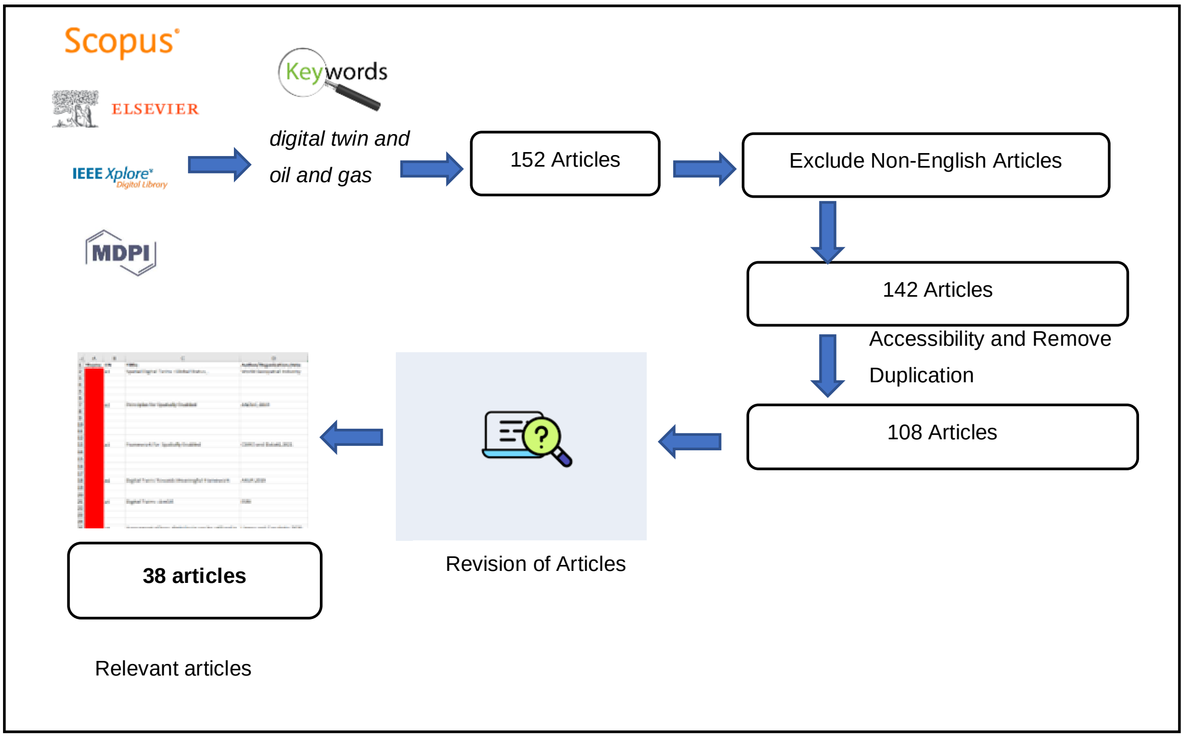



**Figure 3.3: Literature Review Approach**

Consequently, from the systematic literature review, it was found that there was a research gap in bridging the digital twin and geospatial domains in the field of the oil and gas industry. The precise definition of the problem has been already discussed in Chapter One. The problem was worth investigating, as the challenges induced by 2D-based plans, extended in their stored spatial data into SIS, constrain effective visualisation and impact decision-making. The research problem is also significant to the field design process of a typical O & G project. In addition to this, the defined problem is of general interest (digital twin) as various organisations are conducting research and development activities for effective business decision-making. Further, Chapter Two has clearly explained the root cause of the research problem.

## 3.5. Design and Development Stage

The main aim of the design and development was to design and develop an artefact that could address the explicated research problem and facilitate the development of the framework. The research methods used in this stage were literature review and an agile approach as illustrated in Figure 3.4. Four key activities were conducted during this stage that comprised imagining and brainstorming, assessing and selecting, sketching the framework, and finally building the prototype. The explanation of each activity is discussed further in this section.

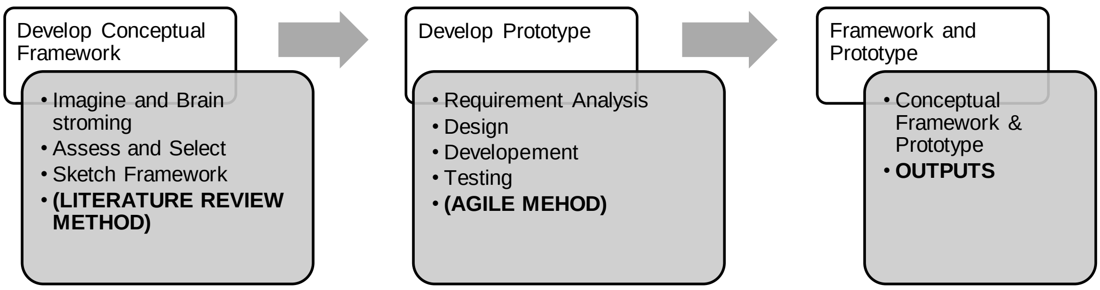



**Figure 3.4: Design and Development Stage**

### *3.5.1.* Imagining and Brainstorming

There are various methods to generate ideas. Johannesson & Perjons (2021) outline four common methods that includes germinal, transformational, progressive, and organisational. In the germinal method, the designer starts with a clean sheet of paper to craft an idea. Brainstorming is an example of this method (Hevner et al., 2004). Similarly, in the transformational method, the designer creates ideas by modifying existing ideas. Random generation represents this method (Peffers et al., 2007).

Further, in the progressive method, ideas are generated progressively by repeating the same steps iteratively (Venable et al., 2012). The method known as 6-3-5 brainwriting is an illustration of this method (Kuechler & Vaishnavi, 2008). Likewise, in the organisational method, ideas are grouped that have already been generated. In this study, Johannesson & Perjons (2021) germinal method was mainly used for designing the framework. A clean sheet of paper was used for brainstorming to map the field design and SIS. The brainstorming paper used during this stage has been attached in Appendix C.

### *3.5.2.* Assess and Select

Johannesson & Perjons (2021) discussed various models to assess and select ideas including the rational decision-making model, bounded rationality, and the garbage model. The rational decision-making model is considered to be an effective approach because relevant ideas are evaluated critically using a systematic approach (decision matrix) to identify the optimal one (Kamari, 2023). In contrast, within the framework of bounded rationality, decision-makers chose to conclude the decision-making process upon identifying one or more sufficiently viable ideas (Johannesson & Perjons, 2021). This typically reduces the perception that further exploration or gathering additional information for a more informed decision would need excessive costs and time (Wu & Xiao, 2022). The major drawback of this model is that in some circumstances, decisions are made without considering alternative solutions altogether (Litvaj et al., 2022). Similarly, in the garbage model, decisions are made on an ad hoc basis by aligning problems with available solutions (Johannesson & Perjons, 2021). These decisions may occur formally during meetings or informally, such as through casual conversations around a coffee machine (Johannesson & Perjons, 2021). Therefore, this study adopted a rational decision model and conducted an assessment of ideas in a systematic approach as presented in Figure 3.5.


**Figure 3.5: Rational Decision Model (Tversky & Kahneman, 1986)**

After the previous step, imagining and brainstorming, two alternatives were identified: Alternative 1 ($I_1$): Developing brand new framework, and Alternative 2 ($I_2$): Customising the existing frameworks. Therefore, specific criteria were formulated to select one idea. The established criteria comprised effectiveness, time, and cost. Developing these criteria and allocating relevant weights were subjectively assigned based on experience obtained by the researcher through the foundation stage (literature review) and in the context of this study. Effectiveness defines whether it is effective to define the new novel model, or if it can be customised in the context of the field design of any O & G project. Similarly, time defines the duration to complete the objective (designing and developing framework).

Subsequently, cost deals with the required resources for developing the framework. For instance, to develop a brand-new framework, various aspects need to be considered (gathering people, conducting workshops, synthesising their ideas, and then finally developing a framework. Secondly, a systematic decision matrix was prepared to evaluate the ideas which is presented in Appendix D. The 1-5 scale was used for assigning the weights. Effectiveness was assigned 5 as it is pivotal and impacts the result of this study. Similarly, time and cost were assigned 3 and 1 out of 5 respectively, as time was more important than cost in this study. Then after, the rating was provided for each idea and the respective criterion. The decision matrix outcome indicates that customising the existing framework is more effective within this study context than developing a brand new framework as customising the existing framework scored 13, while developing a brand new framework scored 5 as illustrated in Appendix D.

### *3.5.3.* Sketch Framework

A sketch of an artefact provides an overview of the components of the structure. In addition to this, an artefact is a framework in the context of this study as it provides relationships between each associated component. To design and build an artefact, Johannesson & Perjons (2021) mentioned instruments such as a use case diagram, use case descriptors, sequence diagram, and user story. A use case diagram graphically represents the functions of the artefact, as well as the actors in its environment. Similarly, use case descriptions typically describe each function of an artefact in only a sentence or two. Accordingly, Johannesson & Perjons (2021) reveal that storyboarding consists of several illustrations in sequence, like a cartoon strip, describing how the user will interact with the artefact. However, Peffers et al. (2007) reveal that the sketch depends upon the type of the artefact. In this study, three tools have been utilised to sketch the conceptual framework that entails a use case diagram, system architecture, and sequence diagram using the Microsoft Visio tool. The results generated from this stage are discussed in detail in Chapter Four.

### *3.5.4.* Build Prototype

Leveraging a framework as a guiding principle in the development of a prototype is a strategic approach to ensuring its practicality and viability (Johannesson & Perjons, 2021). In the system development domain, Agile methodology is considered a widely accepted research method used to develop the prototype because of its flexibility, iterative nature, and emphasis on rapid delivery (Leong et al., 2023; Molina & Pedreira, 2019; Quintana et al., 2022; Weichbroth, 2022). Therefore, this study has also utilised this practice-based methodology to develop the prototype. The key steps involved in the Agile methodology include requirement analysis, design, development, testing, and deployment (Molina  & Pedreira, 2019). In this study, the deployment was not considered as the developed prototype was based on the localhost due to the constraints. The discussion of requirement analysis, design, development, and testing are explained in Chapter Four.

## 3.6. Demonstration Stage

Johannesson & Perjons (2021) suggested that a major goal of the demonstration stage is to assess the feasibility of the artefact to address the problem outlined in the foundation stage. In this study, a conceptual framework is an artefact. It can be certainly said that artefact viability has been partially examined through the creation of a real prototype. Nonetheless, a more in-depth assessment of the feasibility of the prototype is required. Johannesson & Perjons (2021) mentioned that demonstrations can be done utilising various research methods such as action research and case study. Most of the existing studies carried out on the design science paradigm have adopted the case study approach to implement their developed artefacts (Asghari, 2022; Atazadeh, 2017; Kang et al., 2022; Lu et al., 2020; Sharafat et al., 2021) .Therefore, in this study, the case study approach has been selected as a demonstration strategy.

Johannesson & Perjons (2021) suggested that demonstrating the artefact through a case study approach consists of two major sub-activities that encompass selecting a case study area and applying the artefact. The lot 2RP108045 property of the Queensland state of Australia was chosen as a selected case study area. The main reason for selecting this location as the case study area was due to data accessibility. In the context of Australia, mining datasets are very secure. Subsequently, datasets associated with the field design process are also not openly distributed and are protected very securely within the business. However, this study has managed to get approval from the concerned authority to conduct a UAV survey to acquire real-world datasets that could support demonstrating the feasibility of the prototype in real-world scenarios. Similarly, another sub-activity of this stage was applying the artefact. As mentioned in the previous paragraph, the prototype was implemented in this study. The four key steps of the field design process were conducted, including: conceptual engineering design, acquisition of geodatabase (UAV survey), detailed engineering design, and storing and visualising the spatial data of the infrastructure design and associated spatial information into the developed prototype. The detailed discussion of the case study is demonstrated in Chapter Five.

### 3.7. Evaluation Stage

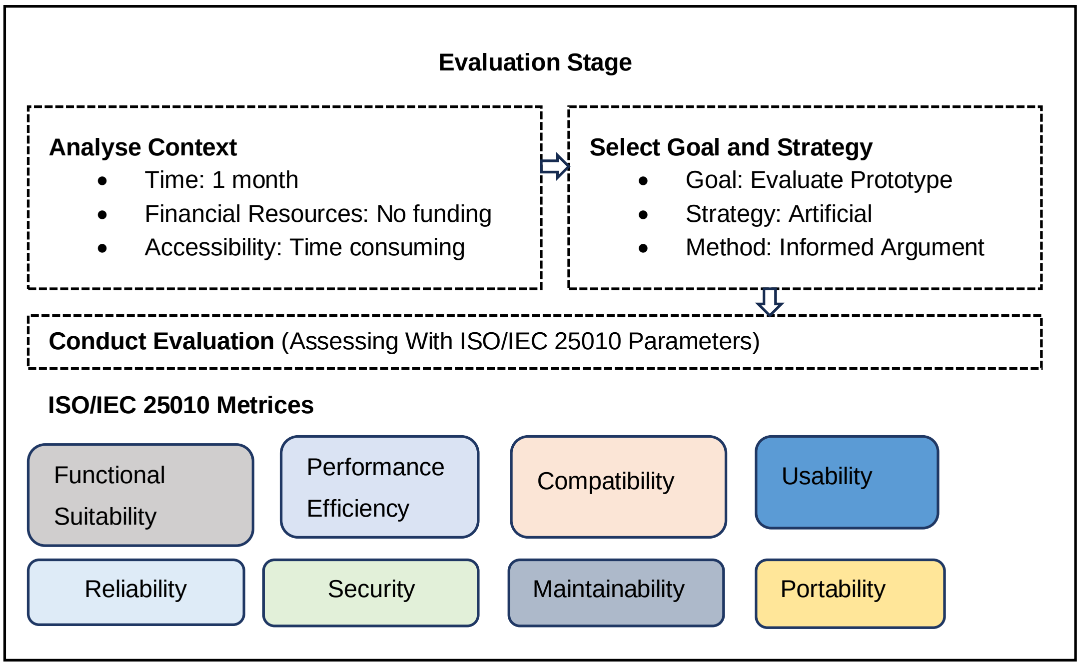



**Figure 3.6: Evaluation Stage**

According to Johannesson & Perjons (2021) the evaluation stage consists of three major sub-activities that include the analysis of context, the selection goals and strategy, and the carrying out of evaluation as depicted in Figure 3.6. The discussion of each sub-activity is given below.

### *3.7.1.* Analyse Context

The assessment of the evaluation context is essential and should be examined before determining the goals and strategy. In this study, analysis of the evaluation context was conducted based on three key criteria, time duration, financial resources, and access to information. The evaluation timeframe was constrained to one month, as indicated in Figure 3.6. Additionally, external funding was not available to carry out the evaluation through subject matter experts and associated stakeholders. Further, throughout the span of this study, it was realised that accessing mining information was difficult in the context of Australia. So, information accessibility was limited in this study.

### *3.7.2.* Selection of Goals and Strategies

The goals and evaluation strategy were selected based on the assessment results generated from the previous step. The acceptable and reliable approach to evaluate the developed conceptual framework and its prototype was by conducting workshops that involved stakeholders' engagement and inputs during the field design process. However, due to lack of financial resources, this was not feasible in this study. While obtaining feedback from stakeholders through an online survey method could have been further done to evaluate the framework and its prototype, it was also not practical in this study. Upon preliminary discussions with stakeholders where the case study area was selected, it became apparent that they could not provide their opinions without obtaining permission from their respective departments. Further, stakeholders also suggested that acquiring administrative approval from the relevant department involved a time-consuming process which was certainly more than at least three to four months.

Before selecting a research strategy, Johannesson & Perjons (2021) suggested that considering what needs to be evaluated at this stage within the design science framework is pivotal. In this study, the viability of the conceptual framework was justified by building the physical prototype, and the feasibility of the prototype was assessed by implementing it into a real-world case study area. Therefore, remaining evaluation further involved evaluating the conceptual framework and the prototype using other methods. The method to further assess the conceptual framework and prototype was through a workshop and interviews which were not within the scope of this study. Therefore, the goal was to evaluate the prototype with available resources.

According to Johannesson & Perjons (2021) there are numerous strategies to evaluate the artefact which mostly depend on the type of artefact or available resources. Venable et al. (2012) have categorised evaluation strategies into two types, naturalistic and artificial. Naturalistic evaluation strategies include: action research, focus groups, interviews, and case studies whereas artificial strategies include logical proof, lab experiments, computer simulations, field experiments, and informed arguments. Venable et al. (2012) has also suggested the pros and cons of these evaluation strategies. Higher effectiveness and higher external validity are two significant advantages that naturalistic evaluation strategies offer to the examining facet of the study. However, more cost and organisational access are needed to carry out this evaluation strategy. Similarly, an artificial strategy offers merits in terms of financial resources (low cost), few stakeholders, and a faster approach. Perhaps, higher effectiveness might not be obtained in comparison to the natural evaluation strategy.

Most of the existing studies that have adopted the design science approach have utilised the survey approach (interviewing the relevant subject matter experts) to evaluate their framework/model. For instance, Atazadeh (2017) interviewed 12 participants to evaluate the BIM model. Similarly, Cemellini (2018) in his Master's dissertation, recruited 20 users to test the usability of the developed 3D cadastral model. Furthermore, Broekhuizen (2021) has utilised the feedback process to validate the conceptual 3D LAS system. Therefore, it can be certainly said that interviewing the stakeholders is considered a reliable method of evaluation. However, as mentioned by Johannesson & Perjons (2021), the evaluation in the design science framework is always based on the context and goal.

There are existing studies within the design science approach that have applied other approaches to evaluate the artefact. A study carried out by Kang et al. (2022) adopted financial modelling (cost-benefit analysis) to evaluate the framework for BIM integrated waste management system. Similarly, another study was carried out by Sharafat et al.

(2021) evaluating the BIM-GIS underground utility management system by comparing it with the traditional 2D-based methods. Similarly, a study conducted by Li et al. (2017) developed the web-based GIS system and compared it with other existing systems as part of the evaluation process. In addition to this, Atazadeh (2017) used objective assessment (comparing with other existing models) to evaluate the developed BIM model using different parameters as part of his PhD study. This indicates there are several methods that have been practiced within the design science research framework to evaluate the artefact which solely depend on the type of artefact and available resources.

Therefore, after considering the context and goal of the evaluation, the selected research strategy and method for this study were: artificial research strategy and the informed argument method respectively. Johannesson & Perjons (2021) suggested that the informed argument method is a cost-effective approach and commonly adapted when assessing highly innovative and still immature artefacts which is the prototype for this study.

### *3.7.3.* Conducting Evaluation

From the above two sub-activities, an informed argument of artificial strategy within the design science framework was selected as a research method.

To assess the quality of the prototype, self-assessment (informed argument) was done based on metrics developed by ISO/IEC 25010 model. Some research scholars have used this framework to assess the product/software/system (Ali et al., 2022; Fahmy et al., 2014; Keibach & Shayesteh, 2022; Miguel et al., 2014). They advised that it covers a broad spectrum of quality characteristics and is applicable in various software development contexts. The international standard, ISO/IEC 25010 is an extended and up-to-date version of ISO/IEC 9126 series (Ali et al., 2022). The ISO/IEC 25010 framework is being widely accepted as it encompasses all the necessary metrics to evaluate the system/model/software from various dimensions (ISO, 2022). The metrics of ISO/IEC 25010 include: functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, and portability (ISO, 2022). The detailed discussion of the evaluation is presented in Chapter Five.

### 3.8. Chapter Summary

This chapter explains the research strategy and method utilised in this study. It has provided a foundational understanding of the design science research framework, explaining its application in the domain of information. As justified in Chapter One design science research approach has been adopted to accomplish the aim of this study. Within the design science research framework, various research methods are utilised throughout the key four stages of this study. In the foundation stage, the literature review method was utilised. Similarly, in the design and development stage, two research methods were used including a literature review to develop the conceptual framework and an agile method for developing the prototype. Furthermore, for the demonstration stage, the real-world case study has been utilised to assess the prototype's feasibility. For the evaluation stage, an informed argument research method was applied using the ISO/IEC 25010 matrices. The design and development of the conceptual framework and prototype are explained in Chapter Four.

# CHAPTER 4: DESIGN AND DEVELOPMENT

## 4.1. Introduction

The previous section of this dissertation discussed the relevant literature review and utilised the research framework which accomplished the main objective and first three sub-objectives of this study. The results generated from the design and development stages are mainly presented in this chapter. Firstly, this chapter explains about data requirements. Then after it explains components of the spatially enabled digital twin framework, followed by system architecture, use case diagram and sequence diagram. Then, the chapter provides details about entity relationship (ER) diagram, and system architecture of the prototype. Finally, the chapter concludes by illustrating the developed prototype.

## 4.2. Data Requirements

Data is crucial at every step of the field design of any oil and gas project. Throughout the field design of any proposed infrastructure, a wide range of data needs to be considered. Incorporating all datasets into the prototype is beyond within the scope of this study. Therefore, firstly, a literature review was conducted to identify key datasets using existing resources (GCQ, 2022; IOGP, 2022; Queensland Government, 2015; Shell QGC, 2017; VIVA Energy, 2020). Secondly, the research candidate engaged in a work experience opportunity at a surveying firm (DSQ Land Surveyors, Queensland, Australia) to ascertain a broader spectrum of data needs aligned with prevailing methods in the industry setting. The research candidate personally communicated with the various stakeholders (GIS Officer, Surveyor, Seismic Operation Coordinator, Cultural Heritage Officer, Safety Officer) to examine the key data involved in carrying out the field design project. Subsequently, six categories of datasets were identified as crucial for field design in the context of Australia: infrastructure, environment, geology, survey measurements, cultural heritage, and safety.

Among the identified data requirements as illustrated in Figure 4.1, infrastructure plays a pivotal role in field design and other datasets are relevant to the different stages of field design. Subsequently, the environment, geology, cultural heritage, and safety are important sources of information from the relevant disciplines which are important information that impact the design of any infrastructure. Survey measurements are identified as essential for understanding the real world site before proceeding detailed engineering design of the proposed infrastructure.

### *4.2.1.* Infrastructure

The infrastructure data primarily includes the oil and gas company infrastructure assets such as production facilities, ROW, pipelines, roads, well pads, and fences. Detailed information on the infrastructure category including field, data types, and LSDM attributes are presented in the Appendix E1 to Appendix E6.

### *4.2.2.* Environment

The environmental category consists of a range of datasets related to the environmental aspect. The datasets include information about the edge of vegetation, land use, habitat, flora and fauna, primary protection zone, and secondary protection zone, environmental constraint area, and characteristics of water and air. Based on the scope of this research, the identified data including LSDM attributes are presented in Appendix F1 and Appendix F2.

### *4.2.3.* Geology

These datasets support the identification of shallow subsurface features, geological condition and any geohazard features that might be hazardous during the construction of the proposed infrastructure. Based on the scope of this research, the identified geological datasets including LSDM attributes are presented in Appendix G1 and Appendix G2.

### *4.2.4.* Surveying Measurements

These datasets are mainly captured before commencing the detailed engineering design. This mainly consists of the geodetic control points as well as onsite surveyed points using various techniques. The consideration datasets in this category including LSDM attributes are presented Appendix H1 and Appendix H2.

### *4.2.5.* Cultural Heritage

In the context of Australia, cultural heritage is considered a pivotal data category because it might impact the overall design of any proposed infrastructure. The dataset considered in this category including LSDM attributes is presented in Appendix I1 and Appendix I2.

#### *4.2.6.* Safety

In the context of Australia, safety is considered a pivotal data category because it might impact the overall design of any proposed infrastructure. The safety datasets include fire and weather which are real time or time dynamic datasets. The datasets considered for this research is presented in Appendix J1 and Appendix J2.

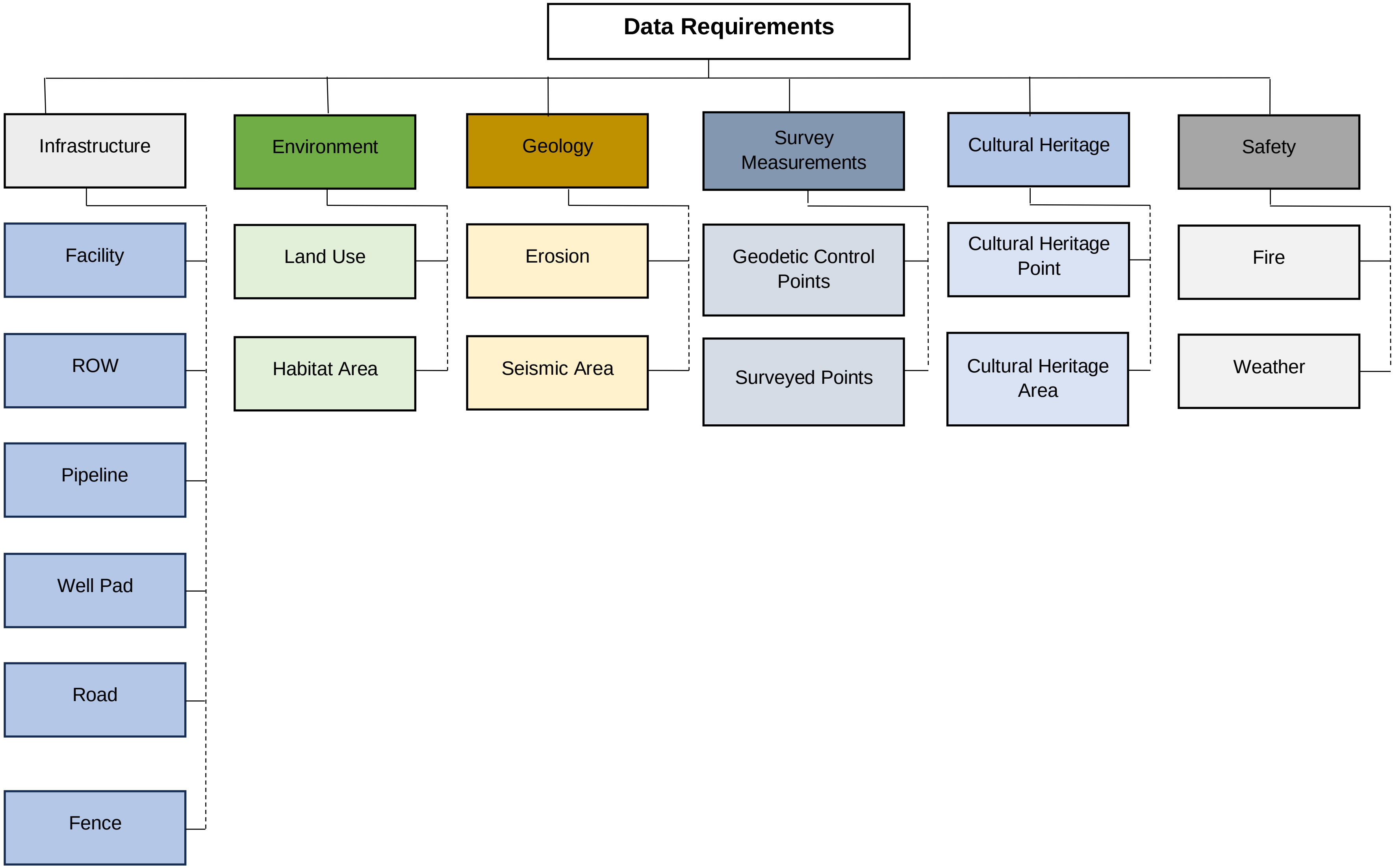



**Figure 4.1: Data Requirements**

## 4.3. Components of Framework

The developed framework entails five key components which are the data, standards, field design, users and application as shown in Figure 4.2. This framework represents a novel approach for managing spatial information in the context of field design within the oil and gas industry. Concepts used in this framework are extended from existing studies discussed in Chapter Two, as they cannot be directly implemented in the oil and gas industry due to the absence of LSDM constituents. The fundamental concept of this framework relies on the generic system architecture for spatially enabled digital twin which was developed by Rajabifard et al. (2022). This study has introduced a new digital twin framework for oil and gas projects which has not been previously investigated, integrating the LSDM. This study has specifically integrated LSDM classes, users, and developed a prototype (spatially enabled digital twin application) that facilitates the decision-making process for field design in oil and gas projects. Therefore, the developed framework, could serve as a starting point to leverage digital twins for managing spatial information in the context of field design in the oil and gas industry. The discussion of each component of the framework and their connection with each other is explained below.

### *4.3.1.* Data

Data is a pivotal component of this framework. It includes classes that fall under LSDM. The key classes within the LSDM include infrastructure, environment, survey measurements, topo geomorphology, and geology. In addition to this, additional datasets are also included in the framework due to their requirement to carry out the field design. The number of other datasets depends upon various factors such as the nature of the O & G projects, the geographical location of the project, rules and regulations of the host country. For example, in the context of Australia, cultural heritage and safety information are pivotal during the field design of typical O & G projects. Therefore, every O & G project should strictly consider these datasets during the field design process. Data is the fundamental backbone of the framework as it is directly associated with other components such as standards, field design, users, and spatially enabled digital twins.

### *4.3.2.* Standards

Standards are also considered a significant element for O & G field design. It acts as the legislative pillar for every department that is involved in the design process of O & G projects. For the engineering department, engineering design specifications play a crucial role in defining the criteria for infrastructure design. For example, when the project is being carried out in Australian territory, every project should follow the AS2885-1997 standard and comply with engineering design norms. Similarly, for the environment and geology department, environmental and geology acts of the host country are significant during the design of the infrastructure. In the context of Australia, O & G projects should adhere to the code of environmental practice for onshore pipelines, as published by the Australian Pipelines and Gas Association (APGA). Similarly, for the surveying department, land surveying acts, surveying techniques, equipment types, and spatial accuracy are valuable standards. In Australia, each state has its own land surveying legislation. For O & G projects located in Queensland, they should be carried out in accordance with the Surveying and Mapping Act, 2003. Besides, the regulatory obligation for any O & G project also extends to country-specific legislation, varying based on the location of the O & G field. In Australia, compliance with cultural heritage acts and safety legislation is crucial as briefly explained in the previous “data” section. For instance, in Queensland, the Native Title Act 1993 should be strictly considered while designing any infrastructure.

### *4.3.3.* Field Design

The field design is considered another crucial element of the conceptual framework. This process is carried out through three key activities: conceptual engineering design, detailed engineering design, and archival of spatial data related to engineering design. Throughout the process of field design, the facilitation of various datasets across involved departments is very crucial. The activities of conceptual engineering design include acquiring factors, preparing conceptual engineering design, and obtaining approvals from concerned departments. Similarly, the detailed engineering design activities involve examining the site conditions, reviewing design specifications, and obtaining detailed design approvals from the stakeholders. Finally, once all the detailed designs of the infrastructures are approved, their spatial data are archived into the application which is, Spatially Enabled Digital Twin. This field design within this conceptual framework has been developed in a way that it ensures collaboration and comprehensive review at each stage facilitating efficiency in the O & G field design process. To clearly present the workflow and its relation to other components, a use case diagram was created as shown in Figure 4.2 and explained in Section 4.3.

#### *4.3.4.* Users

In this conceptual framework, the role of users is significantly important. The users have been given access to specific data categories where stewardship aligns with relevant datasets. For example, the engineering department takes stewardship of infrastructure data, and the environmental, surveying, and geology datasets are handled by the respective departments, environment, surveying, and geology. This demonstrates how users play a crucial role in managing datasets based on their necessity. This specific accessibility would support ensuring the integrity and accuracy of data. The developed framework also incorporates additional users which might be project specific. In the context of Australia, this includes users responsible for cultural heritage and safety. In conclusion, users play a pivotal role in this conceptual framework, acting as stewards. Therefore, users have their own role-based access control to the spatially enabled digital twin which is explained in Section 4.2.5.

#### *4.3.5.* Spatially Enabled Digital Twin

The Spatially Enabled Digital Twin is an application that facilitates storing, managing, visualising, and analysing 2D, 3D, and 4D spatial data associated with respective classes (Rajabifard et al., 2022). As explained previously in Section 4.2.4, users access data according to their roles. For instance, the spatial information management team has administration rights to access all data within the spatially enabled digital twin application. The spatial information management team is significant in ensuring that other departments manage datasets correctly. The departments are restricted to managing their data based on their designated accessibility levels. For instance, the engineering department, is allowed to only manage infrastructure data, while environmental and geological datasets are managed by the environment and geology departments. The developed conceptual framework also incorporates 3D spatial data for infrastructure, providing an interactive approach to engineering design. Similarly, other data, such as weather and fire, is associated with real-time information (4D) which is crucial for safety considerations during O & G field design. Besides, land use, geology, and cultural heritage are typically based on 2D, 3D visualisation is possible based on project requirements. To provide the technical dimensions of this conceptual framework and its interconnection with associated components, a system architecture was developed separately, and its explanation is provided in Section 4.4.

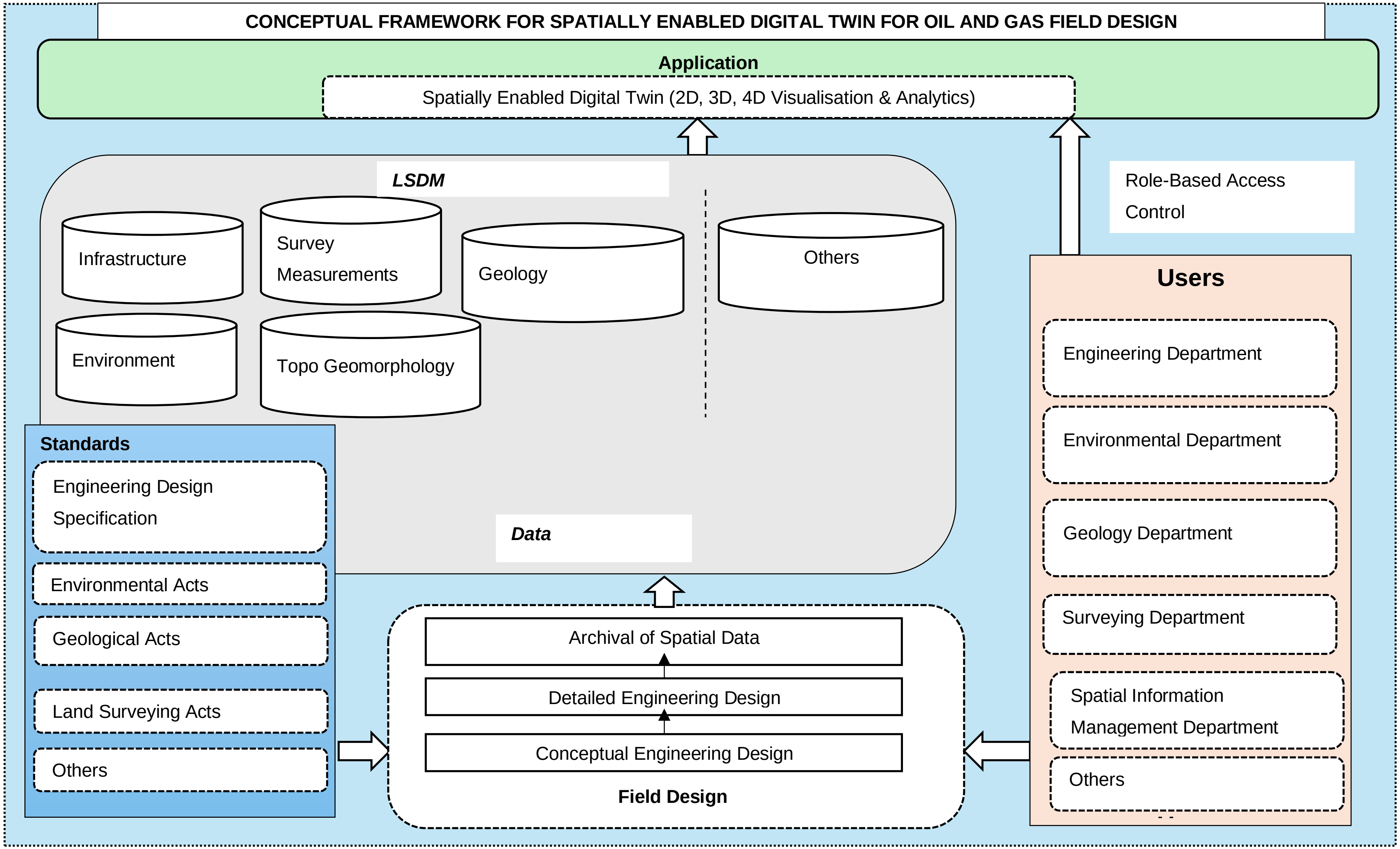



**Figure 4.2: Conceptual Framework**

### 4.4. Use Case Diagram of Framework

Use Case Diagram is a pivotal tool which offers visual representation of the how users interact with the system (Johannesson & Perjons, 2021). It is the basic requirement of the UML model and widely used in software and system engineering domains to support the early stages of the development process (Guiochet, 2016). A use case diagram was developed to visually represent the functional requirements of a conceptual framework. In this study, the primary purposes of creating a use case diagram were to understand system functionality, design system architecture, and illustrate the involved users and their responsibility/association in the workflow of the field design process. To develop the use case diagram, a comprehensive study of industry reports and the personal work experience of research candidate in oil and gas projects were used. The actors, subsystems and flow of the use case diagrams were identified using the literature review that has been discussed in Section 2.7 and 2.9 of Chapter Two. Furthermore, these were successfully verified with the information provided by the relevant stakeholders that includes GIS Officer, Surveyor, Seismic

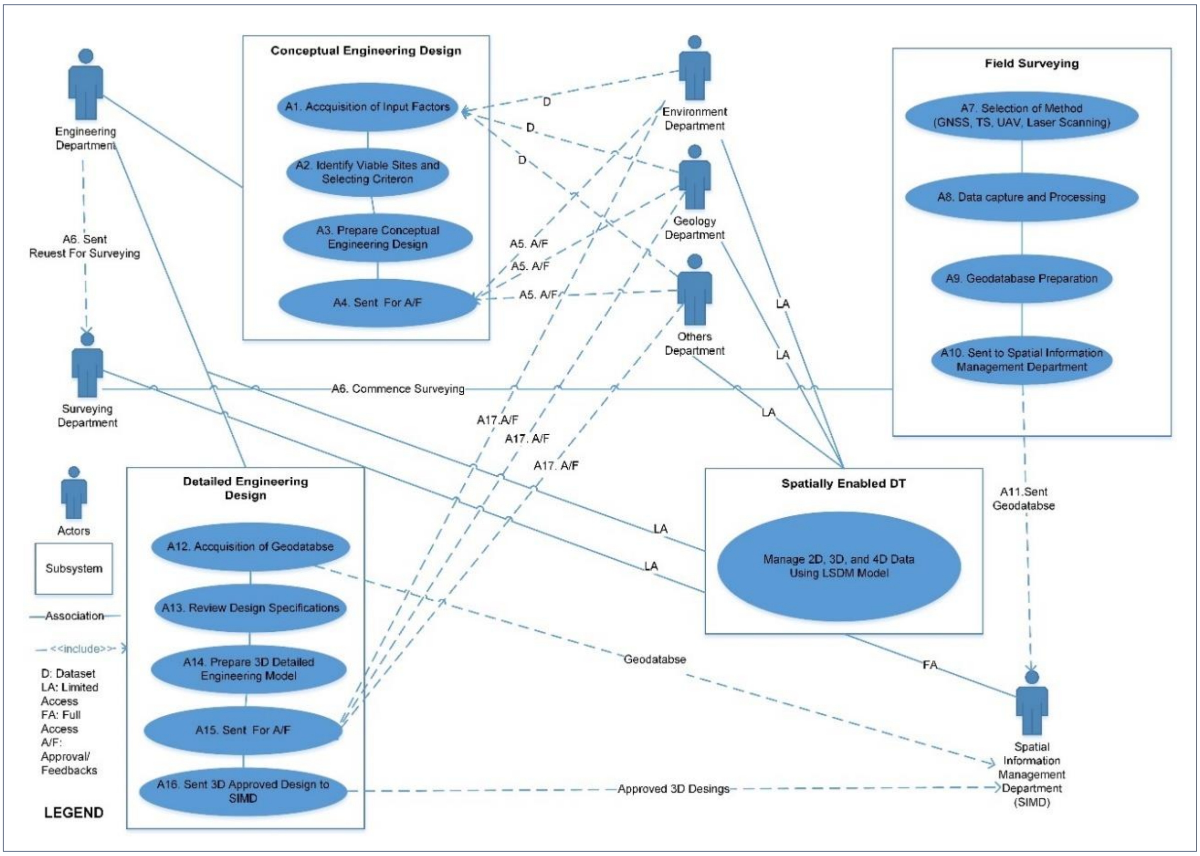



**Figure 4.3: Use Case Diagram of Framework**

Operation Coordinator, Cultural Heritage Officer, and Safety Officer, through personal communication by the research candidate.

Figure 4.3 demonstrates the use case diagram of the conceptual framework. It depicts the major four sub-systems that encompass conceptual engineering design, detailed engineering design, field surveying, and spatially enabled DT.

The involved activities have been represented using A1, A2…. A16. A1 activity is connected to A2 in which the engineering department commences to acquire various information from different departments. Then, A3 and A4 activities are conducted by the engineering department team using the results generated from A1 and A2 activities. In, A3 and A4 preliminary designs of infrastructures are carried out and sent for approval/feedback. Thus, the A5 activity is approval/feedback from every involved department. They have access to the spatially enabled DT where they can acquire the necessary information to make the decision (approved/sent feedback) for the infrastructure design sent from the engineering department. Then, once approvals are obtained from every department, engineering department sends a request to the surveying department to carry out A6 activity for examining the ground conditions.

The surveying department can access the relevant information from the spatially enabled DT system which is required to carry out surveying on the ground, for instance, information might be survey control points and their description, and surveying specifications. Then, the surveying department carries out the A7 activity using the designated method which relies upon the project requirements. They might use the GNSS, total station, UAV, or laser scanner to capture the ground field data. Further, A8 and A9 are conducted by the surveying department and the final geodatabase is sent out through A10 activity to the spatial information management department, whose major role is to ensure the data is captured correctly and meet project requirements.

Once the field surveying is completed and data is correctly stored on the spatially enabled DT, the engineering department again requests the spatial information management department to give them access to the geodatabase to carry out the detailed engineering design. This, A12 activity is accomplished which further facilitates the A13 activity to analyse how much the design needs to deviate from the conceptual design. Then, activity A14 is carried out by the engineering department to prepare the 3D model of the design. Subsequently, a 3D model is sent to every department for approval/feedback. Upon obtaining approval from every department, the 3D design models are again sent to the spatial information management department to archive into the spatially enabled DT.

## 4.5. System Architecture of Framework

The system architecture provides a technical blueprint of the conceptual framework (Rajabifard et al., 2022). It outlines the structure, components, relationships, and interactions within the system, serving as a guide for system development. The system architecture of the developed conceptual framework comprises five primary components, datasets, database management system, map server, visualisation system, and users (Rajabifard et al., 2022; Shahidinejad et al., 2024) as illustrated in Figure 4.4.

The fundamental element of this architecture is datasets that are composed of the data class from LSDM, and other classes as discussed in the above-developed conceptual framework in Section 4.3.

The database management system is one of the major components of the architecture, as it stores all the datasets. The database management system stores three key types of datasets, 3D models, 2D vector, and 2D raster datasets. The various 3D model formats can be stored into the database management system that entails .obj, .kml, .kmz, .gltf, .fbx, .citygml, .dae, .las, .laz. These 3D models are stored in a database system, which is a distributed file system optimised for streaming and rendering in web-based 3D mapping applications of the Cesium Ion. It allows storing 5GB datasets in total without any subscription. However, to store more than 5GB, a commercial subscription could be purchased. Similarly, .shp is the commonly used 2D vector data format worldwide. A widely accepted open-source PostgreSQL database with PostGIS extension is used in this system architecture that can store 2D vector datasets. Further, raster data file formats such as .tif and. geotif can be stored in the file system and published and shared through the GeoServer.

This architecture facilitates in storing LSDM datasets and other datasets available in various file formats. Infrastructure data can be stored into the 3D models.

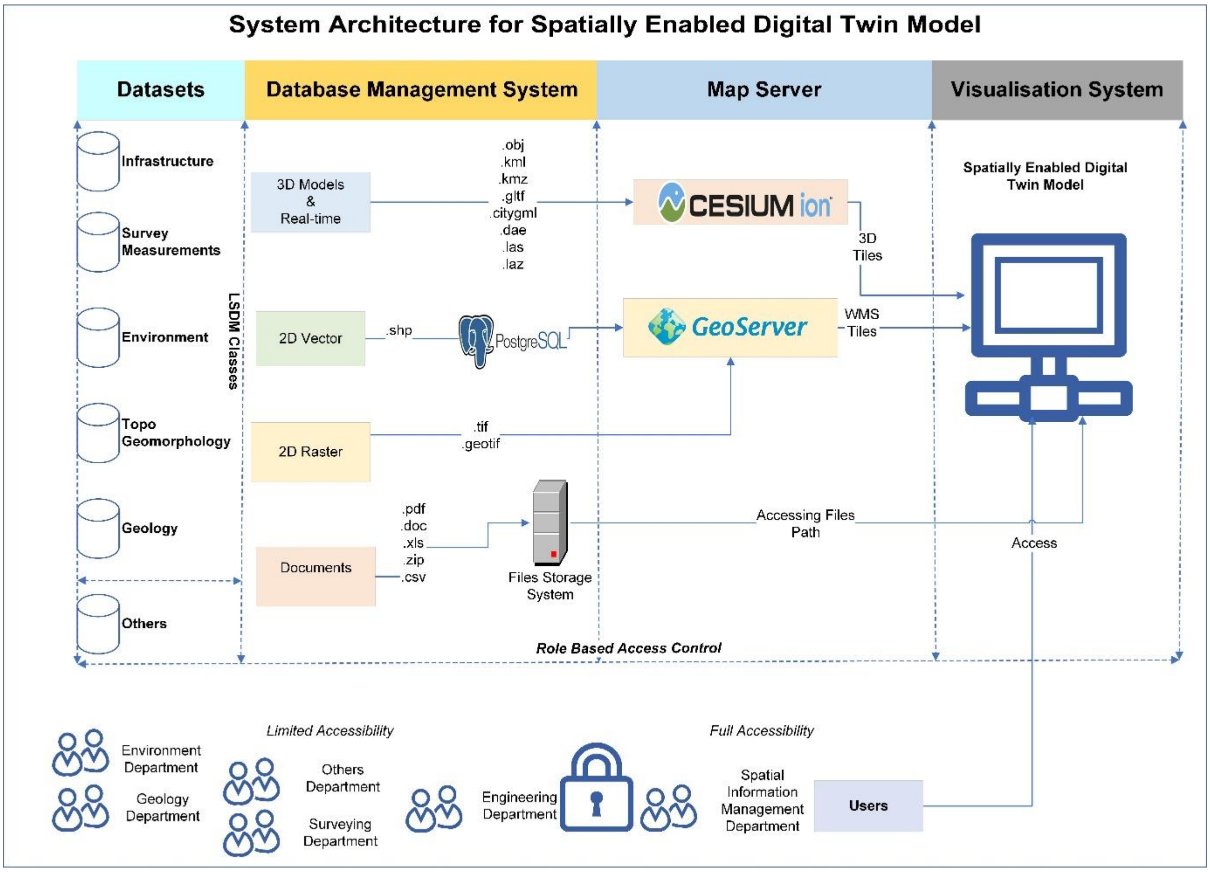



**Figure 4.4: System Architecture of Framework**

In the Architecture, Engineering, and Construction (AEC) industry, the .ifc is commonly used file format to represent 3D models of infrastructure designs, although Cesium Ion does not directly support this format yet. Consequently, third-party software facilitates the conversion of .ifc files to formats compatible with Cesium Ion as illustrated in Figure 4.4. Similarly, a 2D vector can be used to store the 2D line works of the infrastructure design. Further, environmental, geology, and topo geomorphology can be stored in the 2D vectors or rasters. For 3D representations, file formats such as .kml, .kmz, .gltf, .obj can be also used.

Capturing ground information through surveying involves varied techniques, resulting in different data formats. UAVs or laser scanners generate 3D point cloud data in .las/.laz file format, while GNSS or total station generates 2D vector points in .shp file format. Similarly, the other datasets such as safety (weather, fire) associated with real-time datasets can be streamed through Cesium Ion directly.

Map Sever is one of the most important parts of architecture because it acts as the bridge between the visualisation and the database management system. Cesium Ion enables steaming 3D tiles of the 3D models stored in its database management system. Similarly, GeoServer supports storing and publishing vector and raster datasets that are stored in the database or file system, enabling web coverage service (WCS), web map service (WMS), and web feature service (WFS). The visualisation system is considered the frontend component of the system architecture. All the 2D, 3D, and 4D datasets that are streamed through map sever are rendered on the visualisation platform. The users of this system architecture are primarily stakeholders associated with the field design of typical oil and gas projects. These stakeholders encompass environmentalists, geologists, surveyors, design engineers, and GIS professionals. Similarly, safety officers and cultural heritage officers are also other key stakeholders in the context of Australia. Users can access the system based on their respective roles.

## 4.6. Sequence Diagram of Framework

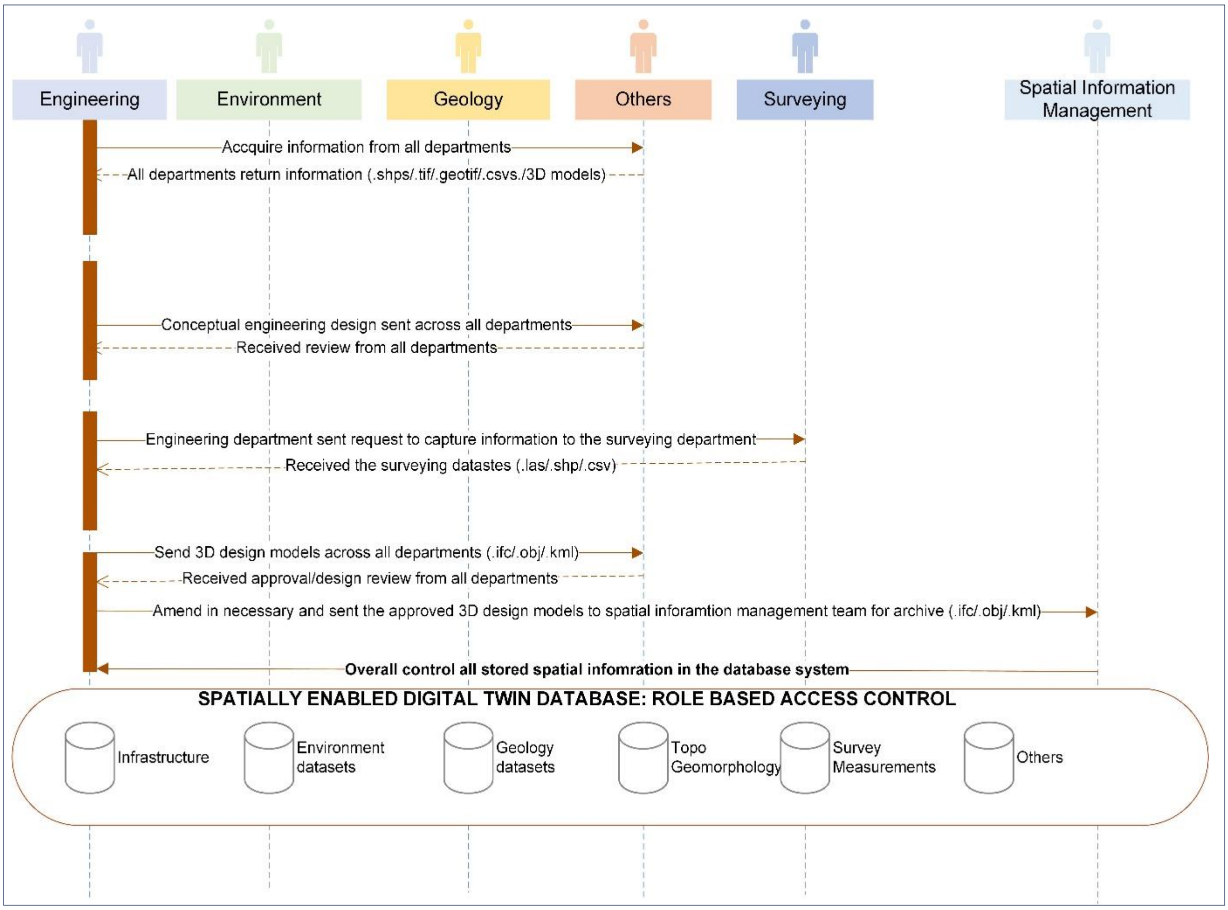



**Figure 4.5: Sequence Diagram of Framework**

The objective of a sequence diagram was to demonstrate the flow of activities and their interactions with actors (Jha et al., 2023). To develop the sequence diagram, integration of a literature review and the personal work experience of the research candidate in oil and gas projects was used as explained in Section 4.4. Figure 4.5 demonstrates the sequence diagram of the above system architecture for managing spatial information flow and exchange.

Firstly, the engineering department acquires all the information across all the departments. Secondly, using that information, the conceptual engineering design of infrastructure is prepared and sent for approval/feedback. Then, based on the feedback received from all the departments, the conceptual engineering design of the infrastructure is finalised. Then, the engineering department sends a request to the surveying department to capture the field data. The surveyor collects the field data and sends it to the engineering department. The engineering department then commences the detailed design of the proposed infrastructure. Subsequently, 3D design models are sent to the respective departments for approval/feedback. Once, the approval/feedback is received by the engineering department, it takes appropriate actions on it. Finally, the approved design models of the infrastructure designs are sent to the spatial information management department for archiving

### 4.7. Prototype ER Diagram

An ER Diagram is a graphical approach to demonstrate the relationships between entities that include objects, people, concepts, or events within the information technology system (Hanna, 2024). Figure 4.6 demonstrates the storage of entities and their relationships in application backend development. There are seven key primary models (relations) that encompass the LSDM class, layer, vector layer, raster layer, cesium layer, KML3Dlayer, and document.

LSDM enables the definition of classes such as infrastructure, environment, geology, survey measurements, cultural heritage, and safety. Similarly, Layer allows the addition of layers and defines the LSDM classes and represents, along with the layer type (vector, raster, cesium, or KML3D). Furthermore, corresponding instances of VectorLayer, RasterLayer, CesiumLayer, and KML3D layer are created based on the defined layer type. VectorLayer contains metadata related to vector layers which are added to the prototype. For instance, the file field stores the vector shapefile in compressed (.zip) format, requiring at least .shp, .shx, .dbf, and. prj extension files. Similarly, the corresponding tables of uploaded layers with provided layer name (eg:

VectorLayerInstance1, VectorLayerInstance2, ……. VectorLayerInstanceN) are created in the default schema within the Postgres database and later published in default workspace in the Geoserver through PostGIS connection. There is no direct relationship between these tables with table ‘Layer’ but datasets are accessed with the defined layer name.

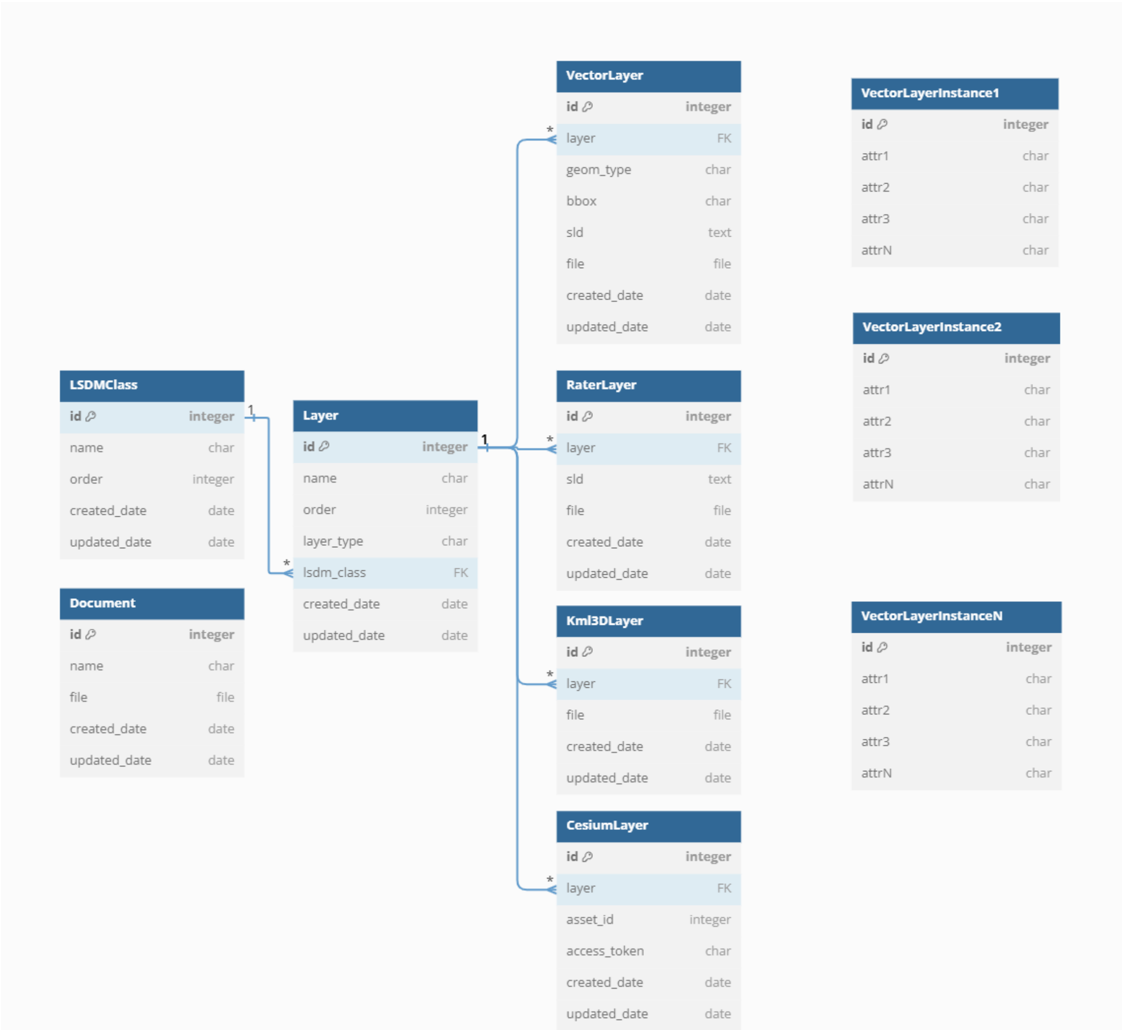



**Figure 4.6: Prototype ER Diagram**

The boundary box (bbox) and geometry type field is auto-populated based on uploaded datasets, while the sld field allows defining styles supported by Geoserver. Then, the RasterLayer table includes metadata related to added raster layers. It allows storing raster datasets in .tif or .geotiff file formats. Furthermore, the CesiumLayer table stores metadata related to added Cesium layers. The asset_id field stores the generated IDs of assets uploaded in the Cesium Ion online platform, requiring users to define their access token. Furthermore, KML3DLayer table stores metadata related to added KML3D layers. The file field stores files in .kml file format. Finally, Document allows saving documents such as the design plan of the field design.

### 4.8. System Architecture of Prototype

A system architecture was developed to present how the backend, frontend, localhost, and users interact with each other. The Microsoft Visio tool was used to design the system architecture of the prototype. This architecture was designed using the overall system architecture of the conceptual framework which was developed previously and incorporated the requirement analysis.

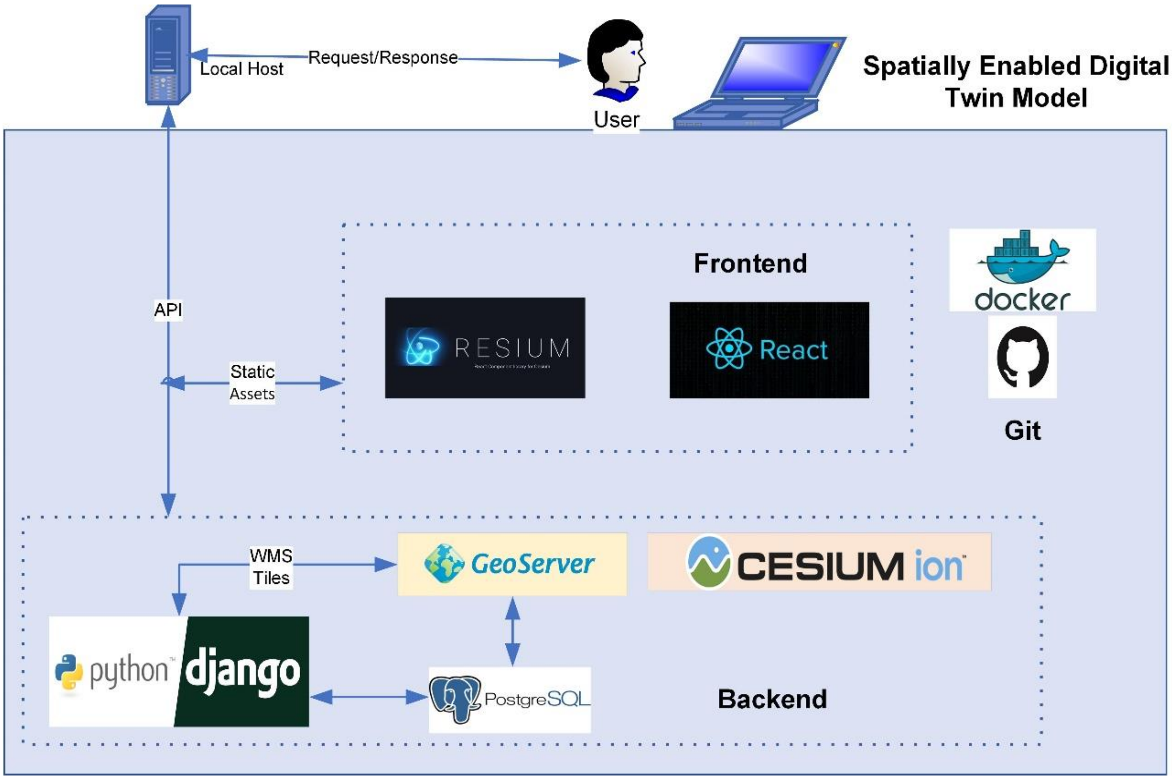



**Figure 4.7: System Architecture of Prototype**

The system architecture of the prototype mainly comprises four key components: backend, frontend, localhost, and users, as illustrated in Figure 4.7. The backend development is the most crucial part of this prototype, involving the creation of server-side components that power the prototype's functionality. In this prototype, Django is used for backend development, a high-level Python framework that follows the Model-View-Controller (MVC) architecture pattern (Netek et al., 2023).

Similarly, following the system architecture framework, PostgreSQL with the PostGIS extension is utilised as the database in this application to handle 2D spatial data. PostGIS is a powerful geospatial database extension that facilitates the storage, indexing, and querying of spatial data (Martinho et al., 2020). Furthermore, using the system architecture of the conceptual framework as a guide, Geoserver and Cesium Ion are employed as the map servers to handle vectors and rasters through Geoserver and 3D data through Cesium Ion.

In this prototype, WMS and 3D tiles have been utilised, allowing the map and model to be visualised in the frontend. Frontend development is also a pivotal part of this prototype which entails building the user interface and managing user interactions within the application. ReactJS, a JavaScript library, is used for frontend development in this application. The Resium library is employed for 3D spatial data visualisations using 3D tiles streamed from Cesium Ion (Cesium, 2020). The frontend interacts with backend APIs through Axios (a JavaScript library) to send and receive data, enabling users to make requests and receive responses. All these developments are built and tested in a docker environment. The frontend and backend codes are hosted in github repository. The prototype has been hosted on the localhost, based on the scope of this study. Finally, users interacting with the local computer can perform the functionalities that the application provides which are explained in the next section.

### 4.9. Prototype

Firstly, prototype requirements were identified. The main requirement for this prototype was that it should act as physical evidence of the developed conceptual framework which facilitates storing above mentioned six classes of data in 2D/3D formats and ensures the prototype successfully displays the stored attributes of the LSDM for 2D and 3D datasets. Therefore, upon considering the time frame of this study, five major functionalities were considered that include a layer panel, navigation bar, map interface, data upload, and view 2D design plan.

Secondly, a backend system was developed. This involved creating a Django project, configuring the MVC architecture, and defining Django models to represent essential data entities. The PostgreSQL database was augmented with the PostGIS extension for efficient spatial data handling. The Geoserver and Cesium Ion were integrated to handle vectors, rasters, and 3D data seamlessly.

Simultaneously, frontend development was commenced. The setup of a ReactJS project facilitated the creation of a dynamic and responsive user interface. React components were utilised to design an intuitive layout. The Resium library was introduced at the frontend of 3D spatial data visualisations, making use of 3D tiles streamed from Cesium Ion to enhance the overall user experience. The entire development process was carried out in the Git and Docker environment. Git ensures version control and collaborative development through branching, while Docker containers enable consistent deployment across different environments. Finally, the resulting prototype was hosted on a localhost.

The developed prototype is illustrated in Figure 4.8. The excerpts of the backend and frontend are attached in Appendices K and L. The backend interface excerpts are also attached in Appendices M, N, O, and P, and prototype components are discussed further.

### *4.9.1.* Components

This section describes the various components of prototype such as layer panel, map interface, navigation bar, add layer, view 2D design plan and other default components of Cesium Ion.

- **Layer Panel**

The layer panel serves as a crucial component within the prototype, encompassing the various data requirements outlined in Section 4.6. These requirements are categorised into distinct classes, namely Infrastructure, environment, geology, survey measurements, cultural heritage, and safety, as visually represented in the red box in Figure 4.8. This feature provides users with a comprehensive toolset for manipulating and controlling different layers within the prototype. Its functionality enables a systematic approach to handling datasets in accordance with the LSDM categories. Users can also download or delete specific layers by clicking on the respective icons provided for each layer.

- **Map Interface**

The map interface serves as a visual gateway to the 2D, and 3D spatial data encapsulated within the prototype. This essential feature allows users to interact with the spatial data of the infrastructure design and its associated information. The interface empowers users with the ability to navigate through the data, seamlessly transitioning between different sections. Through intuitive zoom functionality, users can focus on specific areas of interest, gaining a detailed perspective on the spatial information presented on the map. Moreover, the map interface provides a dynamic platform for users to visualise the uploaded data in the prototype. By offering a user-friendly environment for interaction, this feature enhances the overall accessibility of spatial information, making it easier for users to interpret and derive insights. The map interface is shown in Figure 4.8 in the blue box.

- **Navigation Bar**

The navigation bar functions as a pivotal navigational tool, serving as a gateway to essential functions and features embedded within the prototype. This critical element acts as a centralised hub, providing users with convenient access to different sections and capabilities. Typically, the navigation bar is comprised of navigation links, menu options, or buttons strategically organised to facilitate smooth transitions between various views or functionalities, enhancing the overall user experience. Figure 4.8 visually illustrates the components of the navigation bar, showcasing its design and layout. Users can utilise this intuitive interface to seamlessly navigate through the prototype, accessing key features easily. The navigation pane is represented in the yellow rectangle box in Figure 4.8. It consists of the title of the prototype, the ‘Upload Layer’ button and the ‘View 2D Design Plan’ button.

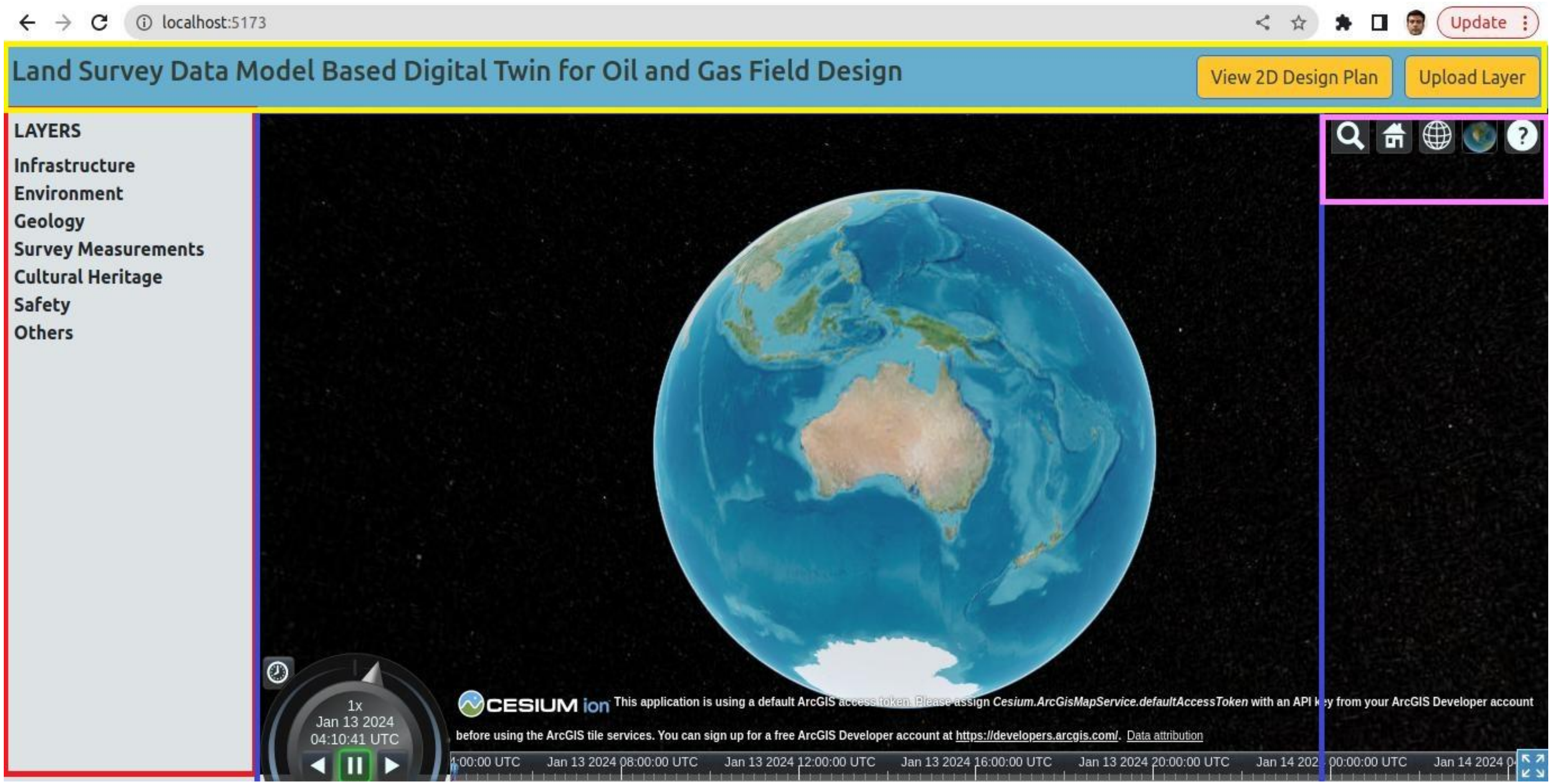



**Figure 4.8: Prototype Interface**

- **Add Layer**

One of the pivotal components of the prototype is the upload layer feature, depicted in Figure 4.9, which serves as a versatile tool for users to seamlessly incorporate diverse 2D and 3D datasets. The user can upload vector data, specifically in the shapefile (.shp) file format. This initial step ensures compatibility and ease of integration with the prototype. Users can select and define LSDM classes for the uploaded layer namely , infrastructure, environment, geology, survey measurements, cultural heritage, and safety, which act as organisational categories for the datasets. Users are required to specify the LSDM class that best corresponds to the nature of their uploaded data.

Further refinement of the dataset categorisation involves selecting a specific layer name from the LSDM data category. This classification ensures that datasets are stored in their respective LSDM classes, fostering a systematic and organised data structure within the prototype. To streamline the visualisation and interpretation of the uploaded datasets, users are then prompted to copy the Styled Layer Descriptor (SLD) based on their specific requirements. This step allows users to customise the appearance of the data on the map, tailoring it to meet their analytical or presentation needs.

Notably, the prototype extends its functionality beyond vector datasets to include the storage and management of raster datasets. The process for uploading raster datasets mirrors the user-friendly approach applied to vector data. Users are guided through a straightforward process, requiring them to select the specific raster datasets that align with their analytical or visualisation needs.

Additionally, the prototype efficiently managed 3D spatial datasets through two primary methods, shown in Figure 4.9. The first approach involved the storage of data via separated Keyhole Markup Language (KML) files, following a process corresponding to that employed for vector datasets. Conversely, the second method centred around utilising Cesium Ion asset IDs for 3D vector data storage. Users were required to input the specific asset id associated with the desired data, a process that involved referencing the Cesium Ion database. Appendix Q provides an excerpt from the Cesium Ion database.

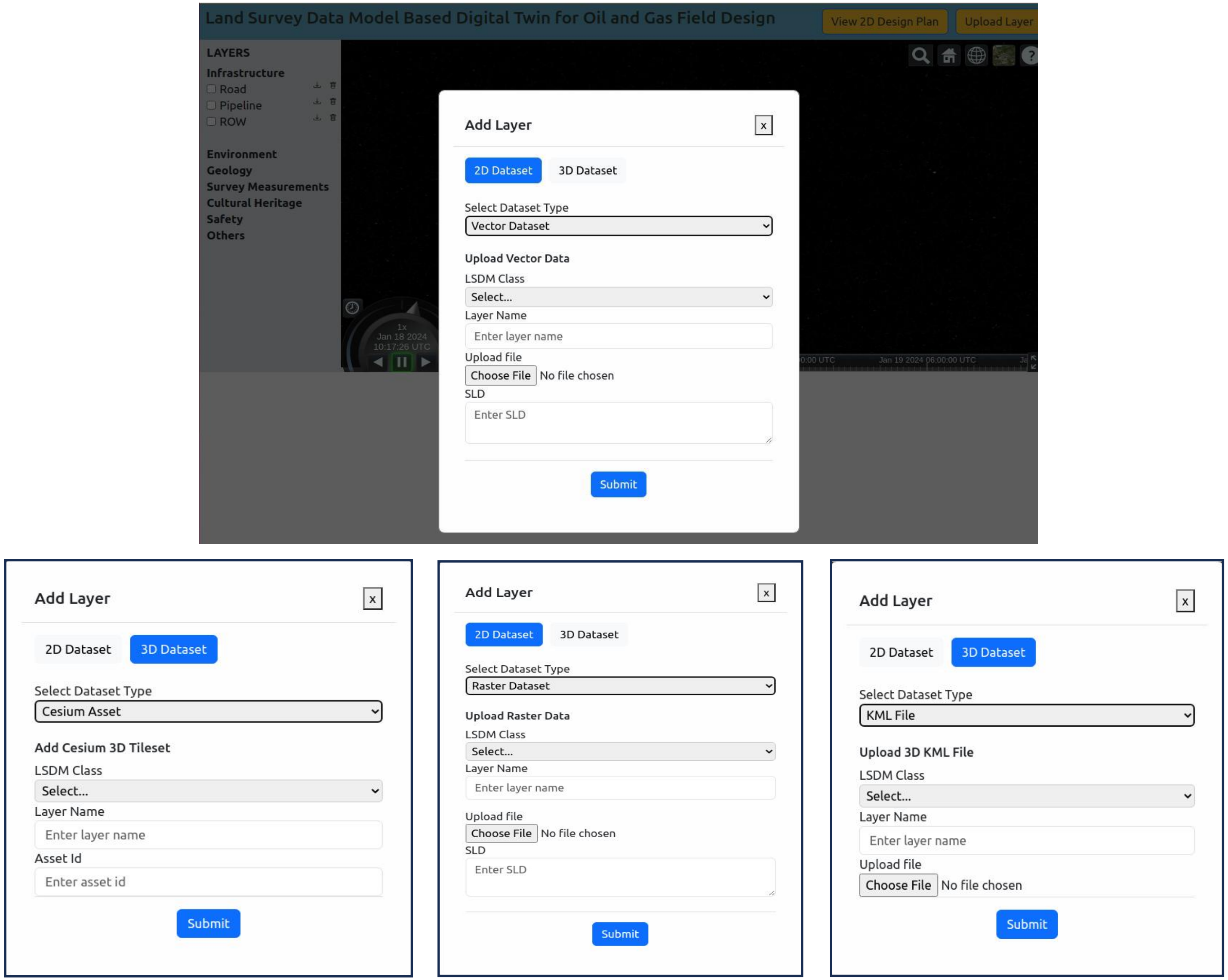



**Figure 4.9: Add Layers**

Therefore, the add layer feature in the prototype plays a pivotal role in seamlessly incorporating and categorising diverse 2D and 3D datasets, ensuring an organised and user-friendly data structure. The tool's versatility extends to vector, raster, and 3D spatial data, emphasising the prototype's adaptability and user-centric design.

- **View 2D Design Plan**

The 2D design plan within the prototype offers users a dedicated mode or perspective, emphasising a two-dimensional depiction of the infrastructure design. This functionality serves as a pivotal tool, enabling users to seamlessly correlate between the 2D design plan and the 3D design model. When the user clicks the ‘View 2D Design Plan’ button, the document opens in a new tab in the browser. The View 2D Design Plan functionality is shown in Figure 4.10.


**Figure 4.10: View 2D Design Plan**

- **Other Components**

The other components are represented as pink box in Figure 4.8. These components are default components of the Cesium Ion that encompasses the search functionality, view home, 2D and 3D view, and base map layers. The search component facilitates efficient and user-friendly exploration of geospatial data. Users can input specific locations, addresses, or points of interest, and the system will provide navigation information. The view home feature acts as a quick navigation tool, allowing users to easily return to a predefined default view or home location within the prototype. This ensures a seamless and consistent starting point for users, improving overall navigation efficiency. The 2D and 3D views support both two-dimensional (2D) and three-dimensional (3D) visualisation modes. The 2D view provides a traditional flat representation of the map, while the 3D view adds depth and perspective, offering a more immersive and realistic experience.

Users can seamlessly switch between these views based on their preferences and the nature of the data being explored. The inclusion of base map layers is integral these serve as the foundational background maps upon which additional geospatial data is overlaid. Base map layers can include various base layers such as street maps, satellite imagery, topographic maps, and more. Users can customise their visual context by selecting the most relevant base map layer for their specific needs. Therefore, search capabilities, view home functionality, 2D and 3D views, and the incorporation of diverse base map layers, collectively contribute to a comprehensive and user-centric navigation experience in both traditional and dynamic geospatial contexts for the developed prototype.

- **Localhost:5173**

The http://localhost:5173 signifies that the prototype development in the local machine on which it has been and running on port 5173 as shown on the top-left of Figure 4.10.

### 4.10. Chapter Summary

This chapter presents the results of the design and development stages. The conceptual framework of the spatially enabled digital twin was demonstrated which comprised five key components: data, standards, field design, users, and application. To better understand the clear interaction between these components, a use case diagram was illustrated. Similarly, to perceive the technical dimension of the conceptual framework, a system architecture was developed. The system architecture clearly illustrates the supported data types, database management system, map servers, and visualisation system. To further demonstrate the workflow of the field design and the system architecture, a sequence diagram was presented. Following this, the identified data from the literature review and industry engagement were comprehensively presented incorporating each dataset and its associated fields.

The identified data cover key classes of LSDM infrastructure, environment, geology, and survey measurements. However, cultural heritage and safety datasets were also added, as these are crucial in the context of Australia. Subsequently, an ER diagram was designed to handle the uploaded datasets within the prototype. Afterward, a system architecture of the prototype was presented to illustrate the key technological stack of a prototype that encompasses the python Django framework and postgresSQL including the Geoserver and Cesium Ion under the backend of the prototype. Similarly, reactJS, resium library were key technological stacks the under frontend development of the prototype. Following this, the interface of the prototype was depicted. Finally, key components and functionalities of the prototype were demonstrated which include the LSDM layer panel, user interface, navigation bar, data uploading, and viewing of 2D design plans.

# CHAPTER 5: DEMONSTRATION AND EVALUATION

## 5.1. Introduction

The previous chapter provides information on the development of conceptual framework and prototype development. This chapter will explain the demonstration and evaluation of the prototype that was developed in the previous chapter. Similarly, Figure 5.1 illustrates the methodology that was adopted for the demonstration of the prototype. Firstly, this chapter provides information on the selected case study area, 2RP108045 land parcel registered under the Department of Resources, Queensland Government. Following this, it provides information on the chosen case within the study area. Thirdly, this chapter explains the methodology employed for the UAV survey conducted in the case study area. In addition to this, it provides information about the geodatabase prepared from the UAV survey deliverables. Fourthly, the chapter briefly discusses the process carried out to prepare 2D engineering plans and 3D models for the case study area. Fifthly, the chapter discusses the integration of LSDM attributes designed in Chapter Four into the spatial data of designed 2D line works and 3D models. Sixthly, the chapter illustrates the demonstration findings obtained after migrating all the prepared 2D and 3D spatial data to the prototype. Finally, the chapter concludes by evaluating the prototype using metrics that encompass functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, and portability under the ISO/IEC 25010 model.

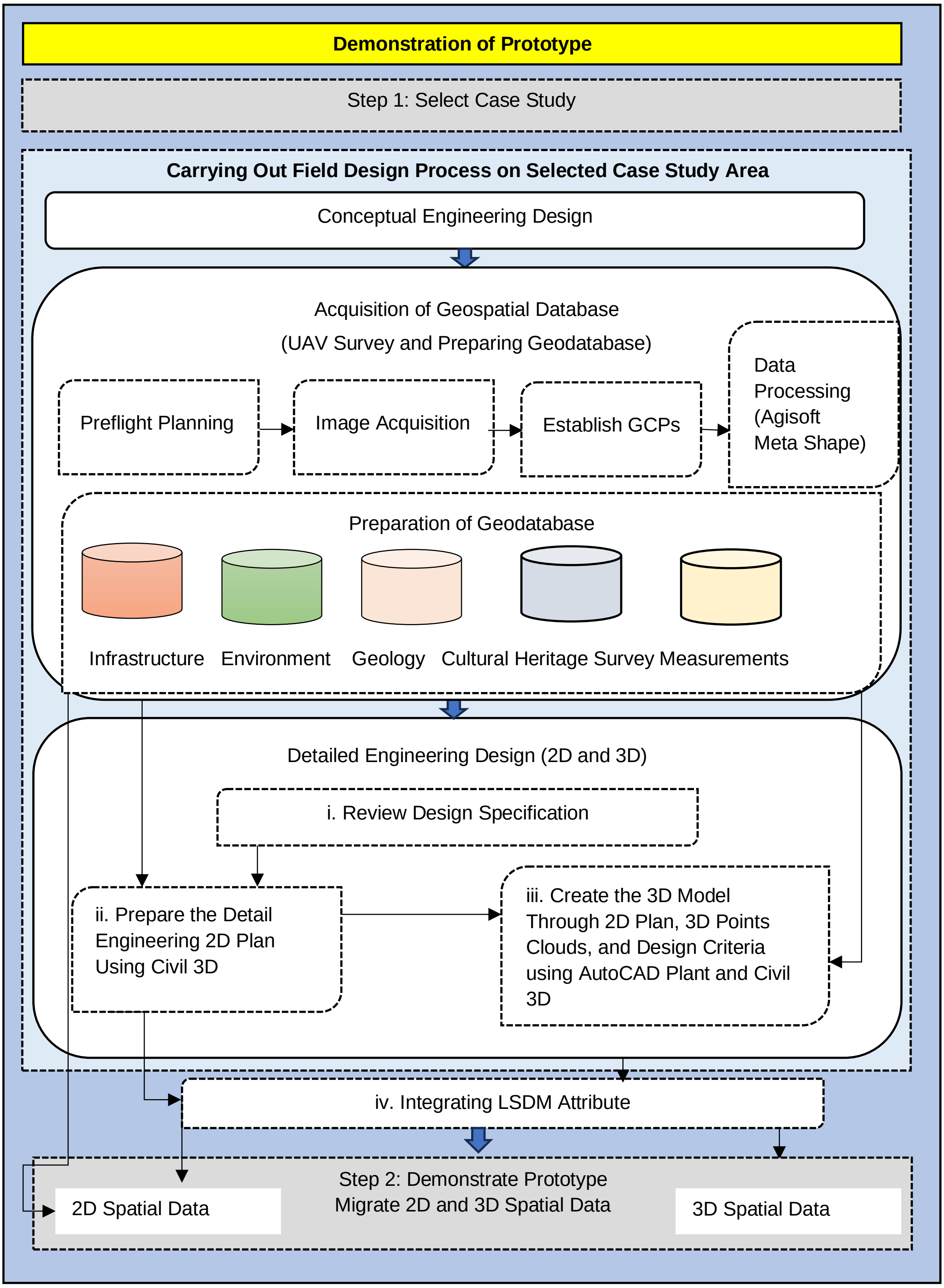



**Figure 5.1: Demonstration Approach**

## 5.2. Case Study

### *5.2.1.* Case Study Area

The case study area was selected based on data accessibility, as previously mentioned in Section 3.7. Figure 5.2 illustrates the chosen case study area along with its elevation range. It is located in Queensland, Australia within the Dalby mining district, in accordance with the regulations of the Department of Resources, Queensland Government. Furthermore, it is situated within the Western Downs Regional Council. This case study area is located at lot number 2RP108045 petroleum lease 229, registered under the Department of Resources, Queensland Government.

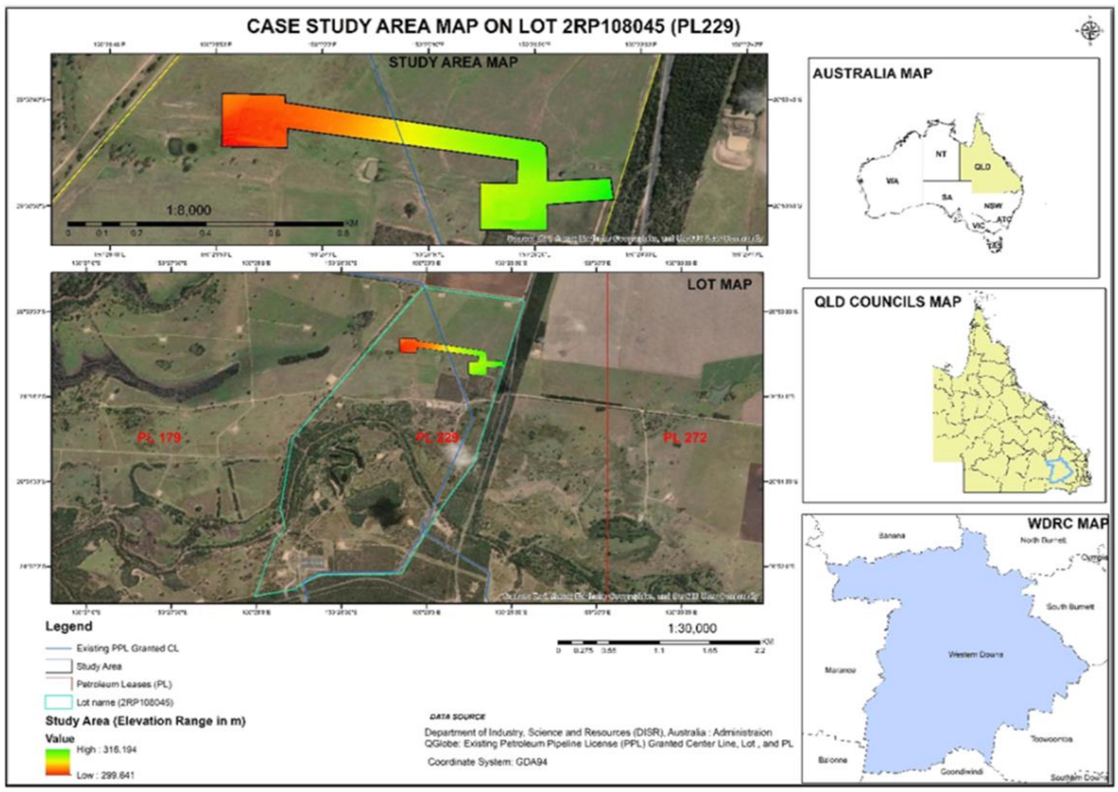



**Figure 5.2: Case Study Area**

### *5.2.2.* Design Case

There are various pieces of infrastructure involved within the entire field design process. In the chosen case study area, existing infrastructure included two plant facilities (vertical separators and their associated components) situated on their respective well pads, an existing access road, and a gathering pipeline network connecting these two well pads. Additionally, there were remnants of small existing fences within the case study area. Considering the availability of these infrastructures, a case was formulated for the study area. Specifically, the proposed Right-of-Way (ROW) corridor was designed adjacent to the existing ROW corridor. The rationale behind constructing the proposed ROW corridor was to enhance productivity from the two existing well pads. The proposed ROW corridor encompasses the proposed pipeline, proposed pipeline ROW, proposed road, proposed road ROW, and proposed well pad, adhering to Australian standards and industry practices (Arrow Energy, 2013; APGA, 2022; NSW Government, 2010; VIVA Energy, 2020). Therefore, as presented in Section 2.7, a typical field design process was undertaken to design these proposed infrastructures.

From Section 2.7, it can be shown that the five key activities of field design were conceptual design, acquisition of geodatabase, detailed engineering, approval from stakeholders, and storing spatial data of infrastructure designs into the spatial information system (SIS). However, in this case study, only four key steps of the field design process were executed: conceptual engineering design, acquisition of geodatabase, detailed engineering design, and storing 2D and 3D spatial data of the designs into the developed prototype. Within the scope of this study, the approval of designs from stakeholders could not be obtained. Therefore, an assumption was made that stakeholders have approved the design of the proposed infrastructure for the purpose of this case study. The explanation of each activity and the results generated from them is explained further.

## 5.3. Conceptual Engineering Design

The conceptual engineering design of the Right-of-Way (ROW) corridor adhered to industry-standards and practices, as detailed in Section 2.7. The design considerations for this study are illustrated in Figure 5.3. Appendix R and S also illustrate the design standard and industry practice. It highlights the presence of an existing 30m pipeline ROW corridor, wherein the access road and gathering pipe have already been constructed, as indicated by their centrelines. The nominal width of the existing access road is 4.5m. Similarly, a proposed ROW corridor of 30m was designed, comprising a proposed 10m access corridor and a 20m pipeline corridor. The width of the proposed access road is 4.5m, aligning with industry-standards and practices discussed in the case study background. Additionally, the centre of the proposed pipeline is positioned 16.5m from the edge of the ROW corridor.

Furthermore, the design includes a proposed well pad. The industry practice for designing the well pad is 100m*100m. This dimension is available in the corporate reports (Arrow Energy, 2019; Shell QGC, 2020). However, after further analysis, it was determined that a 15m extension from the existing well pad was sufficient to align with the new proposed 30m ROW corridor. The next activity explains the acquisition of the geodatabase (field design step) carried out through the UAV survey.

### 5.4. Acquisition of Geodatabase (UAV Survey)

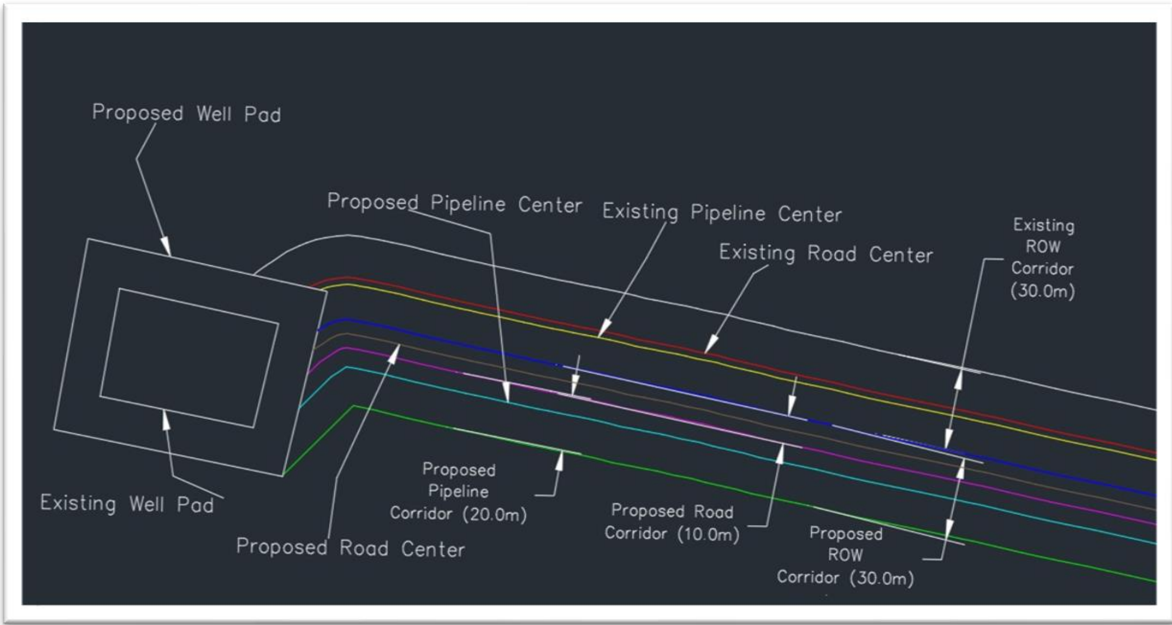



**Figure 5.3: Conceptual Engineering Design**

In the context of field design, there are various approaches to acquiring geodatabase data, with key methods including GNSS, total station, terrestrial laser scanning, UAV, and LiDAR (IOGP, 2022). In this study, the UAV survey was chosen as the spatial data acquisition approach for three primary reasons. Firstly, the selected method needed to facilitate the generation of digital twins (3D models), a capability for which UAVs are widely recognised across the research community (Sun et al., 2022). Secondly, the relevant authorities only approved the use of UAV surveys in accordance with their protocols. Thirdly, the UAV survey was not only accessible for this study but also cost-effective compared to terrestrial laser scanning, which also provides 3D models (Mohammadi et al., 2021). The entire process conducted through the UAV survey is elucidated below.

### *5.4.1.* Preflight Planning

The primary objective of preflight planning was to ensure a successful and efficient data collection process, with a paramount focus on safety and accuracy. As this UAV survey was also part of the piloting project for DSQ Land Surveyors, preflight planning was completed before carrying out the UAV survey on site. Initially, three teams were established, comprising the management team, safety team, and technical team.

The management team consisted of directors and the chief pilot from DSQ Land Surveyors, along with the thesis supervisor from the university. The directors were responsible for liaising with the relevant authority to obtain approval for UAV flights in the study area and requesting land access confirmation from the relevant authority. The thesis supervisors provided academic guidelines. In the context of Australia, the mining industry places significant emphasis on safety, and given the presence of two vessel plants in the case study area, a dedicated safety team was formed for the UAV survey. This team facilitated communication with the site security personnel and ensured that the survey team members followed safety protocols including the use of personal protective equipment (PPE), and survey vehicles possessed valid biosecurity certificates.

Concurrently, the technical team, comprising the research candidate and DSQ GIS consultants, were responsible for executing the fieldwork on the ground. This team played a crucial role in planning the GCPs layout, flight routes, and image acquisition approach. The proposed GCPs layout and flight paths during planning are depicted in Figure 5.4. All planning activities conducted on desktops were exported as KML layers. Additionally, the technical team utilised the Ok2Fly platform (Civil Aviation Safety Authority, 2023) for analysing the conditions around the flight area such as nearby danger areas, airfields, and heliports. Finally, preplanning was successfully accomplished to carry out further field surveying on the ground. The explanation of how field surveying was carried out is detailed further in the following section.

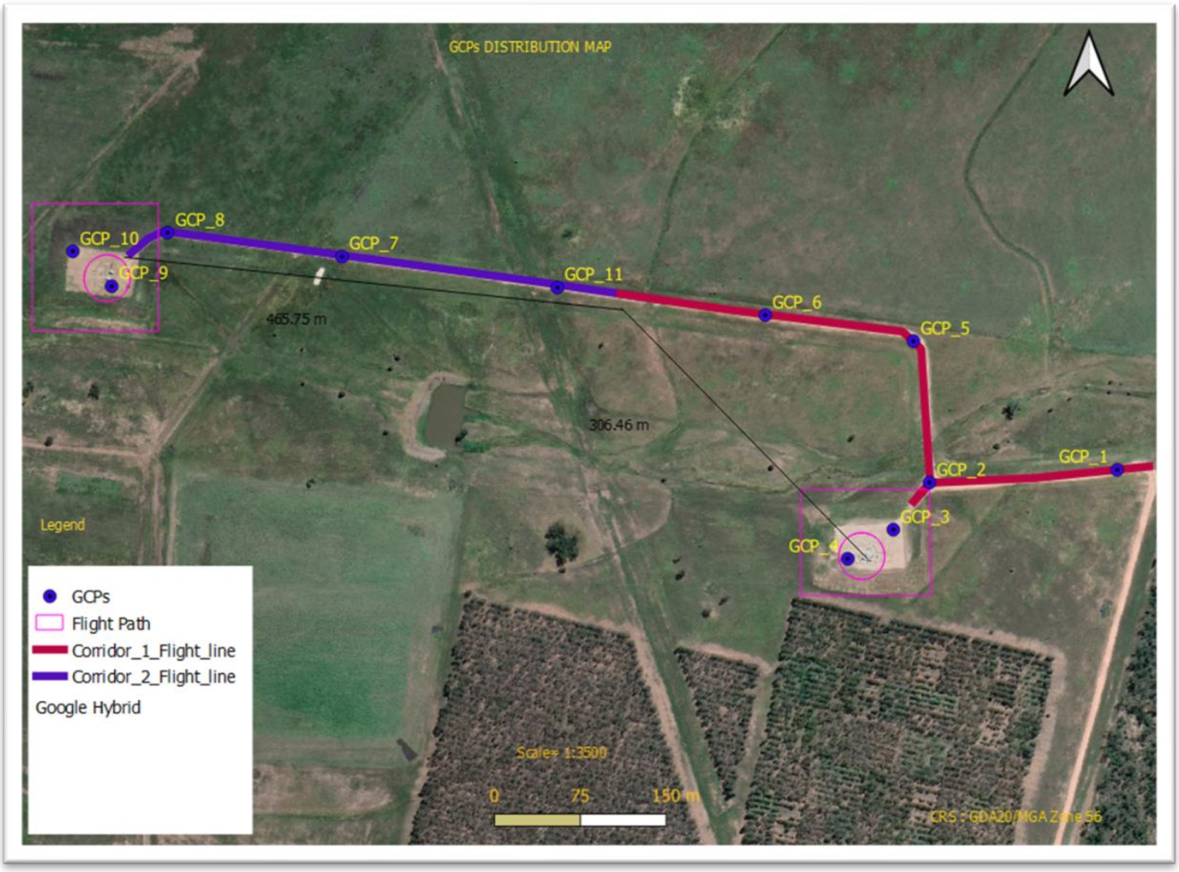



Figure 5.4: Preplanning GCP Layout

### *5.4.2.* Establishment of GCPs

The aim of GCPs establishment was to provide necessary control points for georeferencing the acquired images and connecting them with state datum. The initial step in GCP establishment involved field reconnaissance, utilising the KML layer prepared during the preplanning step. Once the locations of the GCPs were confirmed, a cross-shaped GCP marker was placed at each designated GCP location, following the best practice in UAV surveys (Liu et al., 2022).

For the densification of control points, the RTK-GNSS survey method was used due to its recognised reliability in GCP establishment for UAV surveys (Jaud et al., 2020). Similarly, Trimble GNSS instrument was used in this survey, due to its accessibility and efficiency Additionally, these Trimble products are widely acknowledged due to their reliability in acquiring spatial datasets (Demyanov et al., 2020). The specifications of the Trimble equipment are outlined in Table 5.1. An example of the painted cross marker for one of the GCPs is presented in Appendix T. In RTK GNSS surveying, a base station was established, and other points (rover stations) were established relative to it as the base station transmits real-time satellite positioning corrections to the rover stations. In this case, survey control mark 177091 served as the base station, and its coordinates were obtained from Queensland Globe in GDA 1994 coordinates. Rover stations were then established at the GCP cross markers, with a total of 11 rover points. One of the GCP surveying photos is shown in Appendix U. Then, data were processed during the office work and exported as CSV (.csv) file format. The location map of the established GCPs is presented in Figure 5.5. After the successful completion of the GNSS surveying, the next activity carried out in field surveying was image acquisition which is explained in the next section.

**Table 5.1: GNSS Equipment Specifications**

| **Equipment** | **Specification** | **Image** |
|---|---|---|
| GNSS Receiver | Trimble R10 |  |
| Data Collector | TSC5 |  |
| GNSS Base Tripod | Lecia Heavy Wooden |  |
| GNSS Rover Pole | Trimble 2M Carbon Fiber |  |

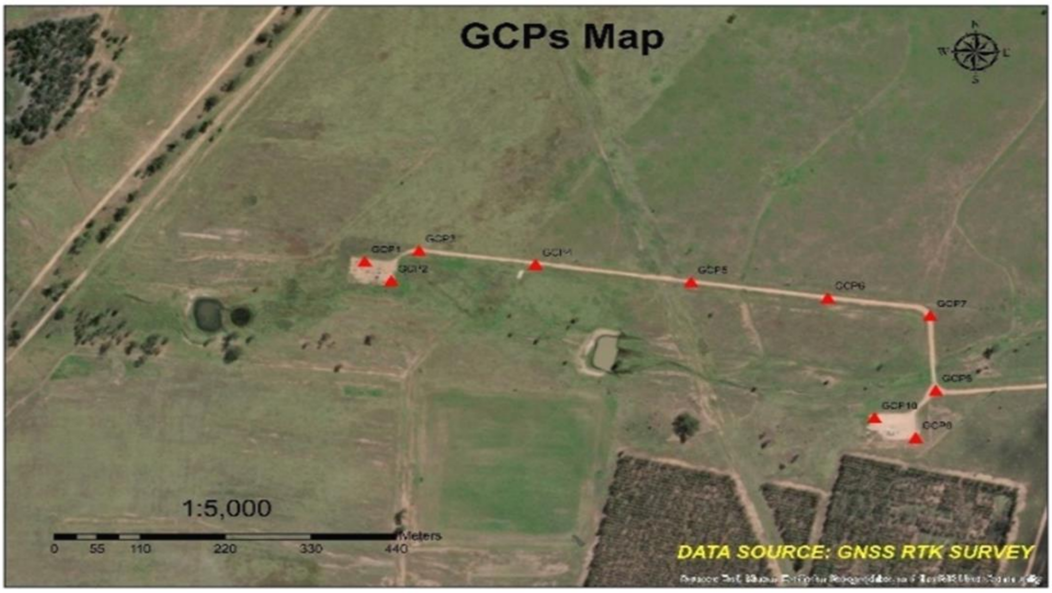



**Figure 5.5: Surveyed GCPs**

### *5.4.3.* Image Acquisition

The main aim of the image acquisition was to acquire essential data to prepare the geodatabase of the study area, carry out the detailed engineering design, and create the 3D models. The UAV equipment used in image acquisition is shown in Figure 5.6.

**Figure 5.6: Unmanned Aircraft System**

Firstly, the calibration process was carried out prior to the actual flight, emphasising the importance of thorough equipment checks for UAVs, remote controllers, and computers. This precautionary measure aimed to prevent crashes and system failures resulting from malfunctions, ensuring meticulous execution to confirm the UAV's functionality and readiness for take-off.

The UAV was linked to the remote controller, facilitating automated flight. However, for safety reasons, manual control was maintained during take-off and landing. The UAV pilot maintained continuous visual access to the aircraft's position, acceleration, speed, and navigation data through the software interface. The UAV flight encompassed three steps: the flight of the first corridor, and the second corridor using nadir flight, and the capture of the two well pad plants through an orbit-based method. The flying height for capturing both corridors was set at 60m, achieving a 2.5cm ground sampling distance (GSD). Similarly, the first well pad was captured at three different flying heights, spanning 360 degrees at 2m intervals, and various gimbal angles. Table 5.2 illustrates the specifications of DJI Phantom 4 which was used to capture images. A flying height of 1.5m was maintained, rotating 360 degrees at each 2m interval with a 0-degree gimbal angle. Secondly, a flying height of 6m was maintained, rotating 360 degrees at each 2m interval with a 15-degree gimbal angle. Thirdly, a flying height of 12m was maintained, rotating 360 degrees at each 2m interval with a 30-degree gimbal angle. Finally, a flying height of 30m was maintained, rotating 360 degrees at each 2m interval with a 90-degree gimbal angle. Subsequently, images were captured.

**Table 5.2: Image Acquisition Specifications**

| **Characteristics** | **Platform** |
|---|---|
| UAV Model, Weight | DJI Phantom 4, 1380g |
| Maximum Flight | 20 min |
| Sensor | 1/2.3” CMOS |
| Image Size | 4000×3000 |
| Lens | FOV 94° 20mm (35mm format equivalent) f/2.8 focus at ∞ |
| Operating Temperature | 32° to 104°F (0° to 40°C) |

### *5.4.4.* Image Data Processing

The primary objective of image data processing was to generate deliverables from the acquired raw images. Agisoft Metashape 1.7.2 was used for image processing as it is widely acknowledged and recognised across the geospatial industry (Jarahizadeh & Salehi, 2024). Initially, nadir images were added, and the number of inserted photographs was verified to ensure correct importation. In total, there were 354 nadir images. The added image location is shown in Figure 5.7.

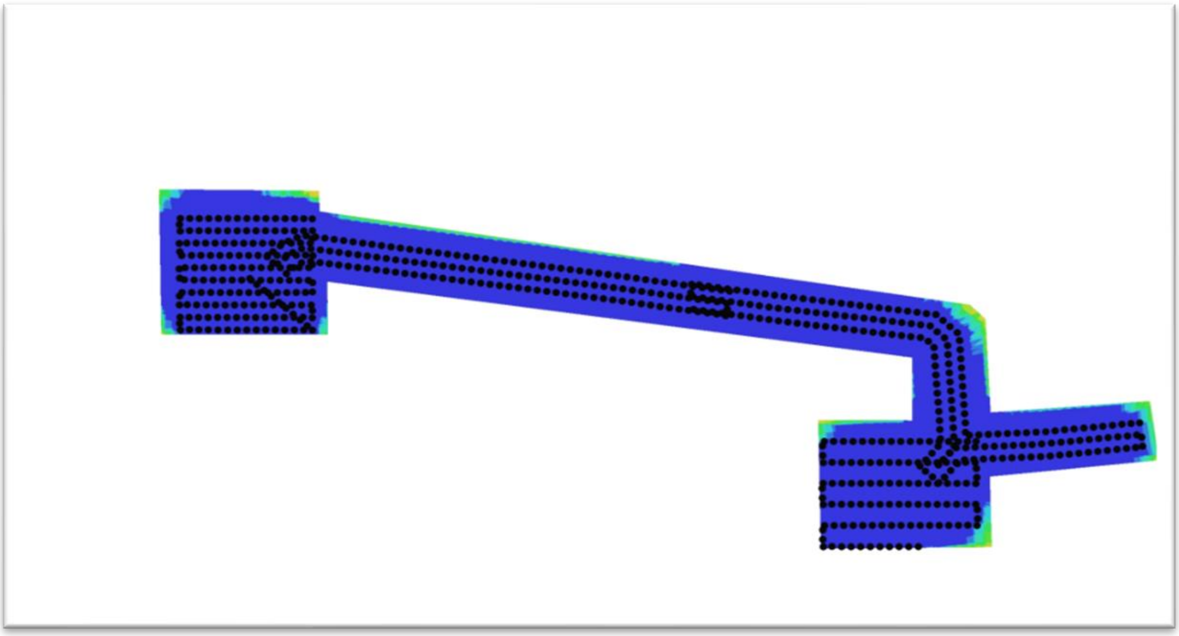


**Figure 5.7: Image Location**

Subsequently, reference settings were employed to check the coordinate system and other measurement accuracy. Following this, camera calibration was performed by entering parameters illustrated in Table 5.3. The value of the used parameter for the image processing is demonstrated in Appendix V.

**Table 5.3: Definition of Calibration Parameters Adapted from Agisoft (2022)**

| Parameter | Definition |
|---|---|
| F | Focal length measured in pixels |
| Cx, Cy | Principal point coordinates |
| B1, B2 | Affinity and non-orthogonality (skew) coefficients (in pixels) |
| K1, K2, K3, K4 | Radial distortion coefficients (dimensionless) |
| P1, P1 | Tangential distortion coefficients (dimensionless) |

These parameters were first chosen from the literature review and adjusted through an iterative process until the desired accuracy was obtained. Then, a GCPs in.csv file format was imported to accurately georeference the images. Image orientation was conducted to align the added photos using the Align Photos module in the software. Subsequently, the GCP was placed at each location using the cross marker, and the images were once again oriented using the same module. This process was repeated until the desired accuracy was achieved. Furthermore, a 3D point dense cloud was generated in high mode. Following this step, the 3D mesh, Digital Surface Model (DSM), and orthomosaics were generated using their respective modules. The generated results from the image processing are shown further.

### *5.4.5.* Results and Accuracy

Upon the successful completion of image data processing, the essential outcomes were exported. The key results derived from UAV data processing encompassed 3D models, orthophoto, and digital surface model (DSM), as depicted in Figure 5.9. The 3D models were exported in. las and .obj file formats, while the orthophoto and DSM were exported in .tif file format. The spatial resolution of the obtained orthophoto and DSM was determined to be 1.5cm and 2.6cm, respectively. Additionally, the accuracy of the GCPs model is illustrated in Figure 5.8. The calculated errors in Easting (X), Northing (Y), and Elevation (Z) were found to be 2.814mm, 3.520mm, and 3.940mm, respectively. These individual errors cumulatively contribute to a total error of 5.989 mm. Further details about the processing parameters and accuracy report have been provided in Appendix W.

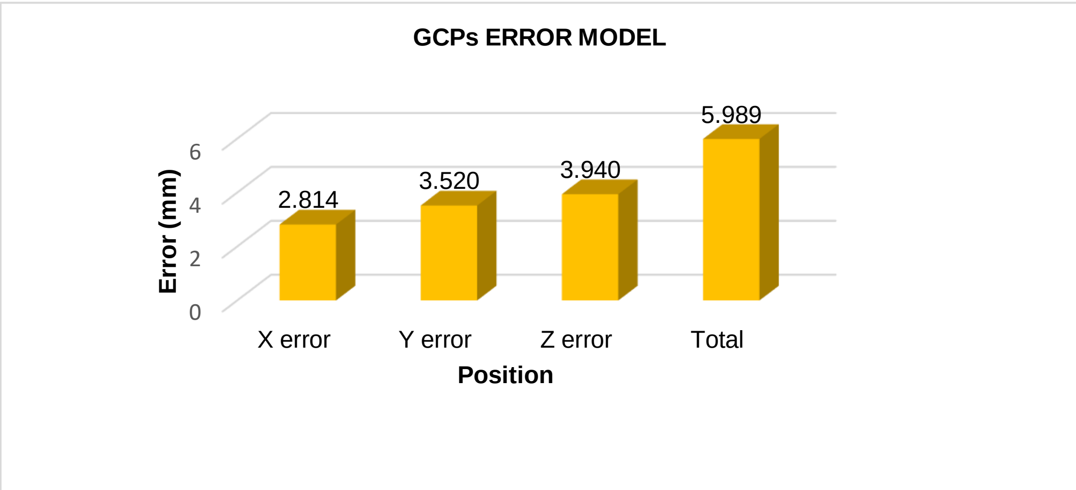



**Figure 5.8: GCPs Error Model**


Figure 5.9: UAV Results

### *5.4.6.* Preparation of Geodatabase

This step is considered a crucial stage in the case study. After obtaining the orthophoto and 3D model from the previous step, the primary objective was to further prepare the geodatabase for the detailed engineering design of the case study area. Initially, the geodatabase was created using the data specifications outlined in Section 4.6. Figure 5.10 illustrates the prepared personal geodatabase for this case study using ArcGIS 10.8. The software was selected as LSDM is based on ESRI data format, was accessible, and is recommended as GIS software in the oil and gas industry by IOGP. This case study encompasses five classes: infrastructure, environment, geology, survey measurements, and cultural heritage. However, erosion data from the geology class and safety class were not considered due to inaccessibility. Table 5.4 provides a summary of the prepared database and its sources. The details regarding the geodatabase preparation process for each class are explained below.

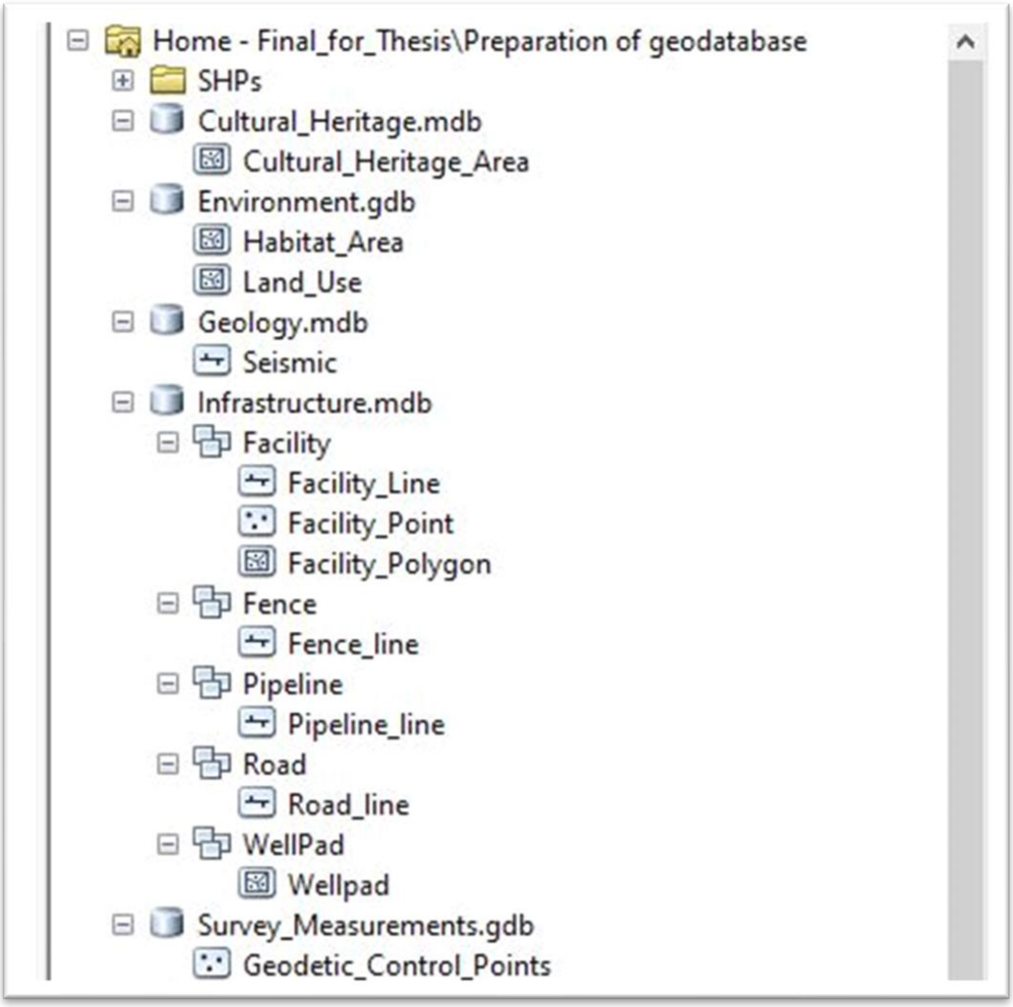



**Figure 5.10: Geodatabase of Study Area**

Table 5.4: Acquired Datasets for Case Study Area

| Class | Datasets | Source |
|---|---|---|
| All data are in .shp file format | | |
| Infrastructure | Facility | Digitised from the orthophoto generated through UAV survey |
| | Fence | |
| | Road | |
| | Well pad | |
| | Pipeline | Created using industry-standard specification |
| | ROW | |
| Environment | Land Use | QSpatial |
| | Habitat Area | Digitised from the orthophoto generated through the UAV survey |
| Geology | Seismic | QSpatial |
| Survey Measurements | Geodetic Control Points | RTK GNSS survey |
| Cultural Heritage Area | Cultural Heritage Polygon | QGlobe |
| **Other datasets used in the case study** | | |
| **Data** | **Format** | **Source** |
| 3D Point Clouds | .las | UAV survey |
| DSM | .tif | |
| Orthophoto | .tif | |
| Land Parcel | .shp | QGlobe |

- **Infrastructure**

Infrastructures are the existing as-built information that were generated through the digitisation of the orthophoto. The existing well pads, roads, fences, and facilities were digitised using the ArcMap 10.8 software. The polygon geometry was used to digitise well pads whereas line geometry was used to digitise roads, fences, and facilities while carrying out the digitisation on orthophoto. Similarly, for existing pipeline and ROW this study has tried to access the centre line of the existing buried pipeline connecting two facilities. However, due to data security reasons the team could not access the underground existing pipeline data from the concerned authority. Therefore, possible options were checked. QGlobe and the national map portal were also explored to acquire the underground pipeline and ROW data. Unfortunately, there was not any information for this case study area. Therefore, the centre line of the existing pipeline and ROW were created using the location of the existing road and following the industry-standard designed model as outlined in Sections 5.2 and 5.3.

Subsequently, after completing the digitisation, Microsoft Excel .csv files were prepared for each dataset category using the Microsoft Excel software. The .csv file contains the values which were only known elsewhere left 'N/A'. Then, prepared .csv files and their respective datasets were joined using the primary key (ID). The ArcGIS join tool was used to integrate the attribute values on .csv files and the feature geometry on the geodatabase.

- **Environment**

The two datasets, habitat area and land use of the environment class were considered for this case study. The habitat area was digitised on the orthophoto, and its relevant attributes were inserted manually on the attribute table. The same process in ArcGIS software was applied as explained for the infrastructure. The separate .csv files were not prepared because the habitat area was small (covering approximately 430 square metres). Similarly, the land use datasets were searched on the QSpatial geoportal of the Queensland government. An email request was sent to the data provider and data was sent as a zipped file through email. Then, the data was clipped for the case study lot (2RP108045) using the ArcGIS software.

- **Geology**

This study incorporates two classes of geology such as erosion and seismic. However, during this case study, only seismic data was considered. The datasets of both seismic lines and areas were explored. However, in this case study area, only a seismic line was found that crosses from the north to the south along the eastern property boundary. The datasets were found in the QSpatial. The same process was applied as explained for land use to access seismic data. After obtaining datasets, a clip tool was used to extract the datasets for the lot (2RP108045).

- **Survey Measurements**

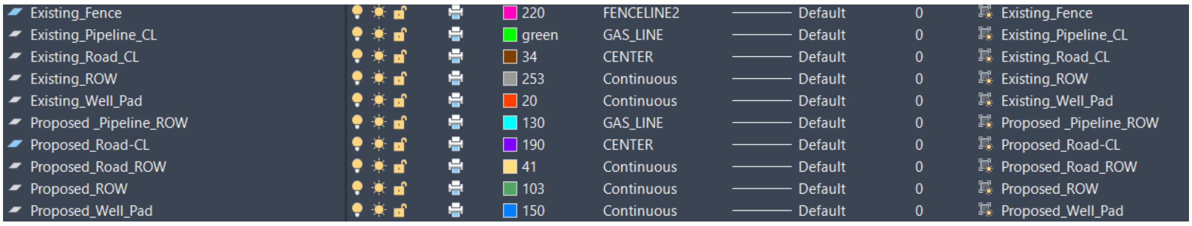
The survey measurements encompass two datasets: geodetic control points and the surveyed points. The captured GCPs during the UAV survey were integrated into the geodatabase geodetic control points feature class. The detailed explanation of how the GCPs were acquired was already explained in Section 5.4.2.

- **Cultural Heritage**

In the context of Australia, cultural heritage is crucial across the mining industry. Normally, during the field design process, respective indigenous communities were requested to assess the ROW of the area to be cleared from them (VIVA Energy, 2020). To carry out the same process was beyond the scope of this case study. Therefore, possible alternatives were explored to acquire the cultural heritage datasets. The datasets were explored on the existing sources through internet. It was found that to access the point cultural heritage data was difficult, however, cultural heritage area (polygon) was found on the QGlobe of the entire tribe boundary. The data was downloaded from the QGlobe and clip tool was used to extract the area of interest for this case study area.

## 5.5. Detailed Engineering Design

After the successful completion of preparing the geodatabase, the detailed engineering design of the case study area was commenced using Civil 3D software. Civil 3D software is widely recognised for designing and modelling within the AEC industry (Ivanova et al., 2023). Subsequently, the line layers template setup for different infrastructures to be designed for detailed engineering design is shown in Figure 5.11.



| | | | | | |
|---|---|---|---|---|---|
| Existing_Fence | 220 | FENCELINE2 | Default | 0 | Existing_Fence |
| Existing_Pipeline_CL | green | GAS_LINE | Default | 0 | Existing_Pipeline_CL |
| Existing_Road_CL | 34 | CENTER | Default | 0 | Existing_Road_CL |
| Existing_ROW | 253 | Continuous | Default | 0 | Existing_ROW |
| Existing_Well_Pad | 20 | Continuous | Default | 0 | Existing_Well_Pad |
| Proposed _Pipeline_ROW | 130 | GAS_LINE | Default | 0 | Proposed _Pipeline_ROW |
| Proposed_Road-CL | 190 | CENTER | Default | 0 | Proposed_Road-CL |
| Proposed_Road_ROW | 41 | Continuous | Default | 0 | Proposed_Road_ROW |
| Proposed_ROW | 103 | Continuous | Default | 0 | Proposed_ROW |
| Proposed_Well_Pad | 150 | Continuous | Default | 0 | Proposed_Well_Pad |

**Figure 5.11: CAD Layers**

### *5.5.1.* 2D Detailed Engineering Plan

To carry out the detailed engineering design, the very first activity was to review the design specification. During the review of the design specification, three major aspects were considered that includes conceptual design, acquired geospatial information, and design specification. After all information were analysed, it was found that same conceptual design could be further carried out for the detailed engineering design. For instance, from the cultural heritage aspect, the proposed infrastructures lie where the first nation communities have already approved areas for construction of infrastructures as per the information illustrated in Figure 5.12 (A).


**Figure 5.12: Justification of Factors**

From an environmental aspect, the proposed infrastructures are on cropping area and should not create any hindrance to build proposed infrastructures as shown in Figure 5.12 (B). Similarly, the edge of habitat area is approximately 39m from proposed habitat area as shown in Figure 5.12 (C). Therefore, it can be concluded that from the engineering design perspective, the proposed infrastructures can be designed same as conceptual design. In addition to this, as mentioned in Section 5.2.1, this study does not consider the approval of the designs from other stakeholders.

Therefore, to validate the layout of the detailed engineering design, the relevant stakeholders were not involved. Subsequently, the same line work was used to prepare the 2D engineering detailed plan. During the detailed engineering design, the offset, hatch, and polyline were common tools used in Civil 3D software. Similarly, during the preparation of plan, dimension aligned tool was also used to prepare the plan. The detailed engineering plan for this study is represented in Figure 5.13. The layout of the detailed engineering was similar to the conceptual design. The dimension and aspect of this layout are already explained in Section 5.3. The zoomed map of the two well pads and detailed engineering design with other spatial information are illustrated in Appendix X.

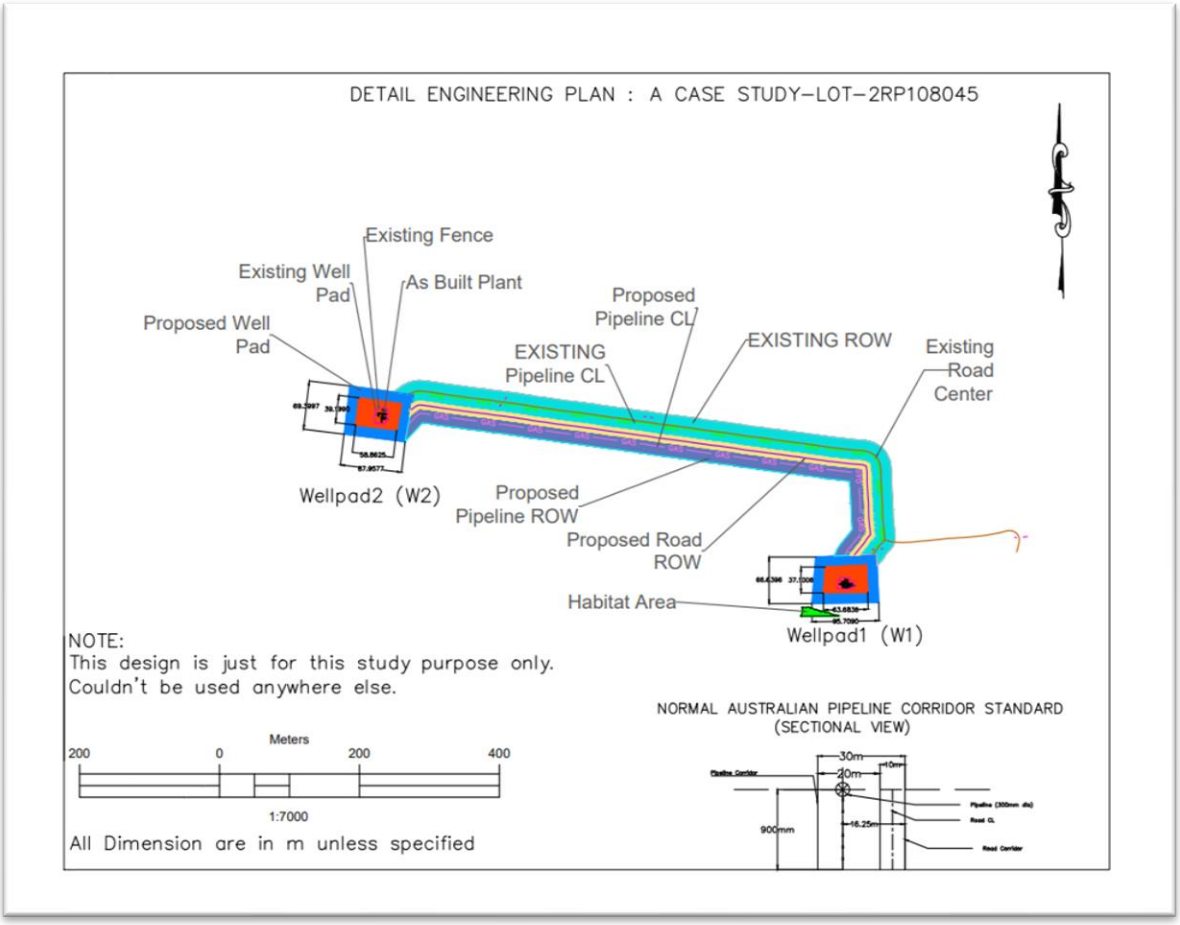



**Figure 5.13: Detailed Engineering Plan**

### *5.5.2.* 3D Detailed Engineering Model

This step was pivotal in this study. As discussed in the research problem, the 2D plans represented in Figure 5.13 are not efficient for communicating the design information. Therefore, a 3D design model of the plan was constructed using the prepared 2D plan in previous step and captured 3D point clouds through UAV survey. The discussion about how the 3D models of the plan were created are described further below.

- **Facility Plant**

To create the 3D model of the facility, the major source of the data was the 3D point clouds captured from the UAV survey and the 2D as-built facility data digitised from the orthophoto. The AutoCAD Plant software was used to build the 3D model. To convert, .las to .rcp file Autodesk ReCap was used. Then after, the unnecessary point clouds were deleted to enhance the efficiency of the modelling. The 3D modelling was started using common components such as the pipe, valve, and structure. However, the boundary fence of the plant was mostly modelled using the 3D structure tool available in the AutoCAD plant. The vertical height of the fence was measured during the UAV survey and was 1.5m. The prepared 3D model of the plant was developed through a generalisation approach.

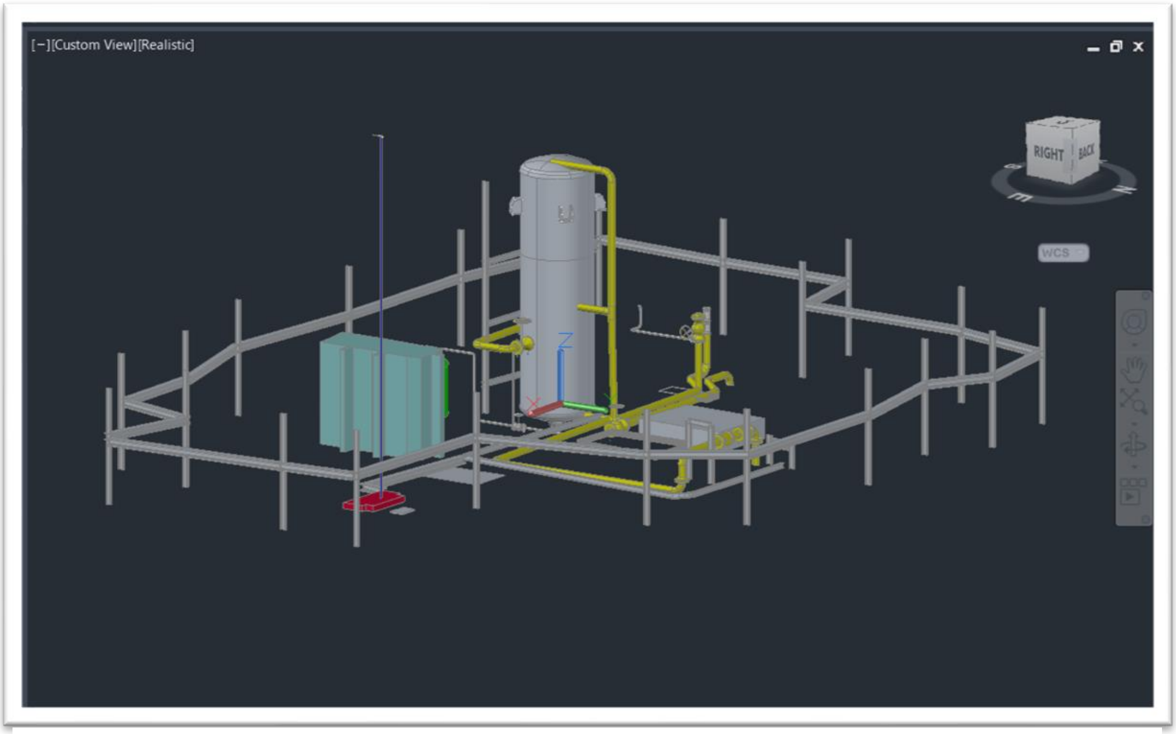



**Figure 5.14: Detailed Engineering Model A**

The common method to build a 3D model of this type of plant is integrating diverse information and key information entails 2D design (2D process piping and valve design plan), 3D point clouds, and auxiliary information. In this case study, the available information was 3D point clouds and 2D as-built data digitised from the orthophoto. The major aim of the demonstration was to implement the prototype. Therefore, consideration was made that generated 3D model of the plant was sufficient to migrate to the prototype and test its feasibility to store and visualise the 3D model. The prepared 3D model of the plant is illustrated in Figure 5.14 and Figure 5.15. Figure 5.14 demonstrates the plant of well pad 1 and Figure 5.15 demonstrates the plant of well pad 2. The two plants were almost identical, so most of the modelling processes were same. One of the challenging tasks during the modelling of this plant was georeferencing the plant. However, AutoCAD geolocation tool supports in approximate georeferencing of the 3D model of the plant as shown in Appendix Y.

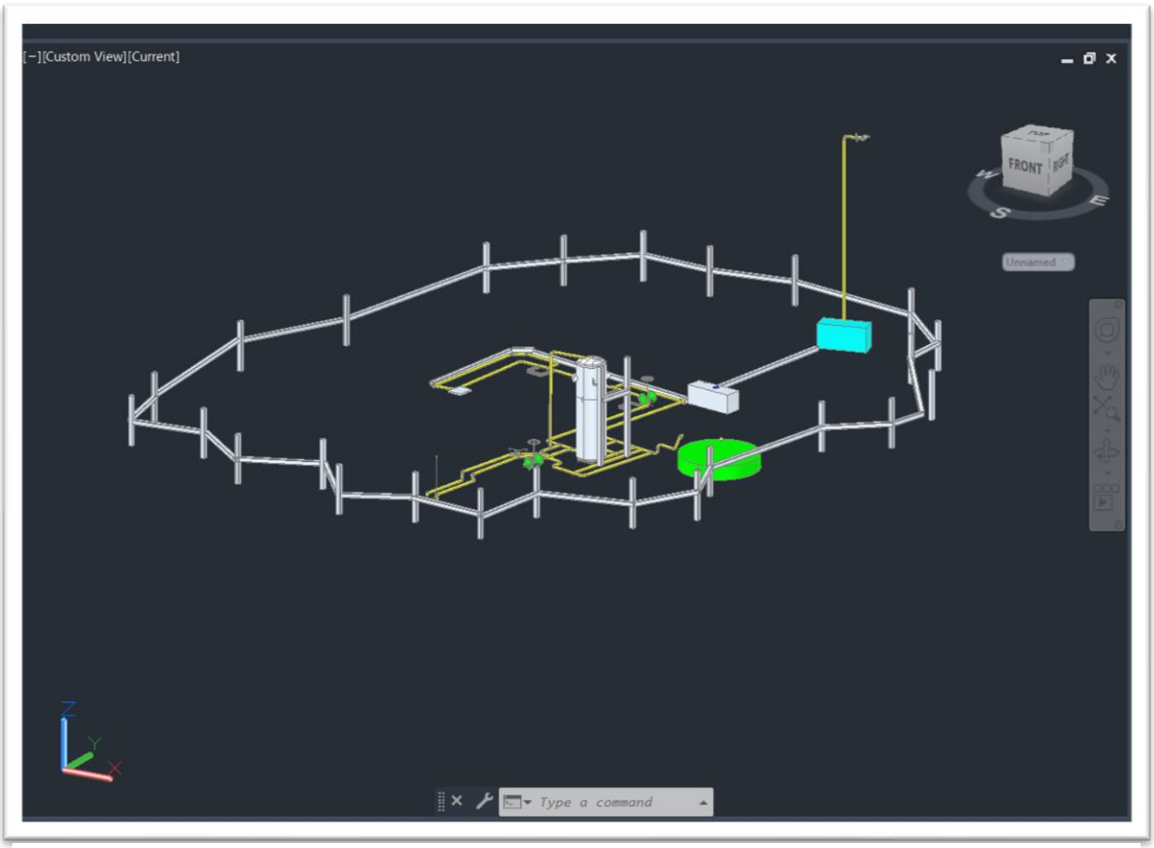



**Figure 5.15: Detailed Engineering Model B**

- **Others**

The other infrastructures from the 2D plan were converted to the 3D model. The other infrastructures in this case study were ROW, road, and pipeline. The Civil 3D software was used to create the 3D model of these infrastructures. The very first activity that was carried out to build the 3D model was finding the relevant dimension. The literature review was carried out using the existing projects and associated resources. It was found that the normal depth of the pipeline in an oil and gas project is 900mm and with a diameter of 300mm as mentioned by Standards Australia (1997).

Further, the sweep and extrude tool of the 3D modelling module of Civil 3D was used to carry out the 3D modelling. The pipe was swept using a 300mm circle, whereas the other infrastructures proposed ROW, pipeline ROW, road ROW, existing ROW, and existing road were extruded 900mm from their surface location which indicates that the underground pipeline is located 900mm above the surface infrastructure. Moreover, after completing the modelling, the rectification and proper colour were applied to enhance the visualisation.

To create the 3D model of the habitat area demonstrated on the design plan, the height of tree was measured 4m approximately on the 3D point clouds and modelling was carried out using the 3D objects available in the Civil 3D. The prepared 3D models of the infrastructure are demonstrated in Figure 5.16 with the associated colours. The same arrow colour has been positioned to represent the relevant 3D objects. View 1 in Figure 5.17 represents the front view of one of the sections of the eastern well pad that encompasses all the infrastructure and 3D habitat area. Similarly, View 2 and View 3 show turnout sections of the corridor and associated infrastructures. Finally, View 4 is the underground view of the corridor where the underground pipes are clearly demonstrated.

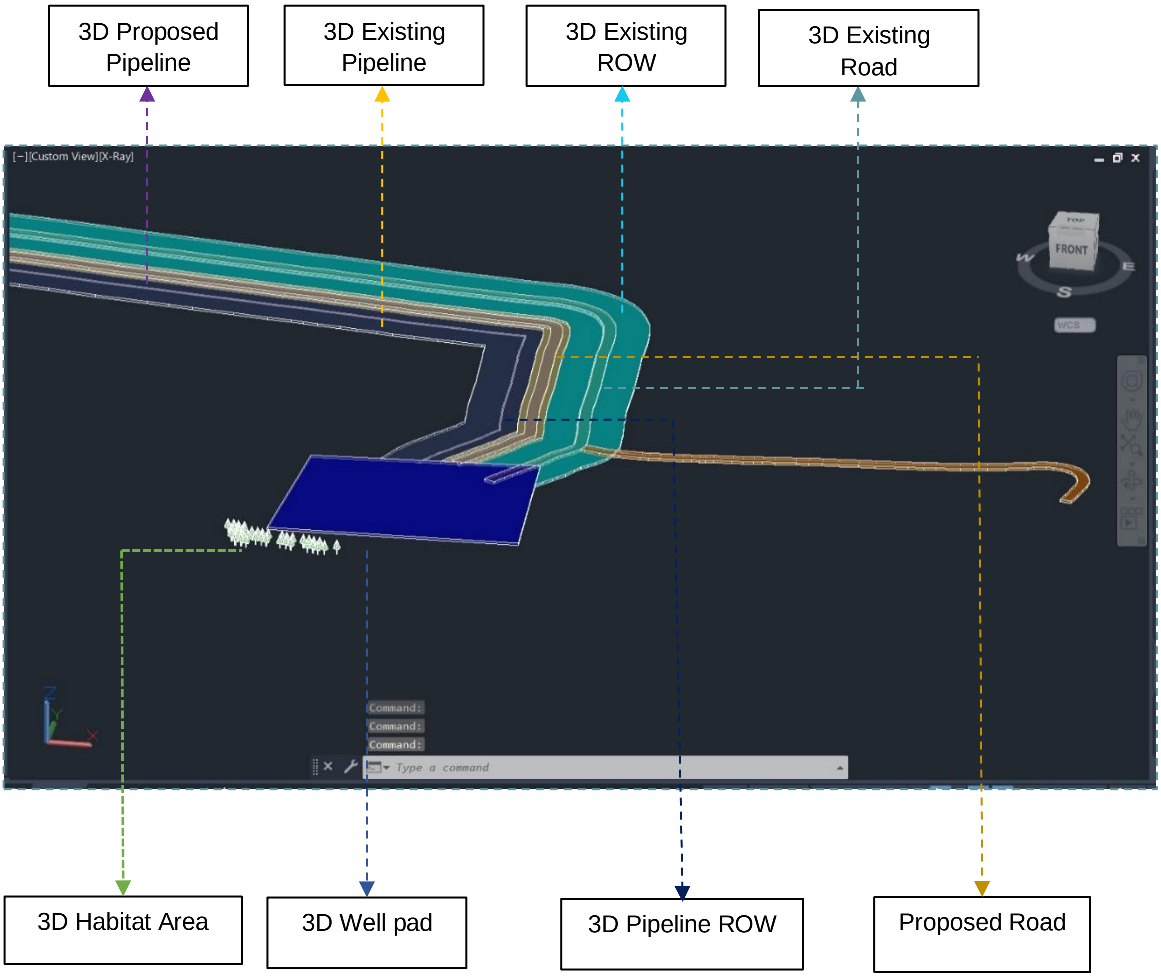



**Figure 5.16: 3D Model of Infrastructures**

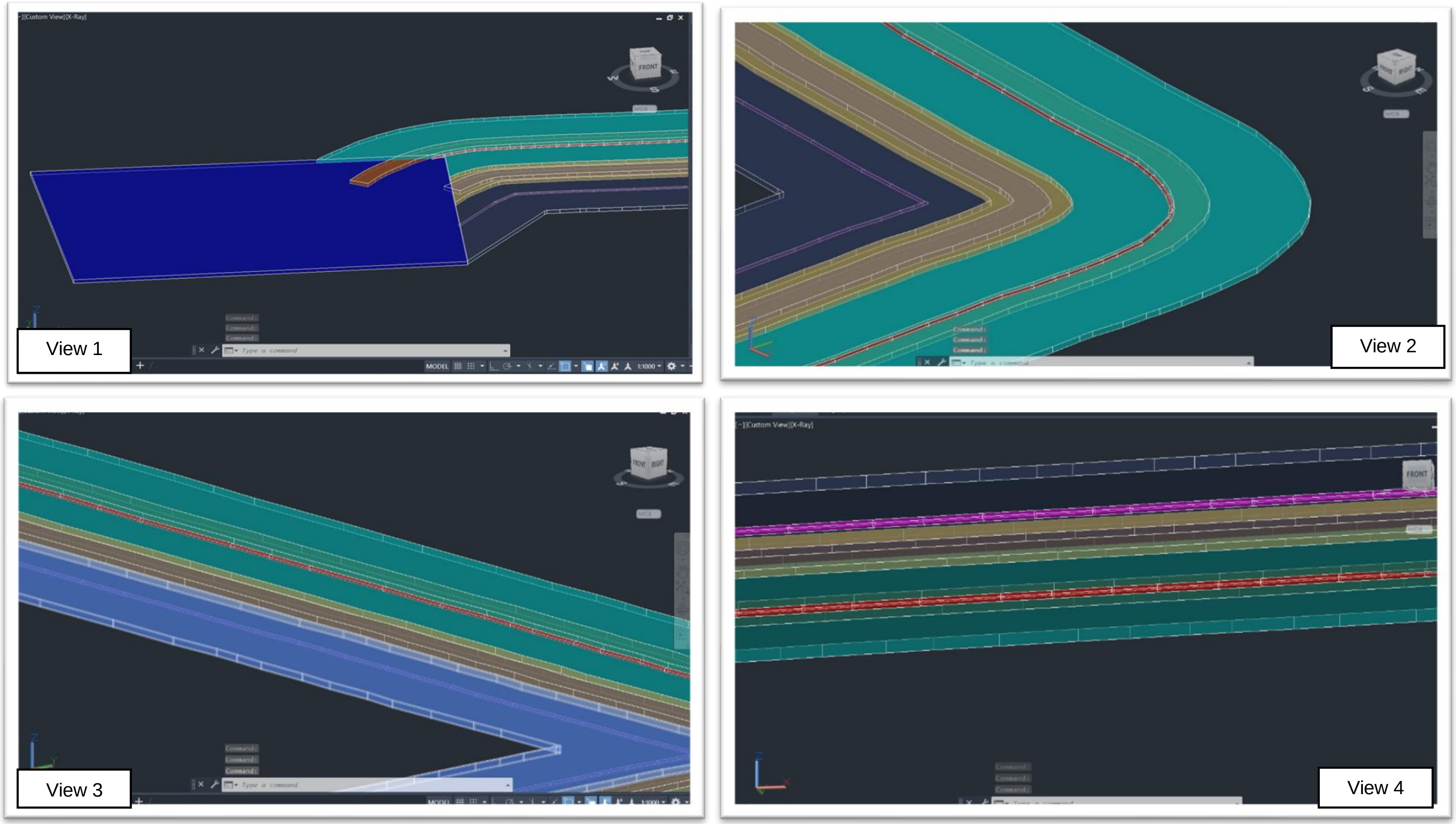



**Figure 5.17: Different Views of 3D Models**

## 5.6. Integrating LSDM Attributes

This was one of the crucial steps in this study. Accommodating LSDM-based attributes and visualising the 2D and 3D infrastructure designs was one of the major tasks in this study. Different alternatives were explored so that 3D geometry and their attributes could be easily stored on the developed prototype. In the context of the 2D design, it was not difficult because Civil 3D itself can export the 2D drawing to the shapefile (.shp) file format through which attributes can be easily incorporated using the GIS software. However, for the 3D objects different approaches were explored, and found that the 3D KML file can store the 3D object as well as attributes using the Navisworks. It is the Autodesk Inc. software designed to handle the CAD 3D models. Subsequently, the approach used to integrate the LSDM attributes into the 2D and 3D designs in this study is illustrated in Figure 5.18. Similarly, Figure 5.19 represents the uploaded model on the Navisworks. The excerpt of the scripted XML (.xml) file for the 3D Well Pad object is presented along with known values in Figure 5.20. All the attributes designed in Chapter Four were scripted using XML language syntax. After successfully preparing the necessary models and spatial information (2D spatial data and 3D spatial data) they were migrated into the developed prototype. The demonstration of the prototype is explained further.

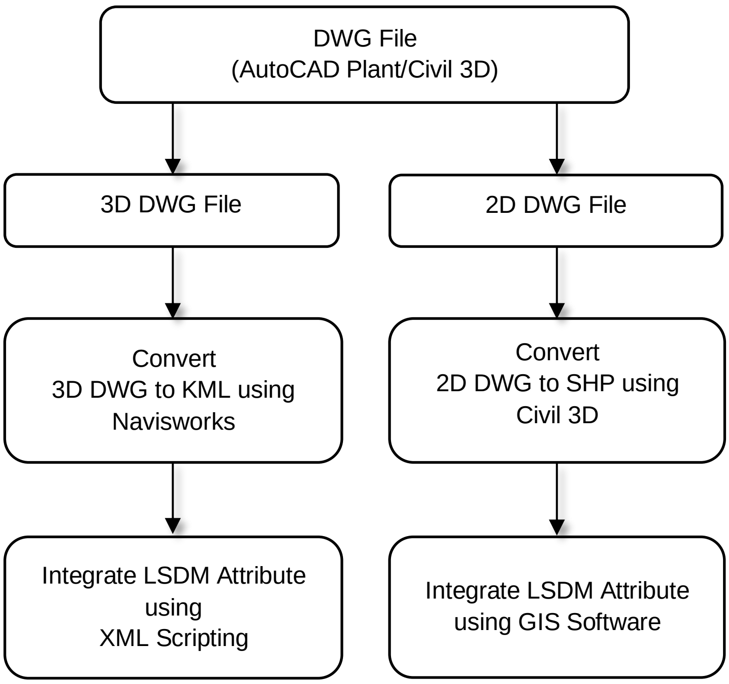



**Figure 5.18: Data Integration Approach**

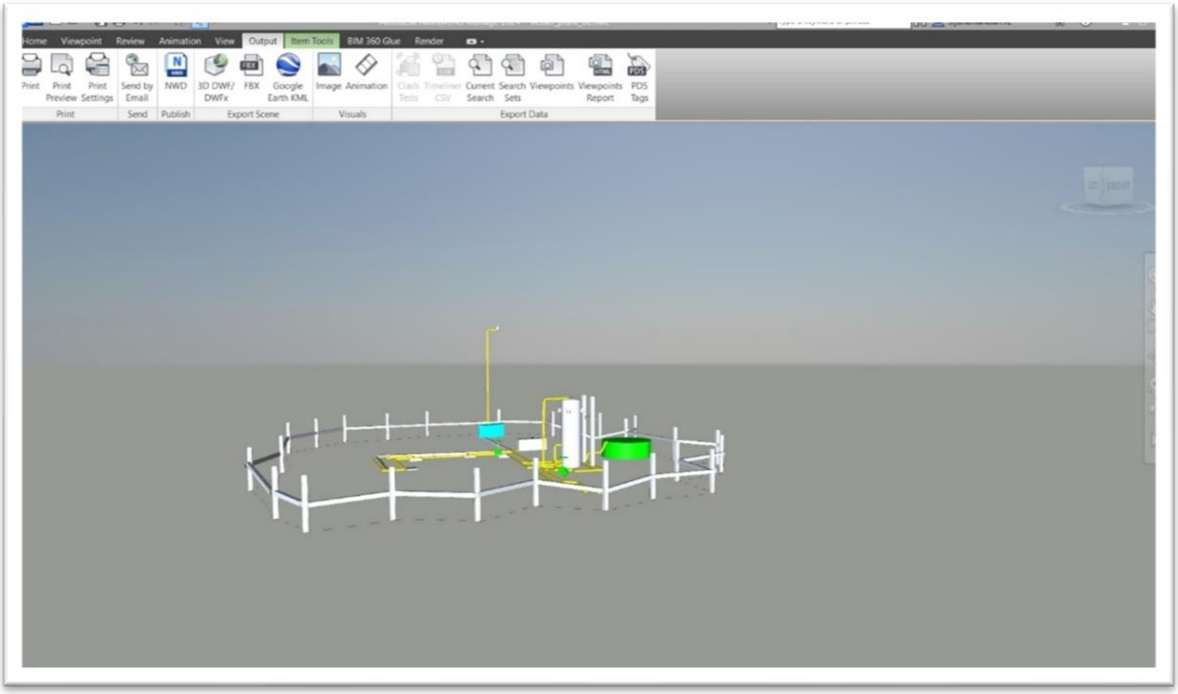



**Figure 5.19: 3D Model on Navisworks**

```
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    <PolyStyle>
      <color>FFFF0000</color>
    </PolyStyle>
  </Style>
   <ExtendedData>
    <Data name="properties">
        <value>
            <![CDATA[
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                SHAPE: 3D Object <br/>
                NAME: W2 <br/>
                PROPERTY: 2RP108045<br/>
                SOURCE: 3D Modeling<br/>
                AREA: 2331.97 <br/>
                CAD_LAYER: Proposed_Well_Pad <br/>
                STATUS: Proposed
            ]]>
        </value>
    </Data>
  </ExtendedData>
  <MultiGeometry>
    <MultiGeometry>
      <Polygon>
        <altitudeMode>relativeToGround</altitudeMode>
        <outerBoundaryIs>
          <LinearRing>
            <coordinates>150.482016940073,-26.8454890815024,0
54420523,-26.8448865844511,0
```

**Figure 5.20: 3D Well Pad XML Script**

### 5.7. Upload to Prototype

#### *5.7.1.* 3D Spatial Data

Firstly, the infrastructure was uploaded as these were in the 3D model format. The results obtained after migrating all the 3D models to the prototype are explained below.

- **Facilities**

The facilities data was prepared in .kml file format and uploaded through the KML data type using the data uploading function of the prototype. The outputs are depicted in Figure 5.21. The facilities were successfully visualised and their relevant LSDM attributes were successfully displayed on the prototype.

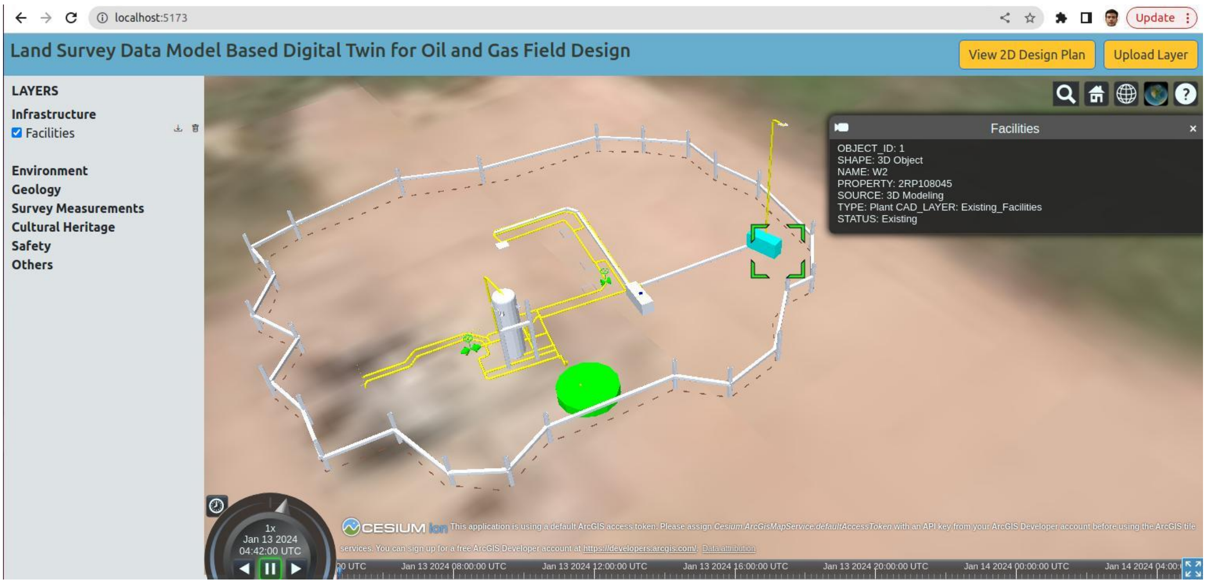



**Figure 5.21: 3D Demonstration of 3D Facilities**

- **ROW**

The data for the ROW was also in .kml file format and was successfully uploaded via the KML data type using the data uploading function within the prototype. The visualisation of the ROW is presented in Figure 5.22, the 3D ROW was effectively visualised, and the corresponding LSDM attributes were successfully displayed in the prototype.

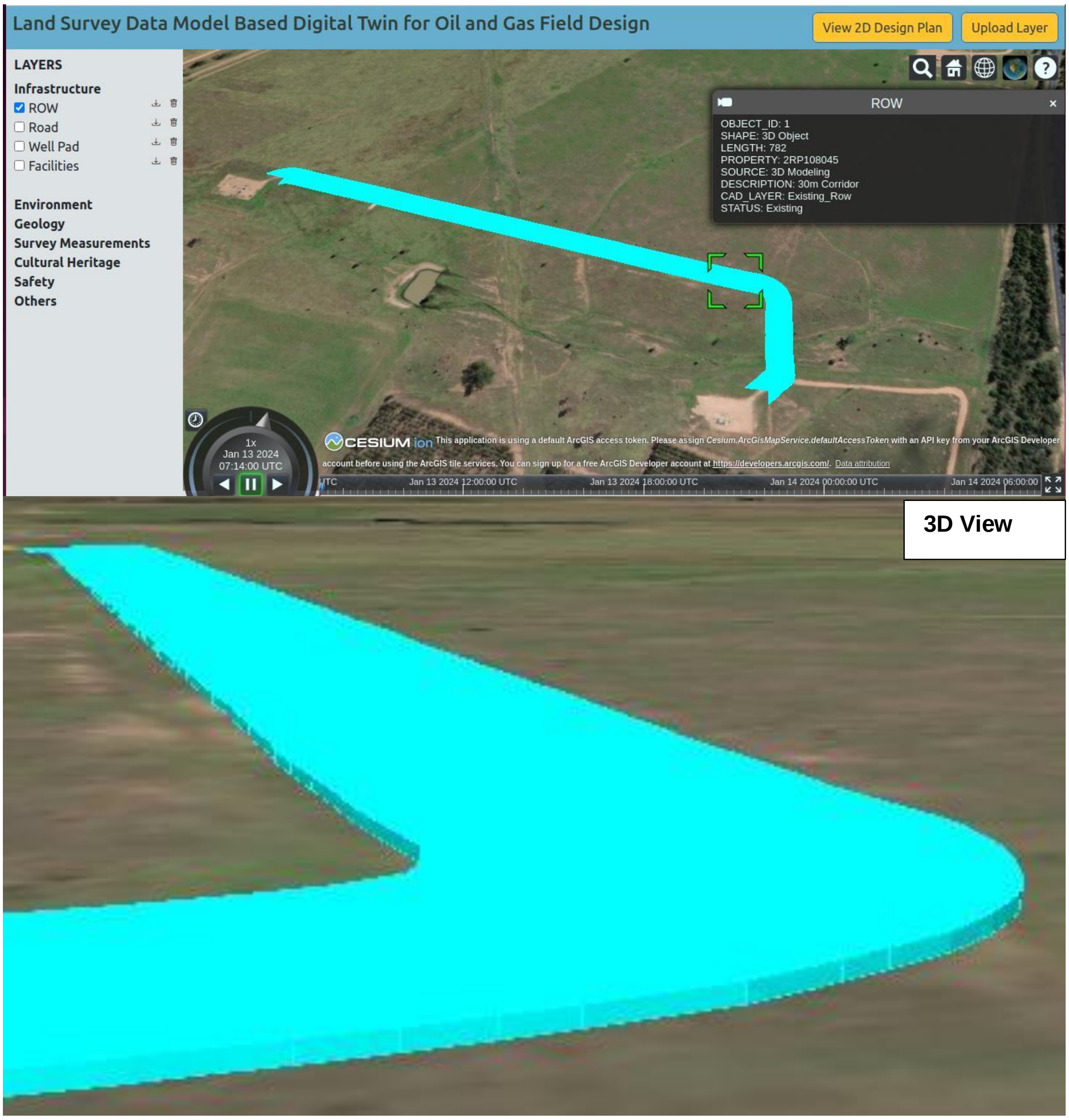



**Figure 5.22: Demonstration of 3D ROW**

- **Road**

The data for the 3D road was also in .kml file format and was successfully uploaded via the KML data type using the data uploading function within the prototype. As depicted in Figure 5.23, the 3D road was effectively visualised, and the corresponding LSDM attributes were successfully displayed in the prototype.

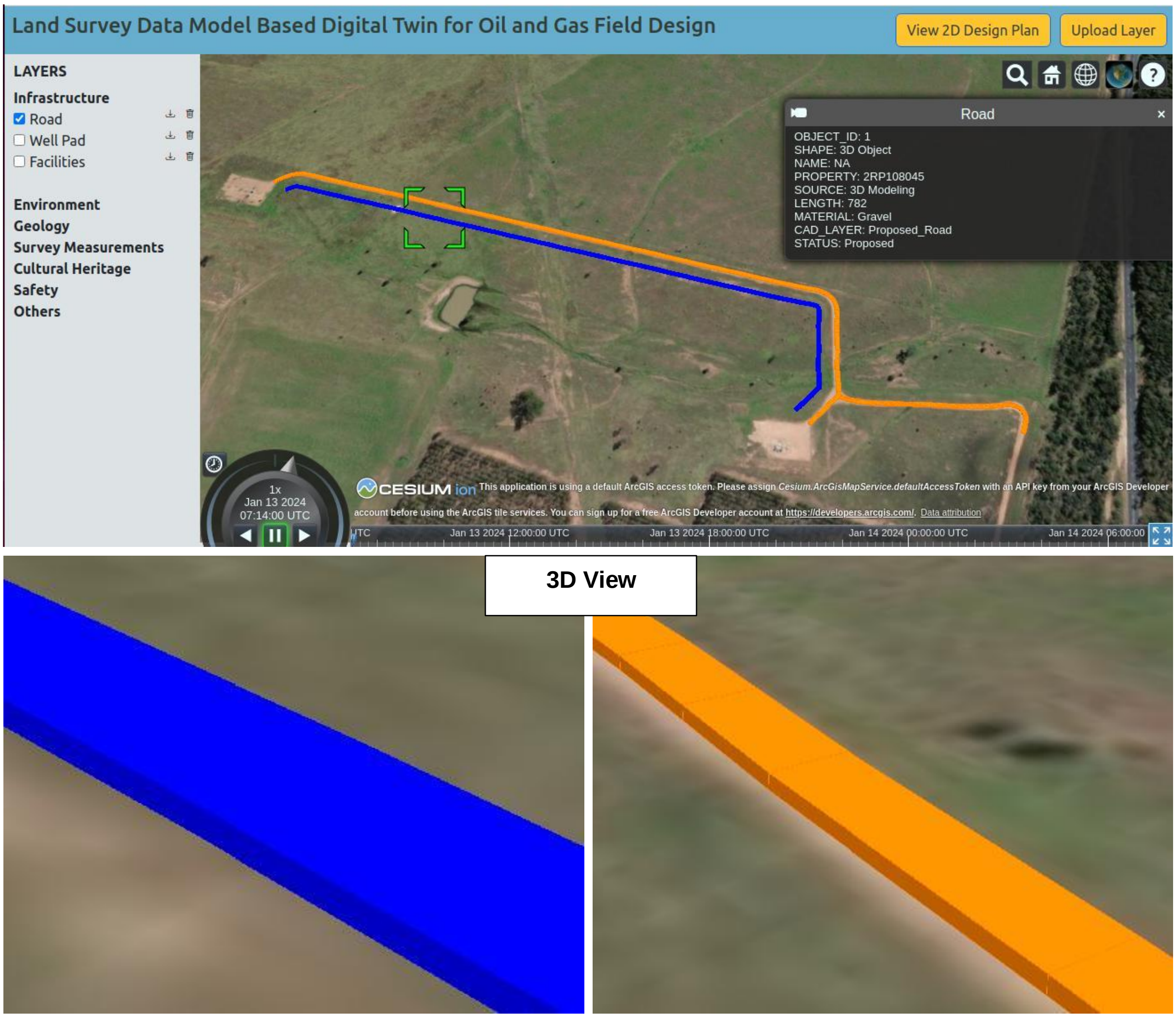



**Figure 5.23: Demonstration of 3D Road**

- **Pipeline**

The pipeline data was also in .kml file format and was effectively uploaded through the KML data type, utilising the data uploading function in the prototype. The visualisation of the pipelines is illustrated in Figure 5.24. The 3D pipeline was successfully visualised, and the relevant LSDM attributes were accurately displayed in the prototype. The pink represents the proposed pipe whereas the orange represents the existing pipe.

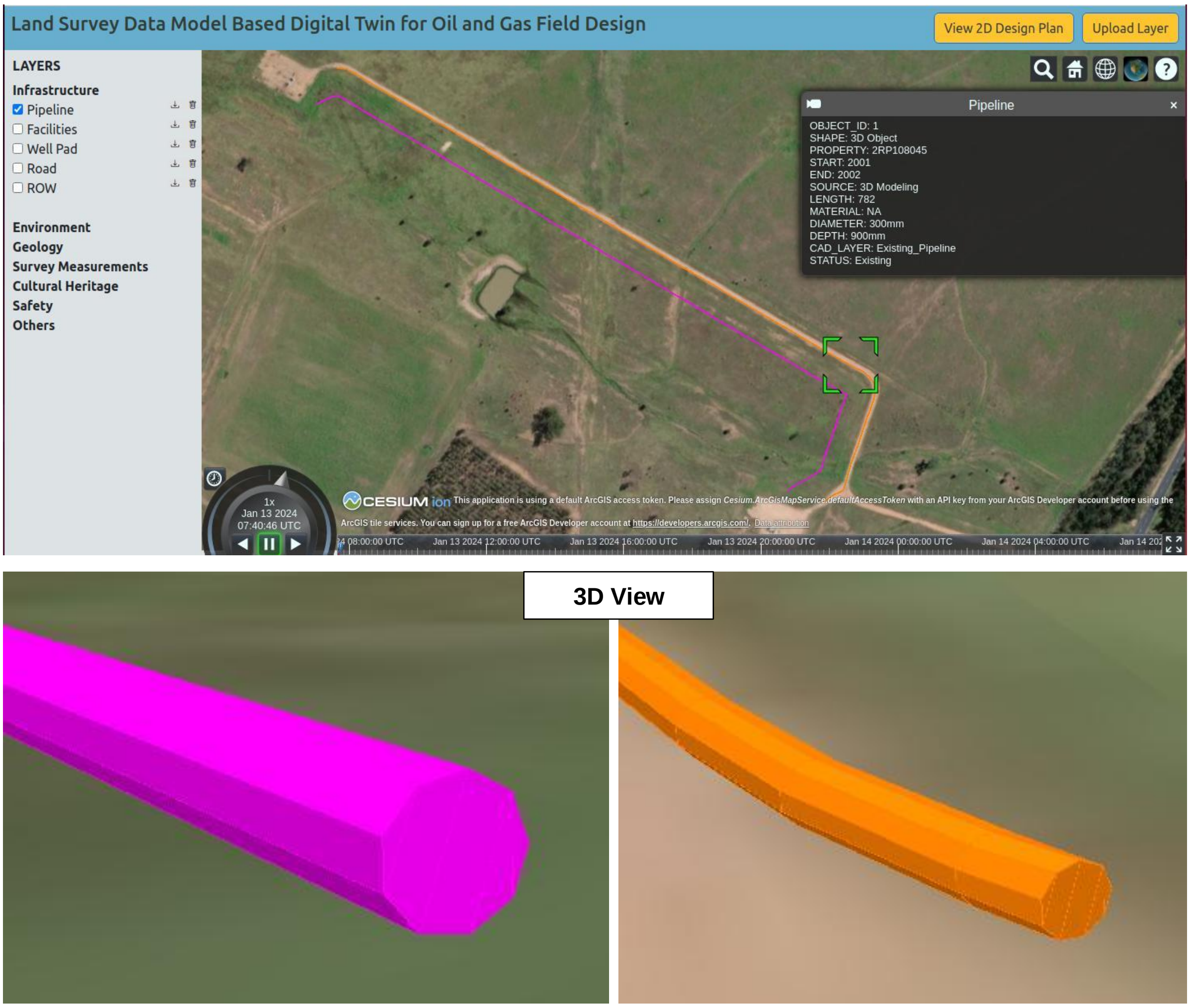



**Figure 5.24: Demonstration of 3D Pipelines**

- **Well Pad**

The well pad data was also in .kml file format and was effectively uploaded through the KML data type, utilising the data uploading function in the prototype. The visualisation of the well pad is shown in Figure 5.25. The 3D well pads were successfully visualised, and the relevant LSDM attributes were accurately displayed in the prototype.

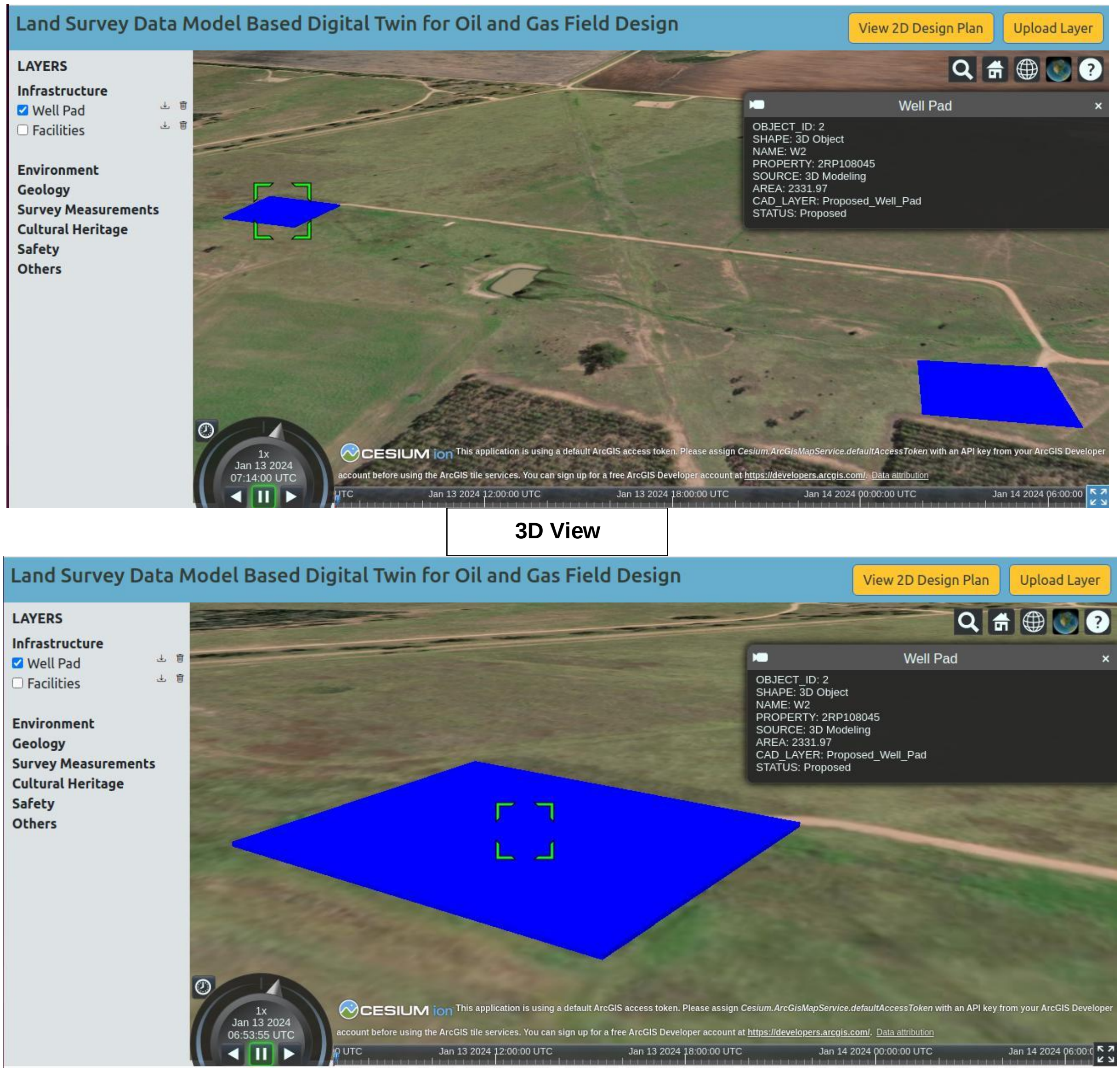



**Figure 5.25: Demonstration of 3D Well Pads**

- **Habitat Area**

The habitat area was also in .kml file format and was effectively uploaded through the KML data type, utilising the data uploading function in the prototype. The visualisation of the habitat area is illustrated in Figure 5.26. The 3D habitat area was successfully visualised, and the relevant LSDM attributes were accurately displayed in the prototype.

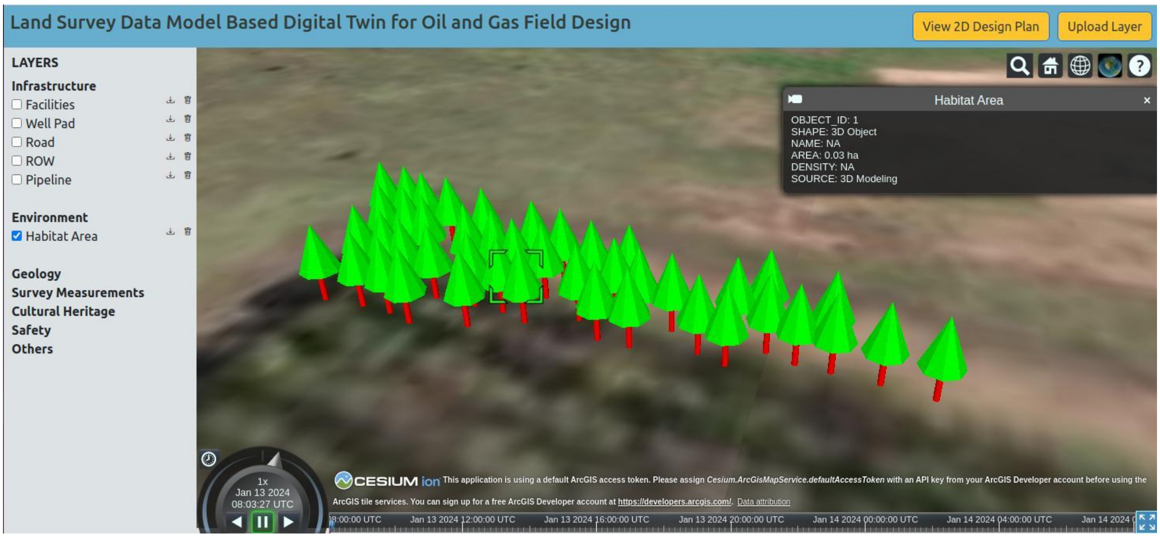



**Figure 5.26: Demonstration of Habitat Area**

- **3D Point Clouds**

The point cloud was in the .las file format when uploaded on the Caesium ion. The Asset ID (2330619) of the cesium database was given and the 3D point clouds were successfully stored and visualised into the survey measurement class on the prototype as depicted in Figure 5.27.

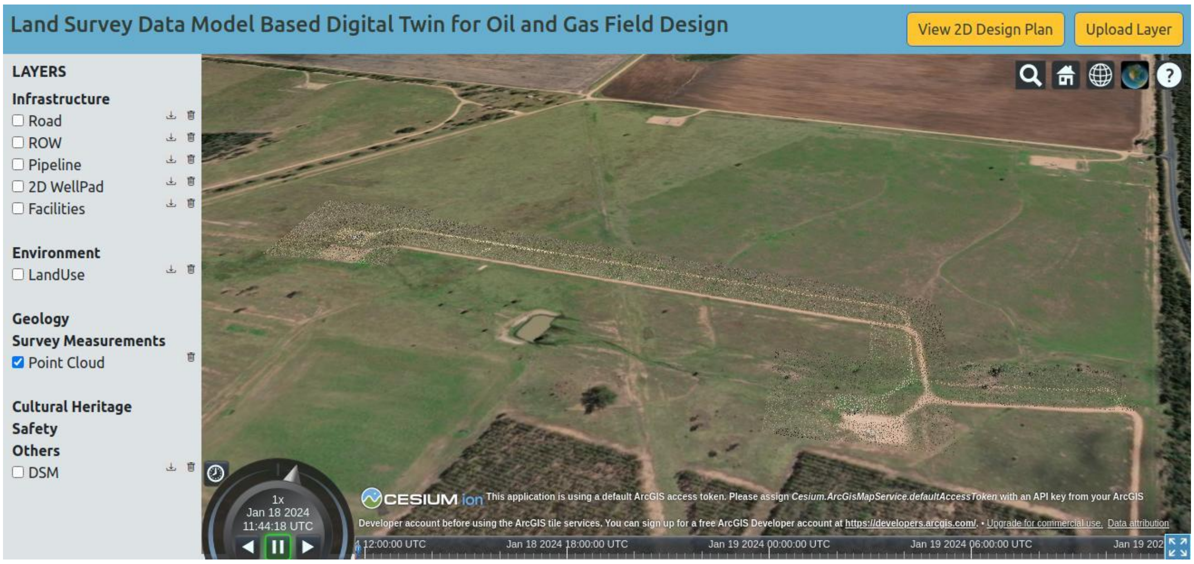



**Figure 5.27: 3D Model from UAV Survey**

- **Digital Surface Model**

The Digital Surface Model (DSM) generated from the UAV survey was on the .tif and was effectively uploaded through the raster data type, utilising the data uploading function in the prototype. The visualisation of the DSM is illustrated in Figure 5.28. This was stored and displayed as other layer category.

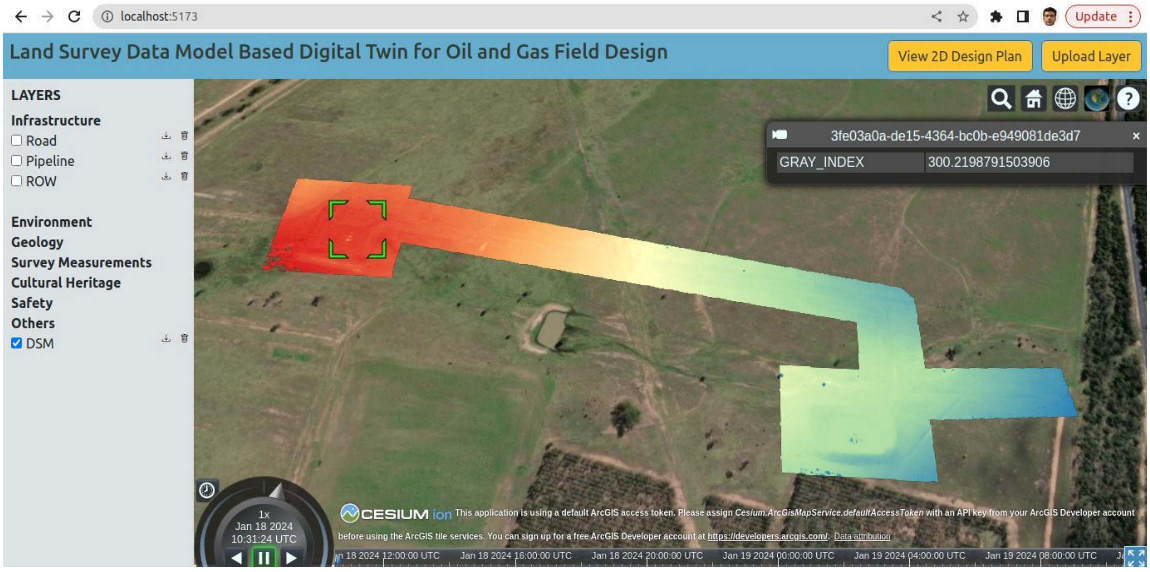



**Figure 5.28: 3D Digital Surface Model**

## *5.7.2.* 2D Spatial Data

- **Well Pad**

The 2D well pad area was in .shp file format and was effectively uploaded through the vector data type, utilising the data uploading function in the prototype. The visualisation of the 2D well pad is illustrated in Figure 5.29. In addition to this, the 3D facility plant was also overlayed on the 2D well pad.

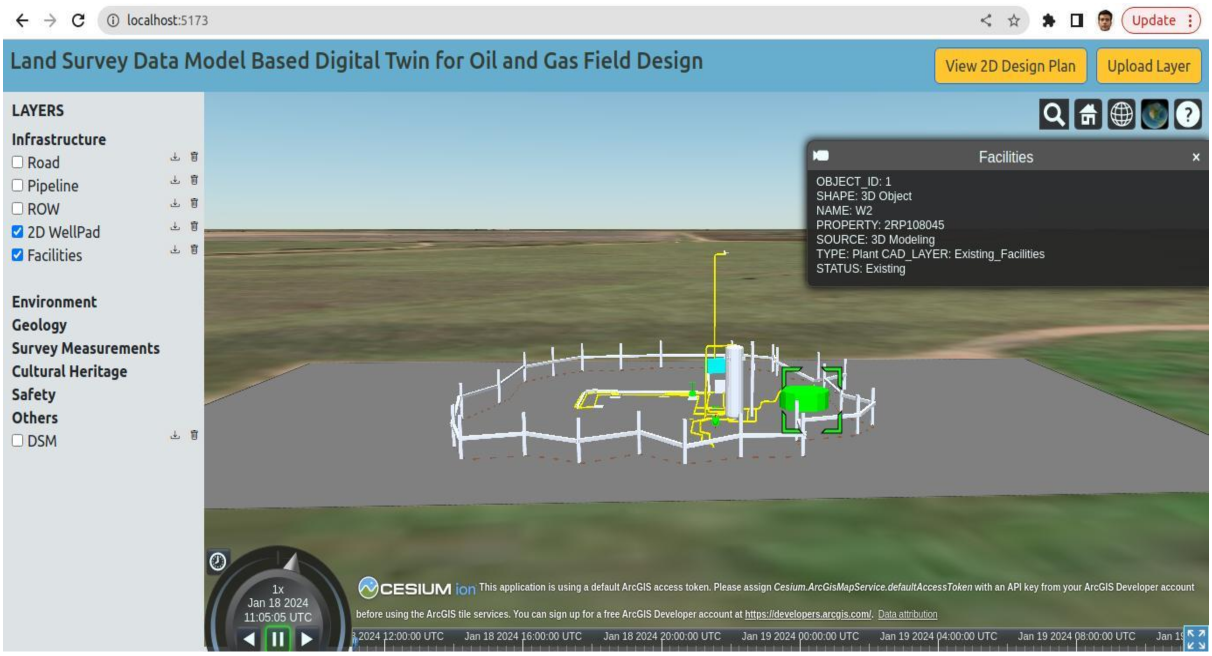



**Figure 5.29: 2D Well Pad**

- **Pipeline**

The 2D pipeline area was also in .shp file format and was effectively uploaded through the vector data type, utilising the data uploading function in the prototype. The visualisation of the 2D pipeline is illustrated in Figure 5.30.

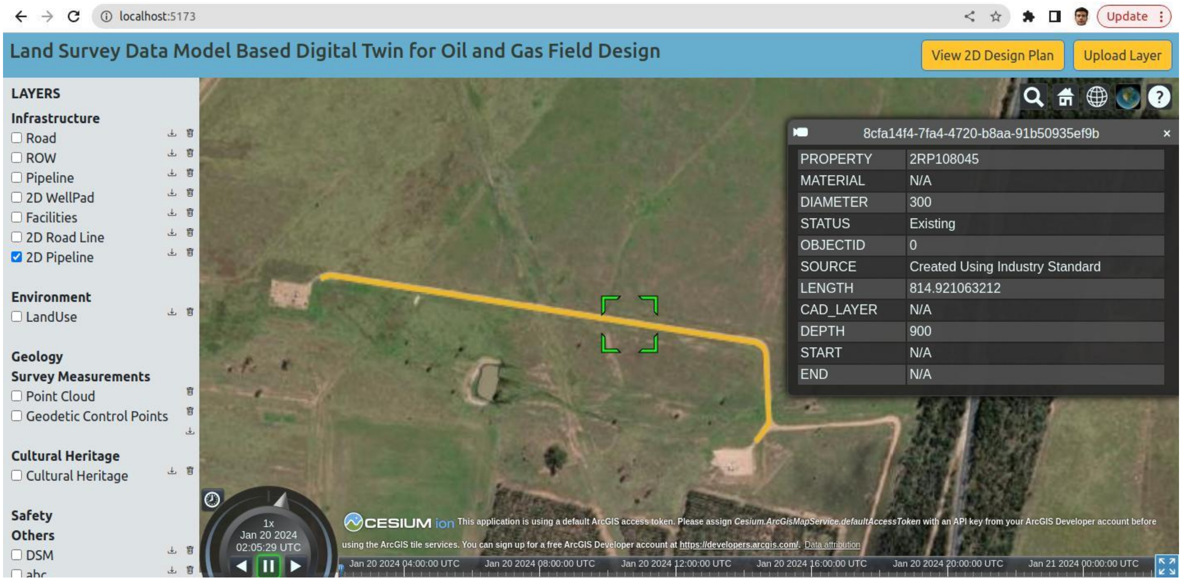



**Figure 5.30: 2D Pipeline**

- **Geodetic Control Points**

The GCPs in .shp format and were effectively uploaded through the vector data type, utilising the data uploading function in the prototype. The visualisation of the geodetic control points is illustrated in Figure 5.31.


**Figure 5.31: Geodetic Control Points**

- **Habitat Area**

The habitat area which was in .shp file format was effectively uploaded through the vector data type, utilising the data uploading function in the prototype. The visualisation of the geodetic control points is illustrated in Figure 5.32.


**Figure 5.32: 2D Habitat Area**

- **Land Use**

The land use category acquired from the Qspatial portal of Department of Resources, Queensland Government was also in .shp file format and was effectively uploaded through the vector data type, utilising the data uploading function in the prototype. The visualisation of land use type of study area is illustrated in Figure 5.33.

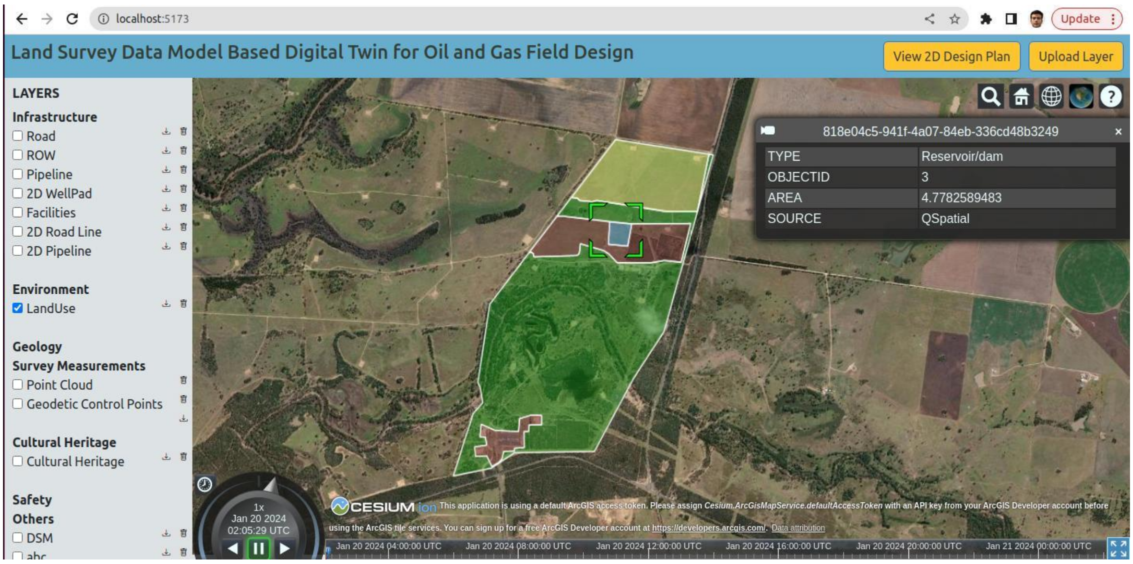



**Figure 5.33: 2D Land Use**

- **Seismic Line**

The seismic line within the case study area accessed through the Qspatial portal, Department of Resources, Queensland Government was in .shp file format and was effectively uploaded through the vector data type, utilising the data uploading function in the prototype. The visualisation of the seismic line is illustrated in Figure 5.34.

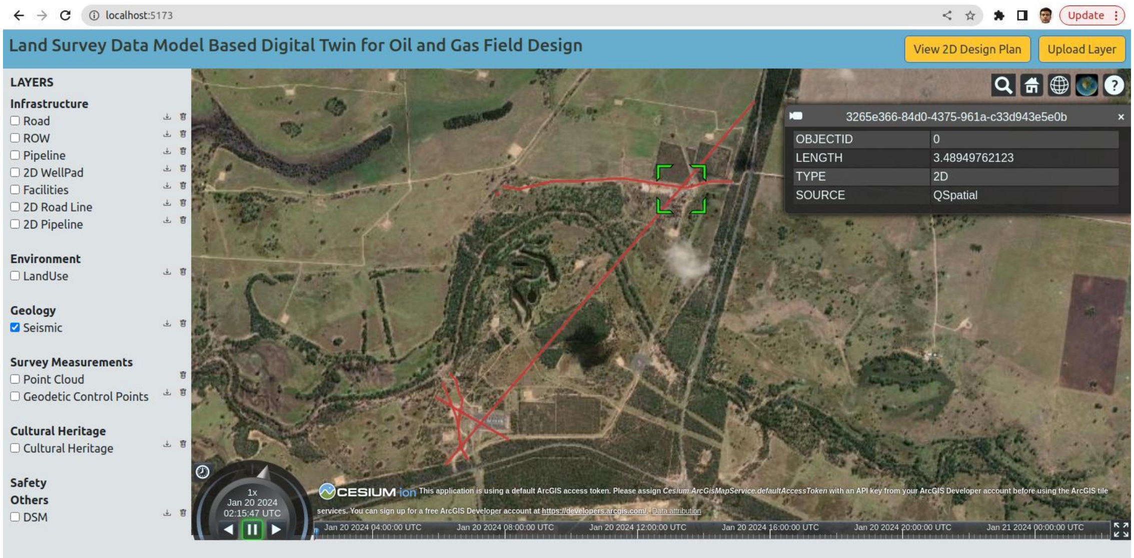



**Figure 5.34: Seismic Lines**

- **Cultural Heritage**

The cultural heritage polygon within the case study area acquired from the QGlobe was in .shp file format and was effectively uploaded through the vector data type, utilising the data uploading function in the prototype. The visualisation of cultural heritage polygon is illustrated in Figure 5.35.

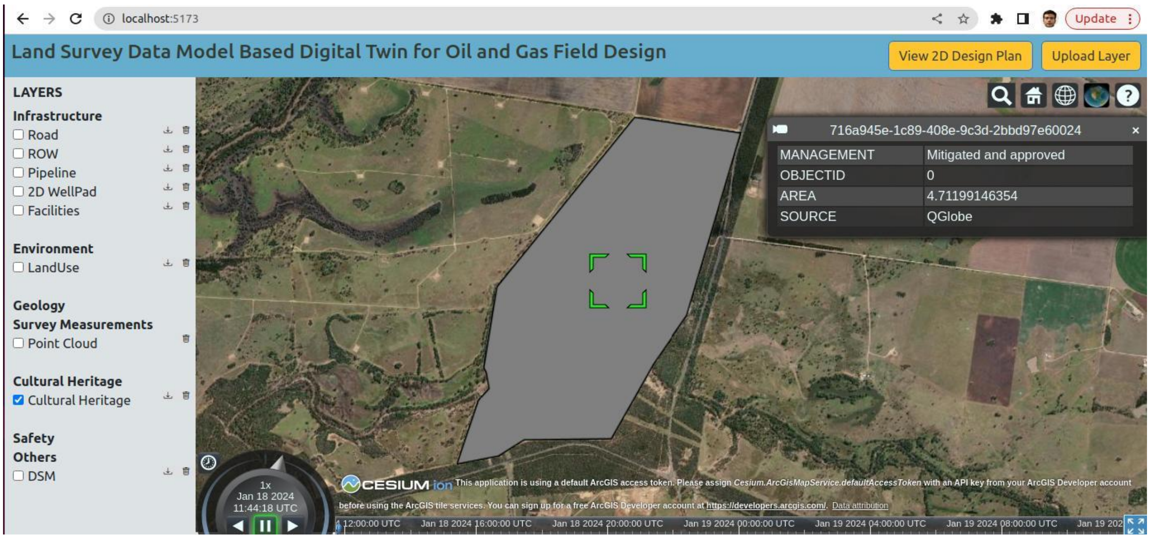



**Figure 5.35: Cultural Heritage Polygon**

- **2D Detailed Engineering Plan**

One of the functionalities of the prototype was the demonstration of existing 2D design plan. The 2D plan was successfully accessed which was saved on the database of the prototype as illustrated in Figure 5.36.

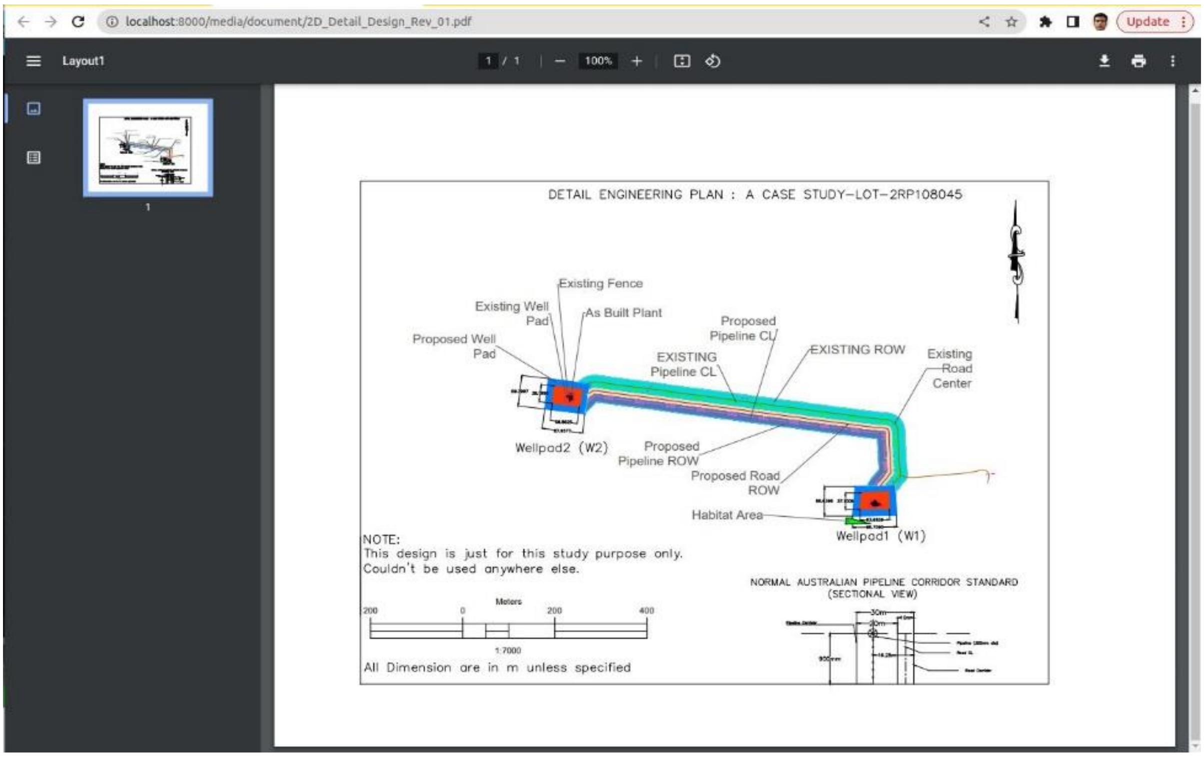



**Figure 5.36: View 2D Plan**

## 5.8. Prototype Evaluation

As discussed in Chapter Three, the prototype evaluation approach was selected as an artificial strategy with the informed argument method within the design science framework. This study has assessed the developed prototype with the parameters of ISO/IEC 25010 as illustrated in Figure 5.37. The assessment parameters encompass functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, and portability.

### *5.8.1.* Functional Suitability


**Figure 5.37: ISO/IEC 25010 Model (ISO, 2022)**

- **Explanation**

This parameter is defined by three key criteria: functional completeness, correctness, and appropriateness (Abu Bakar et al., 2022). Functional completeness evaluates the extent to which a system includes all necessary functions to meet defined objectives comprehensively (Ali et al., 2022). Similarly, functional correctness ensures that the system generates accurate outcomes aligned with expected results. Further, functional appropriateness assesses how well these functions support users in achieving specific objectives, considering usability and efficiency in task accomplishment (Echeverria et al., 2021). Together, they ensure a system that not only encompasses required functions but also delivers accurate results and effectively aids users in reaching their goals.

- **Evaluation**

The major aim of prototype development was to store the 3D spatial data of the infrastructure design in a virtual 3D environment for enhancing visualisation along with storing the associated spatial information based on the LSDM. The developed prototype was successfully capable of performing this task as demonstrated in Section 5.7. The LSDM-based attributes of the associated 3D spatial data of the infrastructure design were successfully populated while clicking on the 3D object. In addition to this, associated 2D spatial information involved in the field design was also successfully stored and visualised based on LDSM attributes as well.

- **Reflection**

The above discussion indicates prototype has accomplished functional completeness, functional correctness, and functional appropriateness within the scope of the study.

### *5.8.2.* Performance Efficiency

- **Explanation**

This parameter is defined through three key criteria that include time performance, resource utilisation, and capacity (Keibach & Shayesteh, 2022). Time performance measures how well a system meets requirements in terms of response time, processing speed, and throughput rates while executing its functions (Al-Mohamadsaleh & Alzahrani, 2023). Similarly, resource utilisation evaluates how effectively a system utilises various resources in quantity and type while carrying out its functions to meet specified requirements (Kato & Ishikawa, 2024). Finally, capacity assesses how well the system meets stipulated requirements concerning its maximum thresholds or limits for specific parameters.

- **Evaluation**

To evaluate the performance efficiency, the developed prototype was compared with a similar existing DT platform (Digital Twin Victoria) developed in the context of Australia. The comparison was done based on the three criteria (time, resource utilisation, and capacity) outlined in the above explanation section.

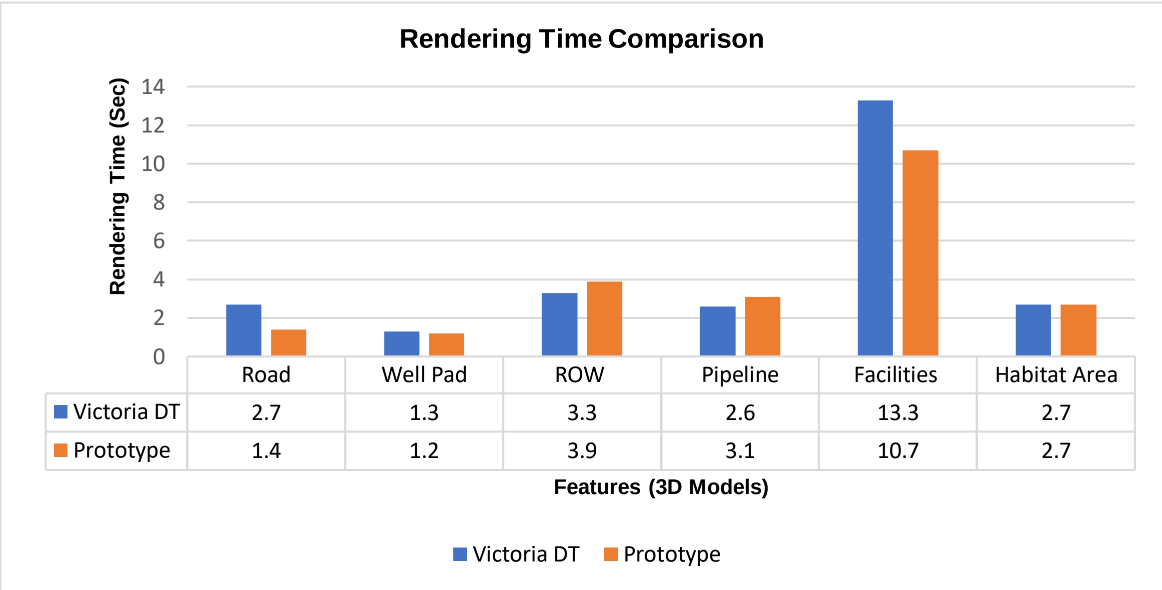
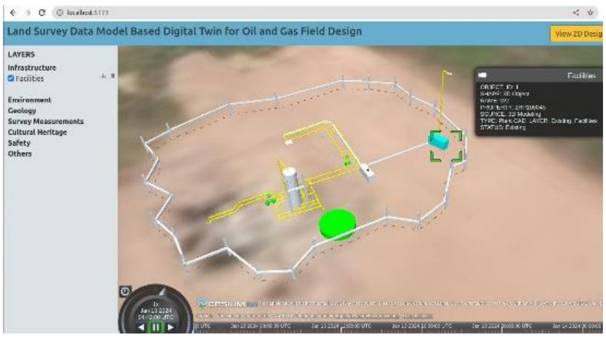
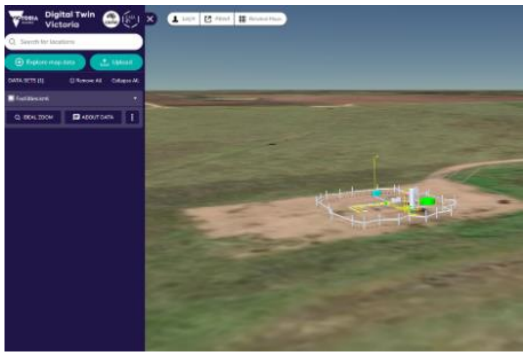



**Figure 5.38: Rendering Time Comparison**

To compare time, an experiment was done on the computer. In an experiment, tasks (uploading 3D objects of the case study) and their rendering time were recorded in seconds which depends upon response time, processing speed, and throughput raters. In the rendering time, how long each system took to render and visualise each 3D object was specifically measured. The specifications of the computer where an experiment was carried out was a Dell Intel i7-10700 CPU with 16GB RAM and, a 64-bit operating system with Windows 10. The stopwatch app available on Google Pix6a phone was used to record the rendering time. The experiment result obtained is illustrated in Figure 5.38.

The above bar chart represents data regarding the rendering times of various 3D objects on two systems: the Digital Twin Victoria (DTV) and the prototype. The DTV is an initiative by the State Government of Victoria that brings together masses of 2D and 3D and live data in a single platform and empowers government, industry, research groups, and the community to compare, analyse, and share information about the built and natural environment (Victoria Government, 2023). Notably, the most complex 3D object in the provided Figure 5.38 is facilities, which took 10.7 seconds to render in the developed prototype, whereas the Victoria DT platform took 13.3 seconds. This approximately 3-second discrepancy may be attributed to the vast amount of data within the Victoria DT platform, covering areas from administration to the built environment to transportation. Similarly, other smaller 3D objects, such as roads, well pads, ROW, and pipelines, showed rendering time discrepancies within an approximate 1-second difference. This slight variation could be due to different internet bandwidths while uploading the 3D models at different times. Furthermore, one of the complex data (facilities) was successfully uploaded to the DTV as shown in Table 5.5. Therefore, it can be stated that the developed prototype is capable of rendering 3D objects within a reasonable amount of time.

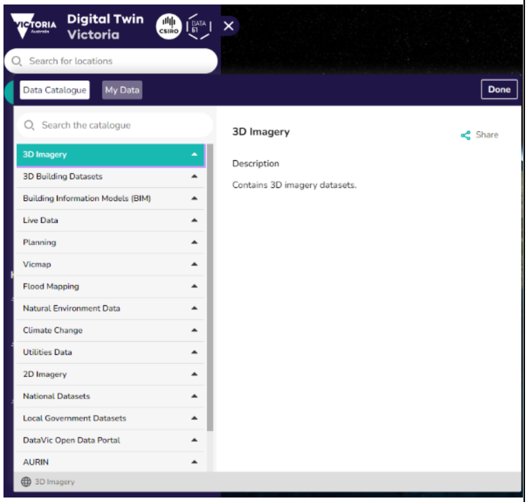
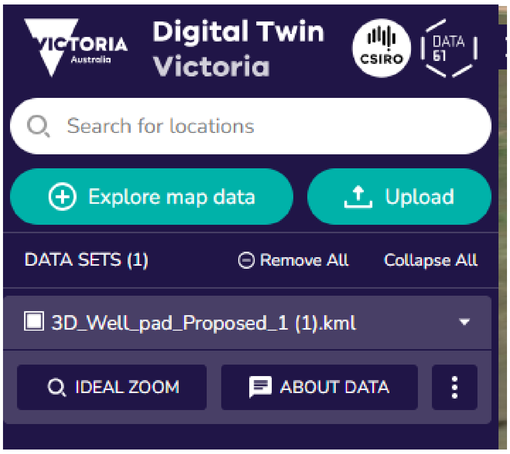
**Table 5.5: Facilities in Prototype & DT Victoria**

| Prototype | DT Victoria |
|---|---|
|  |  |

The resources (libraries) utilised in the prototype are free and open-source libraries such as Geoserver, Cesium Ion (free subscription), and PostgreSQL for visualisation and populating the LSDM attributes. On the other hand, the Victoria DT core components are also built using free and open-source libraries.

In terms of capacity, the prototype can visualise the 3D objects and associated spatial information involved in field design based on LSDM attributes for specific O & G projects. This is significantly important. However, the DTV is more focused on the built environment and the public sector. Currently, prototype has a maximum of 5GB storage to hold the datasets through Cesium Ion free subscription. DTV can manage various themes of data in the context of the built environment ranging from cadastre, land administration, transportation, railways, etc as illustrated in Table 5.6. The reason for this is, DTV is based on Cesium Ion (Commercial license). The prototype has the unique functionality of downloading the uploaded 3D object which is not available in DTV as illustrated in Table 5.6.

**Table 5.6: Capacity of Prototype**

| **Prototype** | **Victoria DT** |
|---|---|
|  |  |
|  |  |

- **Reflection**

The preceding assessment indicates that the prototype performs well in terms of rendering time, resource utilisation, and capacity within the scope of the study.

### *5.8.3.* Compatibility

- **Explanation**

Compatibility is explained as the extent to which a system is capable of both sharing information with other systems and executing its intended functions within a common hardware or software environment (ISO, 2022). This attribute consists of the two key underlying criteria that include co-existence and interoperability (Kato & Ishikawa, 2024). Co-existence refers to the level at which a system maintains efficient functionality while sharing resources and an environment with other systems without causing any negative impact on those other systems (Galli et al., 2021). Interoperability, on the other hand, signifies the extent to which multiple systems can effectively exchange information and utilise the exchanged information for their respective purposes (Abu Bakar et al., 2022).

- **Evaluation**

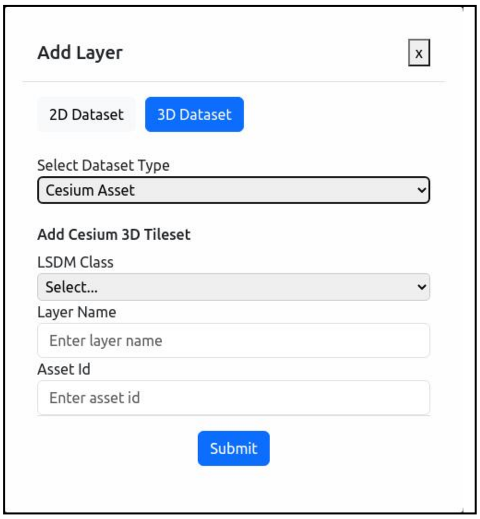
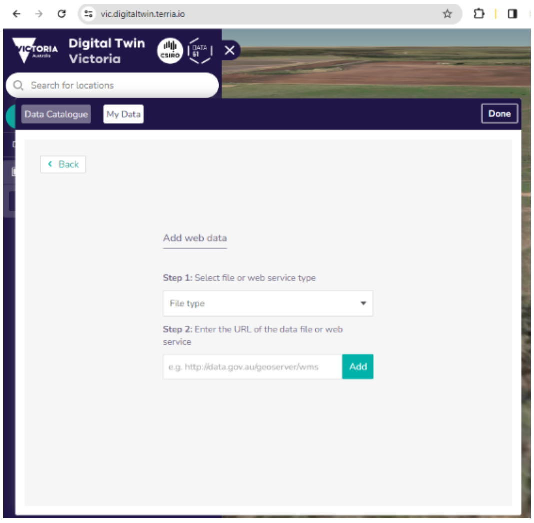
To evaluate the compatibility, the developed prototype was again compared with the Digital Twin Victoria (DTV). The comparison was done based on two criteria that encompass co-existence and interoperability.

The Victoria DT can access and visualise the datasets from other sources if the URL is given, whereas the prototype can store the datasets on Cesium Ion through Asset ID as presented in Table 5.7. In the context of interoperability, the prototype and Victoria DT accessed all types of 3D data formats to store the 3D objects that are accepted by the Cesium Ion.

- **Reflection**

The above assessment signifies the prototype is compatible while assessing with Victoria DT.

**Table 5.7: Co-existence of Prototype**

| Prototype | Victoria DT |
|---|---|
|  |  |

### *5.8.4.* Usability

- **Explanation**

The extent to which a system, within a specified context of use, enables specified users to achieve predefined goals with effectiveness, efficiency, and satisfaction (Fahmy et al., 2012). This parameter comprises criteria which are appropriateness, learnability, operability, user error protection, user interface aesthetics, and accessibility (Keibach & Shayesteh, 2022). The definitions of each criterion are illustrated in Table 5.8.

- **Evaluation**

To evaluate the usability, the prototype was assessed against the six criteria outlined above. Firstly, it could be certainly stated that the prototype is appropriate for the field design process of the O & G project and developed focusing on specific industry-standard LSDM. Therefore, the prototype is appropriate (Ap) and learnability (L). Secondly, the prototype only contains the datasets that are specifically relevant to the O & G project. For instance, DTV entails a large set of the built environment, cadastre, and urban planning datasets which might not be useful for the field design process. Therefore, the prototype is simple to operate (O) in the context of the O & G project. Following this, the user interface aesthetics (UIA) of the prototype is decent. It contains 3D zoom-in/zoom-out functionalities, 3D format selection, and an LSDM class section.

Further, Accessibility (Ac) can be easily enhanced by hosting it on a cloud/web server. User error protection (UE) is not in the scope of the evaluation because this parameter is not assessed in the beta version (prototype).

**Table 5.8: Usability Definition**

| **Criteria** | **Definition** |
|---|---|
| **Source: ISO/IEC 25010** | |
| Appropriateness (Ap) | The extent to which users can determine if a system aligns with their requirements and is suitable for fulfilling their needs. |
| Learnability (L) | The extent to which specified users can achieve their intended goals of learning to use a system effectively, efficiently, safely, and with satisfaction within a specific context of use. |
| Operability (O) | The extent to which a system possesses characteristics that facilitate its ease of use and management. |
| User error protection (UE) | The level at which a system safeguards users from making mistakes or errors. |
| User interface aesthetics (UIA) | The extent to which a user interface allows for enjoyable and satisfying interaction from the user. |
| Accessibility (Ac) | The level to which a system can be utilised by individuals with diverse characteristics and abilities to accomplish a defined objective within a specific context of use. |

- **Reflection**

The above assessment signifies prototype is usable for the field design process in the oil and gas project.

### *5.8.5.* Reliability

- **Explanation**

The extent to which a system fulfils specific functions within predefined conditions and over a specified duration is referred to as its reliability (ISO, 2022). This parameter can be assessed by maturity, availability, fault tolerance, and recoverability (Ali et al., 2022). The level to which a system satisfies reliability requirements during regular operation is defined as maturity. Similarly, availability can be defined as the extent to which a system is available and accessible as needed for its intended use (Galli et al., 2021). The degree to which a system continues to function according to its intended design despite the existence of hardware or software faults is termed fault tolerance (Echeverria et al., 2021). Further, the level at which a system when facing an interruption or failure, can retrieve the affected data and restore the system to its desired state is known as recoverability (ISO, 2022).

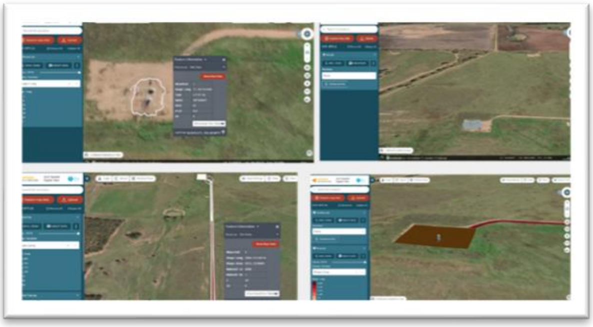
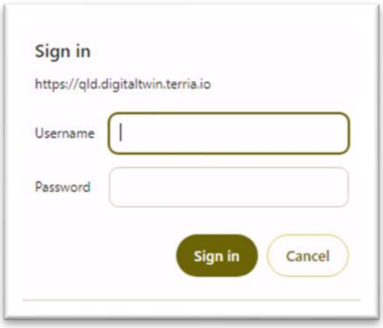
- **Evaluation**

To evaluate the reliability of the prototype, it was again compared with the Digital Twin Victoria (DTV) using the criteria that include maturity, availability, fault tolerance, and recoverability. In terms of maturity, the prototype is mature within the scope of the study. However, DTV is better in terms of maturity as it is developed through government-funded project and encompasses various functionalities such as georeferencing capabilities, access control, etc. Perhaps, the prototype can perform the specific required functions (visualisation of the 3D object based on LSDM). In terms of availability, the Victoria models might not be very reliable in the future and it is not open to the public. For instance, there was a similar DT platform (QLD DT) which is no longer accessible to public users as illustrated in Table 5.9. It is uncertain that how long these government-funded projects are accessible to the public. On the other hand, the prototype can not be accessed against the availability as it is limited to the local server. In terms of fault tolerance and recoverability, the existing DTV has a data backup system in case of system faults/system crashes. The prototype is also capable of backing up the datasets in the localhost.

- **Reflection**

The above assessment implies the prototype is reliable within the scope of the study because it can perform the core field design functionalities based on LSDM.

**Table 5.9: QLD DT Accessibility**

<table>
<tr><th>Before Accessible</th><th>After Inaccessible</th></tr>
<tr><td></td><td>
</td></tr>
</table>

### *5.8.6.* Security

- **Explanation**

This parameter signifies the extent to which a system safeguards information and data, ensuring appropriate access levels based on authorisation types and levels (ISO, 2022). The parameter needs to be assessed through confidentiality, integrity, non-repudiation, accountability, and authenticity.

**Integrity:** The level at which a system prevents unauthorised access to or alteration of computer programs or data (Kato & Ishikawa, 2024).

**Nonrepudiation:** The degree to which actions or events can be reliably proven to have occurred, eliminating the possibility of later denial (Ali et al., 2022).

**Accountability:** The level at which the actions of an entity can be distinctly traced back to that specific entity (ISO, 2022).

**Authenticity:** The extent to which the claimed identity of a subject or resource can be convincingly verified or proven (Abu Bakar et al., 2022).

- **Evaluation**

This parameter is mostly evaluated when the system is sent to the market for real business purposes. The prototype in this study is just a beta version.

- **Reflection**

The above assessment implies this parameter is not relevant to compare within the scope of this study.

### *5.8.7.* Maintainability

- **Explanation**

This parameter denotes the level of effectiveness and efficiency in modifying, correcting, or adapting a system to enhance its performance or align it with changes in the environment and evolving requirements (Kato & Ishikawa, 2024). It encompasses several criteria which are modularity, reusability, analysability, modifiability, and testability (ISO, 2022).

**Modularity:** The extent to which a system comprises distinct components, ensuring that changes to one component have minimal impact on others (Abu Bakar et al., 2022).

**Reusability:** Degree to which an asset can be utilised across multiple systems or can be employed in constructing other assets (Echeverria et al., 2021).

**Analysability:** Effectiveness and efficiency in evaluating the effects of intended changes to parts within a system (ISO, 2022). It involves diagnosing deficiencies or causes of failures and identifying areas for modification (Ali et al., 2022).

**Modifiability:** The level at which a product or system can be modified effectively and efficiently without introducing defects or compromising existing quality (Galli et al., 2021).

**Testability**: The effectiveness and efficiency in establishing test criteria for a system, product, or component and conducting tests to verify whether those criteria are met (Kato & Ishikawa, 2024).

- **Evaluation**

The developed prototype was assessed with the above-mentioned criteria. In the context of modularity, the developed prototype has discrete components such as a database management system, map, server, and visualisation components which are independently handled through the backend and frontend systems. Similarly, in the context of reusability and modifiability, the prototype developed through this study can be easily replicated and modified by other oil and gas companies and enhanced the prototype as per their requirements in the field design process as it is specifically designed for this purpose. Similarly, analysability and testability are the criteria that need to be assessed when the prototype is tested across the stakeholders of the field design process of the O & G project.

- **Reflection**

The above assessment indicates the prototype has been developed in a way that it can be easily maintained if needed in the future which shows the prototype is maintainable.

### *5.8.8.* Portability

- **Explanation**

The degree of effectiveness and efficiency in which a system can be shifted from one hardware, software, or operational environment to another is called as explanation (ISO, 2022). This characteristic encompasses adaptability, 'installability', and replaceability (Al-Mohamadsaleh & Alzahrani, 2023). The extent to which a system can be efficiently and effectively adjusted to suit diverse or changing hardware, software, or operational environments is called adaptability (Keibach & Shayesteh, 2022). Similarly, 'installability' is the level of effectiveness and efficiency in successfully installing and/or uninstalling a system within a specified environment (ISO, 2022). The degree to which a system can replace another specified software for the same purpose within the same operational environment is called replaceability (Ali et al., 2022).

- **Evaluation**

In terms of, adaptability and replaceability the developed prototype can be easily deployed to the O & G field design project context to store the 2D and 3D spatial data of the infrastructure designs.  The developed prototype is based on LSDM attributes therefore it can exactly replace the current 2D central SIS that is currently used in the field design process of the O & G project. As this is a web-based model, the 'installability' is not relevant in this context.

- **Reflection**

The above assessment indicates the prototype has been developed in a way that can be portable if it is needed to be replicated in the field design process of an O & G project. A real-world demonstration has been also done which justifies that the prototype can be used to store and visualise the LSDM attributes of the 3D object.

### *5.8.9.* Overall Evaluation

The preceding discussion reveals that the prototype has achieved functional completeness, correctness, and appropriateness within the defined study scope. The assessment further highlights the prototype's standard performance in terms of rendering time and resource utilisation. The compatibility assessment signifies that the prototype is compatible when assessed with Victoria DT. Furthermore, the usability assessment indicates that the prototype is suitable for the field design process in the oil and gas project. The prototype can perform essential field design functionalities based on LSDM. Security parameters of the prototype are mostly evaluated when the system is deployed to the market for real business purposes since the prototype is just a beta version. The developed prototype has been built in a manner for easy maintenance in the future. Moreover, the developed prototype is portable for replication in the field design processes of O & G projects. In a nutshell, the prototype encompasses a standard level of all parameters in the ISO/IEC 25010 framework within the scope of the study.

## 5.9. Chapter Summary

In summary, this chapter has been instrumental in bridging the theoretical underpinnings of our conceptual framework and prototype development with the practical realm. The real-world demonstration and subsequent evaluation were successfully carried out on the prototype in a specific case study area: the 2RP108045 land parcel registered under the Department of Resources, Queensland Government. Further, this chapter provides the detailed and comprehensive process of the field design that has been carried out in the study area. The chapter also explains the detailed process of the UAV surveying that was carried out on the case study area and how its captured imagery was used for the development of the geodatabase. The generation of 2D engineering plans and 3D models were also discussed in detail. Moreover, the chapter has delved into the integration of LSDM attributes into the 2D and 3D design models emphasising the synergy between our theoretical framework (as developed in Chapter Four) and the practical implementation within the prototype. This integration of the LSDM into the prototype adds significant value to this study, enhancing its utility and relevance. By migrating all prepared 2D and 3D spatial data to the prototype, the chapter provides a demonstration of the prototype's functionality in handling real-world data.

The concluding section of the chapter adopts an informed argument approach within the design science framework to evaluate the prototype, employing metrics aligned with the ISO/IEC 25010 model. This systematic assessment covers a spectrum of attributes, including functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, and portability. The assessment of the prototype indicates it performs at a standard level across all parameters within the defined study scope.

# CHAPTER 6: DISCUSSION AND CONCLUSIONS

## 6.1. Introduction

The concept of a spatially enabled digital twin is emerging as a powerful tool across various industries that deal with spatial information. Industries such as infrastructure, utility, construction, asset and facility management, and mining are increasingly using this technology to enhance visualisation, improve analytics, and enable socio-economic applications. The O & G industry is also adapting digital twin technologies for various applications that encompass asset monitoring, drilling, virtual commissioning, and the development of intelligent oilfields. However, there is a limited existing academic literature that provides evidence of the adoption of spatially enabled digital twins based on the LSDM in O & G projects, particularly during the field design phase. Therefore, this study aims to address this gap by developing a conceptual framework for spatially enabled digital twins, with a specific focus on the field design phase of a typical O & G project. The framework comprises five key components which are data, users, standards, field design, and application (spatially enabled DT). Additionally, the study has developed a prototype to assess the viability of the conceptual framework and has demonstrated the prototype by taking the case of an oil and gas field site located near a mining town, Chinchilla at the Western Down Regional Council in Queensland, Australia. The results obtained from the demonstration signify that the prototype was successfully able to visualise and display the LSDM attributes.

This study serves as a significant step in the development of digital twin technology in the field design process of the O & G projects. Chapter Six assesses the outcomes achieved during this study, highlights the significance of the research, and provides scope for future research.

## 6.2. Accomplishment of Aim and Objectives

Chapter One outlined the main aim of this study was to develop a spatially enabled digital twin framework accommodating the LSDM which facilitates storing and visualising spatial data of infrastructure designs in a virtual 3D environment along with enabling management of other crucial spatial information used during the field design process of O & G projects.

To accomplish the main aim, this study has utilised a widely accepted design science research framework. Subsequently, Chapter Two provided insights on the review of the existing digital twin frameworks, field design process, and LSDM which identified the gap in existing knowledge and facilitated in developing a conceptual framework. Similarly, Chapter Three discussed the adopted research approach i.e. design science framework to achieve the research aim and objectives. Furthermore, Chapter Four demonstrated the design and development of the conceptual framework, relevant diagrams and a prototype. The developed prototype was a spatial digital twin platform that facilitated storing and visualising the 3D design models of the infrastructure and associated 2D spatial information based on LSDM used in the field design process of the O & G project. Then, Chapter Five discussed the assessment of the prototype in the real-world case study. Further, the prototype was evaluated using the ISO/IEC 25010 eight parameters that encompass functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, and portability. The achievements of the objectives of this study were reviewed and discussed below.

### *6.2.1.* Objective 1: To review the DT concepts, existing frameworks, field design process, and LSDM for developing a conceptual framework

This study found that the theoretical definition of the DT is a 3D model/virtual reality. In this study, twenty-two DT frameworks were identified and classified into three major categories including spatial science, O & G, and others to examine their strengths and weaknesses. The literature review signified that twenty-two DT frameworks have various strengths, but shortfalls in facilitating the DT development of the field design process in the O & G industry due to the lack of integration of LSDM. Therefore, it was identified that for full industry adoption, there should be a conceptual framework for spatially enabled DT for the field design process of O & G project that integrates LSDM components. The key results generated from the literature review revealed that the typical field design process includes: conceptual engineering design, acquisition of geospatial information, detailed engineering design, and archiving the spatial data (X, Y, Z) of infrastructure design into the spatial information system (SIS) of the project.

This study has also carried out a desktop assessment to understand the existing practice of communicating design information in the context of Australia. The results of the assessment indicate that most O & G projects in Australia are still using the 2D design plan to communicate the design information among the stakeholders and are storing 2D design line works in SIS. In Chapter Two, LSDM's theoretical aspects were presented. The identified classes in LSDM were infrastructure, survey measurements, topo-geomorphology, environment, and geology. Finally, the knowledge acquired from the literature review facilitated the development of a spatially enabled digital twin conceptual framework which is presented in Figure 4.2.

### *6.2.2.* Objective 2: To develop a conceptual framework of spatially enabled digital twins by encapsulating LSDM

The systematic literature review carried out in Chapter Two facilitated the development of the conceptual framework and prototype. The developed conceptual framework is novel in the context of the field design of the oil and gas project which has been presented in detail in Chapter Four.

The framework includes five key components such as data, standards, users, field design, and application (Spatially Enabled DT). Data is a pivotal component of the framework that consists of the datasets from LSDM, and additional data, such as cultural heritage and safety which are significant in the context of Australia. The standards are also major components that include engineering design specifications, and environmental and geological acts, which are essential for project integrity and regulatory compliance. The field design process is a central component of the framework that involves conceptual and detailed engineering design, fostering efficiency through dataset coordination. Users are an essential part of the framework which are linked to specific data categories and plays a vital role in managing data within their expertise, with the acknowledgment of additional users for specific project needs. The spatially enabled digital twin application, a pivotal element, facilitates the storage, management, and analysis of spatial data, providing role-based access control for data integrity. Further, the framework also demonstrated the use case diagram, offering a clear representation of the user’s interactions with the workflow of the field design process.

A system architecture was developed to present the technical dimensions, supported data types, database management system, map servers, and visualisation systems. Further, to illustrate a comprehensive understanding of the field design workflow and the system architecture, a sequence diagram was presented. Overall, the developed, comprehensive framework addresses the gap in academic literature, specifically focusing on the field design phase of O & G projects.

### *6.2.3.* Objective 3: To utilise the developed framework as a guiding principle for building a prototype to ensure framework viability

This objective has utilised the developed conceptual framework as a guiding principle in developing a prototype to assess its viability. A detailed explanation of the prototype has been presented in Chapter Four. The prototype was developed utilising the agile methodology which includes requirement analysis, design, development, and testing of the system architecture. The key components of the system architecture are data types, map servers, database management systems, and visualisation systems. Chapter Four has provided information on the frontend and backend aspects of the prototype. The successful incorporation of the frameworks throughout the prototype development not only validates its viability, but also highlights its adaptability and relevance in real-world applications. In essence, the integration of the conceptual framework served as a foundation for prototype development.

### *6.2.4.* Objective 4: To demonstrate the prototype for assessing its feasibility through a case study approach

In Chapter Five, prototype feasibility was assessed through a case study approach. Lot 2RP108045 near the mining town Chinchilla at the Western Down Regional Council, Queensland, Australia, was selected as a case study area to evaluate the feasibility of the prototype for the field design process. The prototype demonstration was carried out through three key activities that encompass migrating the spatial data, visualising them, and displaying their associated LSDM attributes. The 2D and 3D spatial data were integrated and migrated to the prototype. In total, seven 3D spatial datasets and nine 2D spatial datasets were successfully migrated. Furthermore, the developed prototype was fully able to visualise all these migrated spatial datasets in an interactive 3D virtual environment on the spatial Digital Twin portal. Finally, all the LSDM attributes of these spatial datasets were successfully displayed by the prototype. Through the case study, this study demonstrated the viability of the prototype's performance for real-world datasets. In conclusion, the results obtained from the demonstration stage contribute to further upgrading the prototype and guiding future implementations.

### *6.2.5.* Objective 5: To evaluate the prototype using ISO/IEC 25010 parameters

The prototype evaluation was carried out using eight metrics of ISO/IEC 25010. The results generated from the evaluation indicate the prototype has successfully achieved functional completeness, correctness, and appropriateness within the scope of this study. Further, in terms of rendering time and resource utilisation, the prototype was able to achieve standard performance. In addition to this, evaluation signifies that the prototype was compatible when assessing it against the Digital Twin Victoria (DTV) platform. Similarly, usability assessments verified its suitability for oil and gas projects in the field design process. The prototype was successfully able to execute essential field design functionalities based on LSDM. Further, the evaluation of security parameters was not assessed as a prototype as it was in the beta version. Moreover, the evaluation indicates that the prototype is portable as it enables its replication in the field design processes of O & G projects. In summary, the prototype meets the specified criteria outlined in the ISO/IEC 25010 framework within the study's scope.

## 6.3. Responses to the Research Questions

In Chapter 1, the main research problem of this study stated as “2D design plans have limitations, and these limitations are inherited in their spatial data, causing challenges in visualising design information stored in spatial information system. Spatially enabled digital twins would address this limitation. However, existing DT frameworks have not considered the industry-standard models such as LSDM, which are essential. Based upon this research problem Two key research questions were formulated. This section answers these two research questions, with references to the chapters and related contributions.

### *6.3.1.* Can existing theoretical frameworks on DT be directly utilised in the field design process to store and visualise the spatial data of infrastructure designs based on the LSDM?

In order to address this research question, comprehensive literature review was carried out in Chapter Two. The results obtained from Chapter Two identified Twenty-Two DT frameworks (as illustrated in Appendix B). Among these, Nine frameworks were relevant to the spatial science domain. Similarly, Seven frameworks were relevant to the O and G sector whereas Six frameworks were relevant to the others paradigm that includes mining, construction, and underground infrastructure.

Furthermore, the findings from Chapter Two also concluded that existing frameworks contributed immense value in DT development in research community. It has also been found that the basic aspects of the DT framework remained the same across every industry. However, for complete industry adoption to leverage full benefits of DT, a new extended framework was proposed to store and visualise spatial data of the infrastructure designs based on LSDM because none of these existing frameworks accommodate the LSDM attributes which was found essential in storing spatial data of infrastructure designs during the field design process of the O & G projects, thereby impacting complete industry adoption. LSDM classes are crucial in the field design process of O & G projects as the International Association of Oil and Gas Producers (IOGP) has directed oil and gas companies to manage all their spatial information involved in field design phase based on the LSDM. In addition to this, this study successfully developed spatially enabled DT frameworks for the field design process of oil and gas projects. The developed framework has been extended using widely accepted framework developed by Rajabifard et al. (2022). However, the current form of the framework of Rajabifard et al. (2022) found very generic and study itself suggested that it should be customised incorporating industry requirement. The developed framework in this study could serve as a starting point to leverage digital twins for managing spatial information in the context of field design in the O & G projects. However, physical evidence (prototype) of this framework has not been validated through SMEs due to time and regulatory constraints. In addition to this, prototype of this framework has been only demonstrated in a Queensland, Australia that also effects on study results causing geographical and thematic limitations. Therefore, it is recommended that the prototype need to be validated and necessary adjustments should be applied to utilise it in different geographical and thematic context.

### *6.3.2.* What is an appropriate approach for developing spatially enabled digital twin framework to store and visualise the spatial data of infrastructure designs and other associated spatial information?

In Chapter 1 Section 1.3, various approaches of developing conceptual frameworks associated with information system, digital twins, 3D GIS and BIM was discussed. Design science approach is well acknowledged in the research community for developing conceptual frameworks related to information systems, digital twins, 3DGIS, and BIM. The articulation signified that most of the studies Asghari (2022); Atazadeh (2017); Kang et al. (2022); Kehily and Underwood (2015); Pan and Zhang (2021) adopted design science framework and was widely recognised among research community for developing the conceptual frameworks. In Chapter 3, several approaches in the design science research paradigm were outlined which were developed by numerous (Ahmad et al., 2013; Blessing & Chakrabarti, 2009; Hevner et al., 2004; Johannesson & Perjons, 2021; Kuechler & Vaishnavi, 2008; Markus et al., 2017; Maung et al., 2011; Muntaheen, 2021; Peffers et al., 2007) and the fundamental principle used for each was found similar.

This study has utilised design science framework developed by Johannesson & Perjons (2021) to develop the spatially enabled digital twin framework to store and visualise the spatial data of the infrastructure designs and other associated spatial information. The main aim of this study and its research objectives were accomplished through four stages of design science research methodology as discussed in Chapter 3. For instance, in the foundation stage, the systematic literature review was conducted to explore the research problem and develop a conceptual framework that encompasses key components including data, standards, field design, users, and application. Following this, in the design and development stage, the data requirement was explored and the system architecture of the framework, use case diagram, sequence diagram, and ER diagram were presented to illustrate the technical dimension of the framework. Similarly, a prototype was developed and successfully demonstrated through case study approach during design and development stage and demonstration stage respectively. The prototype was successfully able to visualise 2D and 3D spatial data and associated LSDM attribute information. The prototype was validated using the parameters stated by ISO/IEC 25010 in evaluation stage which indicated its success within the defined study scope. The results obtained from foundation stage of this study also found that most of the existing empirical studies related to the DT models (case studies) were sporadically published in blogs, forums and non-academia media which resulted in difficulties in perceiving the comprehensive linkage between the DT applications and field design process of oil and gas projects.

Therefore, this study act as a significant compile resource for the research community that composed of theoretical DT framework and its validation through empirical case study developed using systematic academic research based on design science approach. However, this study has primarily focused on the field design steps of O & G projects. Further, application on the construction set out-step of O & G projects is highly recommended to strengthen the developed conceptual frameworks for wider industry adoption.

### 6.4. Research Contribution

This study represents a significant integration of both theoretical and empirical research, contributing to five key areas of knowledge. First and foremost, it introduces a spatially enabled digital twin framework specifically tailored for the field design process of O & G projects. This framework stands out as a valuable resource, particularly within the context of the oil and gas sector, with a distinct focus on the spatial science domain. The integration of theoretical foundation and practical applications in this framework not only enhances the understanding of spatial innovation and digital twin technology but also offers a concrete tool that will support the field design processes in the oil and gas industry. This contribution establishes a foundation for more informed decision-making through effective 3D visualisation.

In its second key contribution, this study presents a novel approach to seamlessly integrate LSDM attributes into a 3D model using Keyhole Markup Language (KML) files. The significance of this contribution lies in offering a simpler and more efficient alternative to existing methods, particularly those associated with the Architectural, Engineering, and Construction (AEC) paradigm, which is often complex, especially in the context of GIS-BIM integration. By proposing a methodology aligned with the spatial science field, this study addresses a critical gap in the current approaches, providing a streamlined and accessible solution for incorporating LSDM attributes into 3D models. While the basic concept of utilising KML files for integrating spatial attributes was previously introduced by Cemellini (2018) in the domain of 3D cadastre, this study takes a step further by implementing and empirically validating this approach specifically within the context of the oil and gas (O & G) industry.

Thirdly, the study has provided knowledge to all the relevant stakeholders and practitioners to leverage emerging digital twin technology in the geospatial domain of the O & G industry context. The stakeholders include surveying and mapping companies, surveyors, asset engineers/managers, and field construction crews dealing with the geospatial sector of the O & G industry. Fourthly, the research has utilised a design science research approach which provides a theoretical contribution to the information science domain within the O & G industry. Finally, from a high-level perspective, this study contributes to the advancement of Industrial Revolution 4.0 within the mining industry, facilitates better decision-making in the oil and gas industry sector, and enhances the management of energy resources.

## 6.5. Future Research Avenues

The findings of this study have unveiled future research that could be explored further. Therefore, future three key scholarly investigations could be oriented toward the following domains.

### *6.5.1.* Framework and Prototype Evaluation by SMEs

Presently, the prototype was evaluated through the informed argument method using ISO/IEC 25010 parameters, primarily due to constraints in time and resources. To achieve a more comprehensive assessment, it becomes imperative to assess the developed conceptual framework and prototype by subject matter experts (SMEs), who constitute the authentic end users of the prototype. Employing additional evaluation methods, such as conducting interviews with SMEs, is crucial for achieving broader industry acceptance and implementation. This evaluation approach ensures a genuine business perspective, determining the feasibility of investing in further enhancements to this prototype, especially in the context of O & G projects.

### *6.5.2.* Prototype Enhancement

The prototype currently operates exclusively on a local server (localhost). To enhance accessibility and usability, it is recommended to extend its functionality to operate seamlessly on a cloud server. This exploration would promote broader accessibility and utilisation of the prototype. Similarly, the prototype relies on the World Geodetic System (WGS84) coordinate system. However, the exploration of other coordinate systems is affirmed to ascertain their applicability and potential advantages for further construction purposes after field design in the context of O & G is completed. This diversification could enhance the prototype's adaptability to varying spatial requirements. However, more resources (time and money) should be invested to enhance the prototype before deploying to the industrial applications.

### *6.5.3.* Testing in Other Areas

The case study area was selected in a specific O and G project in Queensland, Australia. There are still geographical and thematic limitation (different regulatory frameworks or infrastructure characteristics). The definition of the DT extends to the 4D. This study has only theoretically utilised real-time data in conceptual framework development. Currently, the prototype is not able to handle any real-time datasets. Therefore, integration of real-time data such as weather and fire into the prototype and demonstration is recommended for further exploration with additional investment of time and resources. This will lead further enhance the frameworks effectiveness and pave the way for its boarder adaption and impact within the O & G industry. Further, this study has only focused on the specific field design phase of the O & G projects. The testing of this prototype in the next stage of construction of the oil and gas field is also recommended. Furthermore, safety has always been a major concern in the O & G industry (mining industry). Therefore, the application of spatially enabled DT framework in other areas of mining such as safety for achieving sustainable mining operations is recommended for further research.

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# APPENDICES

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# Appendix A: DT Definitions

| Research Scholar | Year | Definition |
|---|---|---|
| (Shafto et al. 2012) | 2010–2015 | “A Digital twin is an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin”. |
| (Zhang et al. 2019a) | 2016 | “The digital twin is a virtual representation of the real product. It has the product’s information since the beginning of the product’s life until the disposal of the product”. |
| (Grieves and Vickers 2016) | 2017 | “A set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level”. |
| (Brenner and Hummel 2017) | 2017 | “A digital copy of a real factory, machine, worker, etc., that is created and can be independently expanded, automatically updated as well as being globally available in real-time”. |
| (Stark, Kind, and Neumeyer 2017) | 2017 | “A Digital twin is the digital representation of a unique asset (product, machine, service, product service system or another intangible asset), that compromises its properties, condition and behaviour using models, information and data”. |
| (Weber et al., 2017) | 2017 | “A digital representation of all the states and functions of a physical asset”. |
| (Negri, Fumagalli, and Macchi 2017) | 2017 | “The virtual and computerised counterpart of a physical system that can be used to simulate it for various purposes, exploiting a real-time synchronisation of the sensed data coming from the field”. |

| Research Scholar | Year | Definition |
|---|---|---|
| (Blum and Schuh 2017) | 2017 | "A virtual representation of a product on the shopfloor". |
| (Bohlin et al. 2017) | 2017 | "A comprehensive physical and functional description of a component, product or system, which includes more or less all information which could be useful in the current and subsequent lifecycle phases". |
| (Tao et al. 2018) | 2018 | "A real mapping of all components in the product life cycle using physical data, virtual data and interaction data between them". |
| (Scaglioni and Ferretti 2018) | 2018 | "A near-real-time digital image of a physical object or process that helps optimise business performance". |
| (Talkhestani et al. 2018) | 2018 | "A current, digital model of a product or production system that contains a comprehensive physical and functional description of a component or system throughout the lifecycle". |
| (Haag and Anderl 2018) | 2018 | "A comprehensive digital representation of an individual product. It includes the properties, condition and behaviour of the real-life object through models and data". |
| (Liu, Meyendorf, and Mrad 2018) | 2018 | "An integrated multi-physics, multiscale, probabilistic simulation of an as-built system enabled by digital threads, that uses the best available models, sensor information, and input data to mirror and predict activities/ performance over the life of its corresponding physical twin". |
| (Zhuang, Liu, and Xiong 2018) | 2018 | "A virtual, dynamic model in the virtual world that is fully consistent with its corresponding physical entity in the real world and can simulate its physical counterpart's characteristics, behaviour, life, and performance in a timely fashion". |

| Research Scholar | Year | Definition |
|---|---|---|
| (Sierla et al. 2018) | 2018 | "Digital twin: a near-real-time digital image of a physical object or process that helps optimise business performance". |
| (Kunath and Winkler 2018) | 2018 | " The Digital twin of a physical object as the sum of all logically related data, i.e. engineering data and operational data, represented by a semantic data model." |
| (Tharma, Winter, and Eigner 2018) | 2018 | "Digital twin of a real distributed product is a virtual reflection, which can describe the exhaustive physical and functional properties of the product along the whole life cycle and can deliver and receive product information". |
| (Eisentrager et al. 2018) | 2018 | "A digital twin is a digital model of a real object containing lifecycle records and dynamic status data, which are synchronised in real-time. The model will be used to gain knowledge that can be transferred to the real object". |
| (Negri et al. 2019) | 2019 | "An integrated simulation of a complex product/system that, through physical models and sensor updates, on tool twin". |
| (Biesinger et al. 2019) | 2019 | "A digital twin is defined as a realistic model on a current state of the process and behaviour of real objects with its structure and elements that are connected to it". |
| (Kabaldin et al. 2019) | 2019 | "A set of mathematical models characterising in real-time the different states of the equipment, the technological processes, and the business processes in production conditions". |

# Appendix B: Existing DT Frameworks

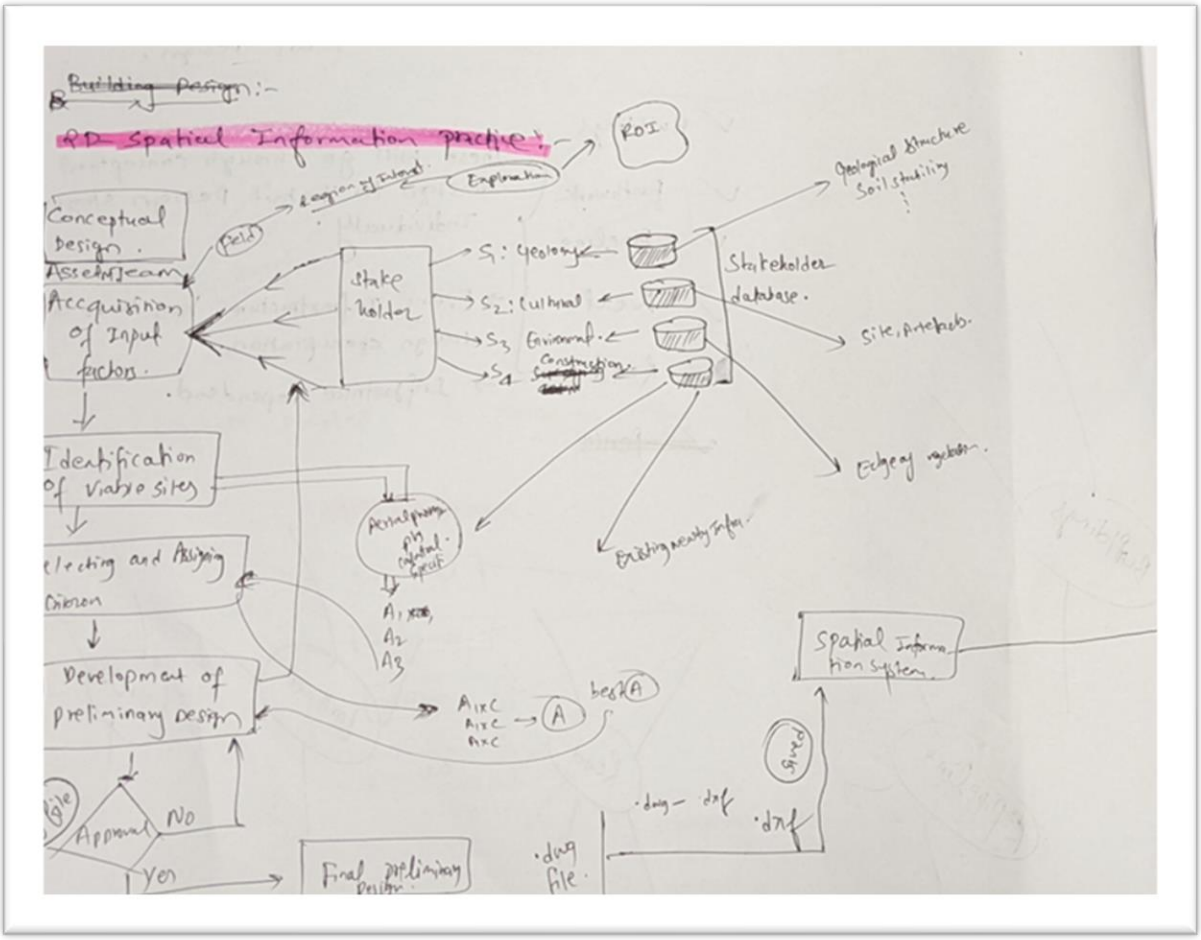
| S.N | Conceptual Frameworks | Strength | Limitations | Source |
|---|---|---|---|---|
| **SS: Spatial Science** | | | | |
| 1 | Conceptual framework for spatial DT | Theoretical DT model for all industries that harness spatial information | Need to breakdown in the context of O & G | (WGIC, 2022) |
| 2 | DT framework for urban land administration | Widely accepted in the spatial science discipline | The absence of empirical studies to support this concept could be seamlessly integrated into the O & G project | (Rajabifard et al., 2022) |
| 3 | System architecture of 3D LAS | Use of FOSS technologies to manage BIM/IFC files | Focused on 3D land administration only | (Broekhuizen, 2021) |
| 4 | DT framework for city and building level | Comprehensive DT system architecture | Explicitly cantered to urban settings | (Lu et al., 2020) |
| 5 | System architecture to manage 3D and real time datasets in built environment context | Offer scientific evidence for managing heterogeneous spatial information | Uncertain about integrating to O & G projects due to lack of incorporating LSDM | (Aleksandrov et al., 2019) |

| S.N | Conceptual Frameworks | Strength | Limitations | Source |
|---|---|---|---|---|
| 6 | DT framework for revamp building O & M | Develop a comprehensive framework for managing various information | Developed from built environment perspective | (Zhao et al., 2022) |
| 7 | IFC to 3D tiles using cesium framework | Innovative research for storing 3D tiles in open-source 3D web GIS based application | Limited to 3D data conversion only | (Chen et al., 2018) |
| 8 | BIM-GIS database model | Develop a methodology for managing BIM-GIS datasets in open-source Postgres SQL | Considered heritage information only and does not incorporate LSDM constituents | (Colucci et al., 2021) |
| 9 | Web based GIS for managing O & G datasets | Create a framework and an interactive system explicitly cantered on managing O & G spatial information | Does not include DT concept and constituents of LSDM | (Li et al., 2017) |
| **O & G** | | | | |
| 10 | DT framework for manufacturing | Theoretically, it can be applied in any industry | No empirical evidence that it could be directly integrated into the field design process/spatial paradigm of the O & G project | (Wanasinghe et al.,2020) |

| S.N | Conceptual Frameworks | Strength | Limitations | Source |
|---|---|---|---|---|
| 11 | DT framework for exploratory oil field multi scale reservoir | Leverage DT technology on reservoir modelling | Does not focus on the spatial science paradigm of the O & G project | (Zhang & Sun, 2021) |
| 12 | DT framework for predicting O & G production | Create optimised model for entire life cycle from conceptual design, detailed design, and operational services | | (Shen et al., 2021) |
| 13 | DT model for process plants | Use the DT reference model for risk control and prevention | No rationale for the field design process of the O & G project | (Bevilacqua et al., 2020) |
| 14 | DT framework for O & G assets | Develop system architecture to manage the O & G asset information | Limited to conceptual framework and pipeline integrity management system only | (Xiangdong et al., 2020) |
| 15 | DT framework for offshore O & G industry | DT framework research pertains to the field design process | Unavailability of empirical evidence | (Lv et al., 2023) |
| 16 | DT framework for oil field virtual twin | | Focused on offshore operations and lacks integration of LSDM | (Konchenko et al., 2020) |
| **Others (Mining, construction, underground infrastructures)** | | | | |
| 17 | DT framework for coal mine safety management | Create innovative DT model and validate through mathematical modelling | Limited to coal mine safety | (Wang et al., 2023) |

| S.N | Conceptual Frameworks | Strength | Limitations | Source |
|---|---|---|---|---|
| 18 | DT framework for asset life cycle management for the mining industry | Developed multi-level architecture for the mining industry | Need further investigation to successfully integrate into the definite field design process of the O & G project | (El Bazi et al., 2023) |
| 19 | Integrated framework for O & M of Gas utility pipeline using BIM, GIS and AR | Innovative empirical study on integrating 2D and 3D datasets focusing on pipeline 3D modelling | Limited to mobile applications and does not incorporate LSDM elements | (Shekargoftar et al., 2022) |
| 20 | DT framework for underground tunnel | Architectural workflow systematic for managing numerous 3D datasets | The case study focused solely on tunnel infrastructure without considering integration possibilities with other geodatabase models like LSDM | (Lee et al., 2023) |
| 21 | BIM-GIS framework | Valuable example for managing spatial and design information of pipelines | More focus on BIM-GIS integration | (Sharafat et al., 2021) |
| 22 | Architecture for DT enabled project management in the construction industry | Validate the value of UAV in building DT | Does not integrate LSDM feature classes | (Pan & Zhang, 2021) |

# Appendix C: Brainstorming



# Appendix D: Decision Matrix

| **Criterion** | **Weight** | **I1:** Developed new framework | **I2:** Customising the existing framework |
|---|---|---|---|
| Effectiveness | 5 | 3 | 5 |
| Time | 3 | 1 | 3 |
| Cost | 1 | 1 | 5 |
| **Total** | | **5** | **13** |

# Appendix E1: Facilities LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| SOURCE | Text | Source of data |
| TYPE | Text | Type of feature plant, base, processing unit etc |
| NAME | Text | Name of feature vessel, tank etc |
| CADLAYER | Text | Name of CAD layer |
| STATUS | Text | Proposed or Existing |

# Appendix E2: ROW LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| SOURCE | Text | Source of data |
| TYPE | Text | Type of feature plant, base, processing unit etc |
| NAME | Text | Name of feature vessel, tank etc |
| CADLAYER | Text | Name of CAD layer |
| STATUS | Text | Proposed or Existing |

## Appendix E3: Pipeline LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| PROPERTY | Text | Parcel number in which pipeline runs through |
| START | Int | Start station number of pipeline |
| END | Int | End station number of pipeline |
| SOURCE | Text | Source of data |
| LENGTH | Double | Length of the pipe in km |
| MATERIAL | Text | Material of pipe |
| DIAMETER | Double | Diameter of the pipe in mm |
| DEPTH | Double | Depth of the pipe from earth surface in mm |
| CADLAYER | Text | Name of the CAD layer |
| STATUS | Text | Proposed or existing |

## Appendix E4: Road LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| NAME | Text | Name of road |
| PROPERTY | Text | Land parcel number in which the road runs through |
| SOURCE | Text | Source of data |
| LENGTH | Double | Length of the road in km |
| MATERIAL | Text | Material of road |
| WIDTH | Double | Nominal width of road in m |
| CADLAYER | Text | Name of the CAD layer |
| STATUS | Text | Proposed or existing |

## Appendix E5: Well Pad LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| NAME | Text | Name of well pad |
| PROPERTY | Text | Parcel number in which well pad lies |
| SOURCE | Text | Source of data |
| AREA | Double | Area of the well pad |
| CADLAYER | Text | Name of the CAD layer |
| STATUS | Text | Proposed or existing |

## Appendix E6: Fence LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| PROPERTY | Text | Parcel number in which fence is located |
| LENGTH | Double | Length of fence |
| HEIGHT | Double | Height of fence |
| SOURCE | Text | Source of data |
| GATE | Text | Relevant gate number connecting the fence |
| GRID | Text | Relevant grid number connecting the fence |
| CADLAYER | Text | Name of the CAD layer |
| STATUS | Text | Proposed or existing |

## Appendix F1: Land Use LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| TYPE | Text | Classification type of land use |
| AREA | Double | Area of land use in ha |
| SOURCE | Text | Source of data |

## Appendix F2: Habitat Area LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| NAME | Text | Name of the species |
| AREA | Double | Area of habitat in ha |
| DENSITY | Double | Spread percentage of respective species |
| SOURCE | Text | Source of data |

## Appendix G1: Erosion LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| CATEGORY | Text | Type of erosion such as rill, gully, sheet |
| AREA | Double | The area of erosion in sqm |
| SOURCE | Text | Source of data |

# Appendix G2: Seismic LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| TYPE | Text | 2D seismic survey or 3D seismic survey area capturing during the exploration phase |
| LENGTH | Double | Length or area of seismic survey in km and sqkm |
| AREA | | |
| SOURCE | Text | Source of data |

# Appendix H1: Geodetic Control Points LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| ORDER | Text | Order of control point |
| TECHNIQUE | Text | Establishment technique (GNSS/TS/CORS) |
| SURVEYOR | Text | Name of surveyor |

# Appendix H2: Surveyed Points LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| TECHNIQUE | Text | Technique of capturing data GNSS or total station |
| PURPOSE | Text | Purpose of the survey |
| SURVEYOR | Text | Name of surveyor |

## Appendix I1: Cultural Heritage Point LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| TYPE | Text | Type of cultural heritage artefacts, sacred trees |
| MANAGEMENT | Text | Avoidance or mitigated and approved |
| SOURCE | Text | Source of data |

## Appendix I2: Cultural Heritage Area LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| AREA | Double | Area of cultural heritage in sqkm |
| MANAGEMENT | Text | Avoidance or mitigated and approved |
| SOURCE | Text | Source of data |

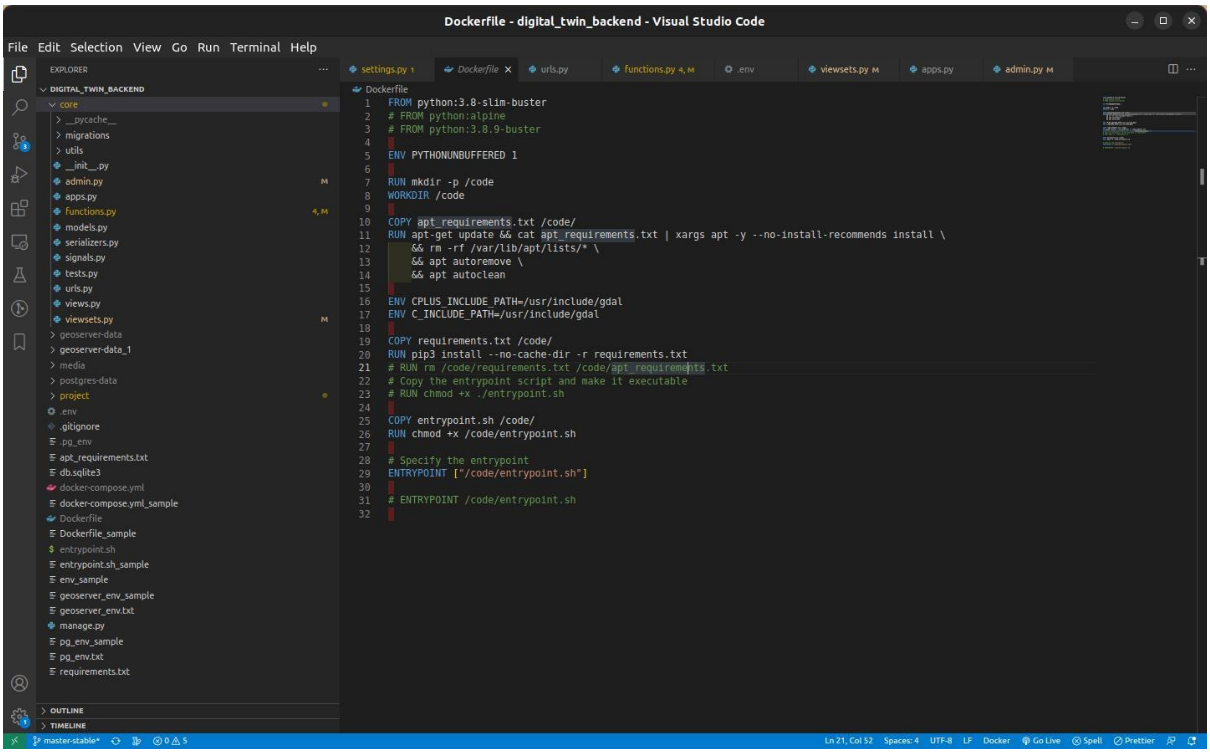
## Appendix J1: Fire LSDM Attributes

| Field | Data Type | Description |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| STATION NAME | Text | Name of station |
| HAZARD LEVEL | Text | It defines the level of hazard (catastrophic, extreme, average, low) |

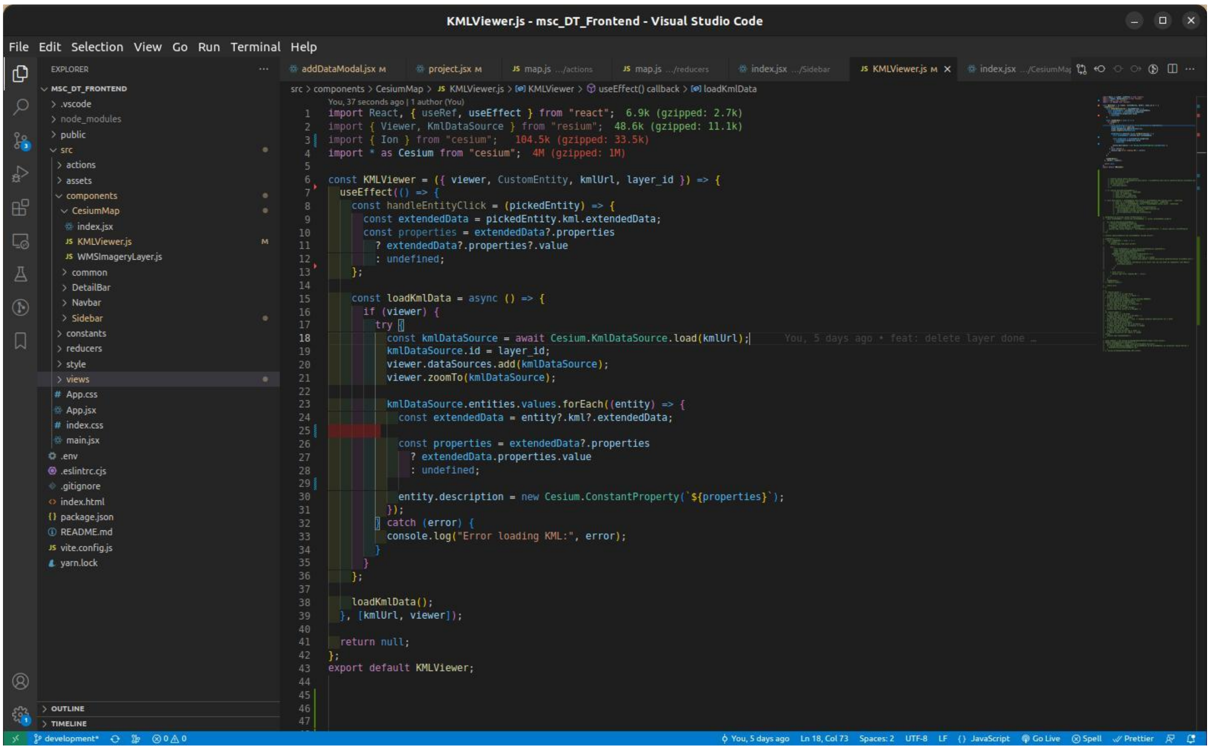
# Appendix J2: Weather LSDM Attributes

| **Field** | **Data Type** | **Description** |
|---|---|---|
| OBJECTID | Int | Primary key |
| SHAPE | Text | Shape of object point, line, polygon, 3D object |
| STATION NAME | Text | Name of station |
| TEMPERATURE | Double | Temperature value in degrees celsius |
| HUMIDITY | Double | Humidity value in % |

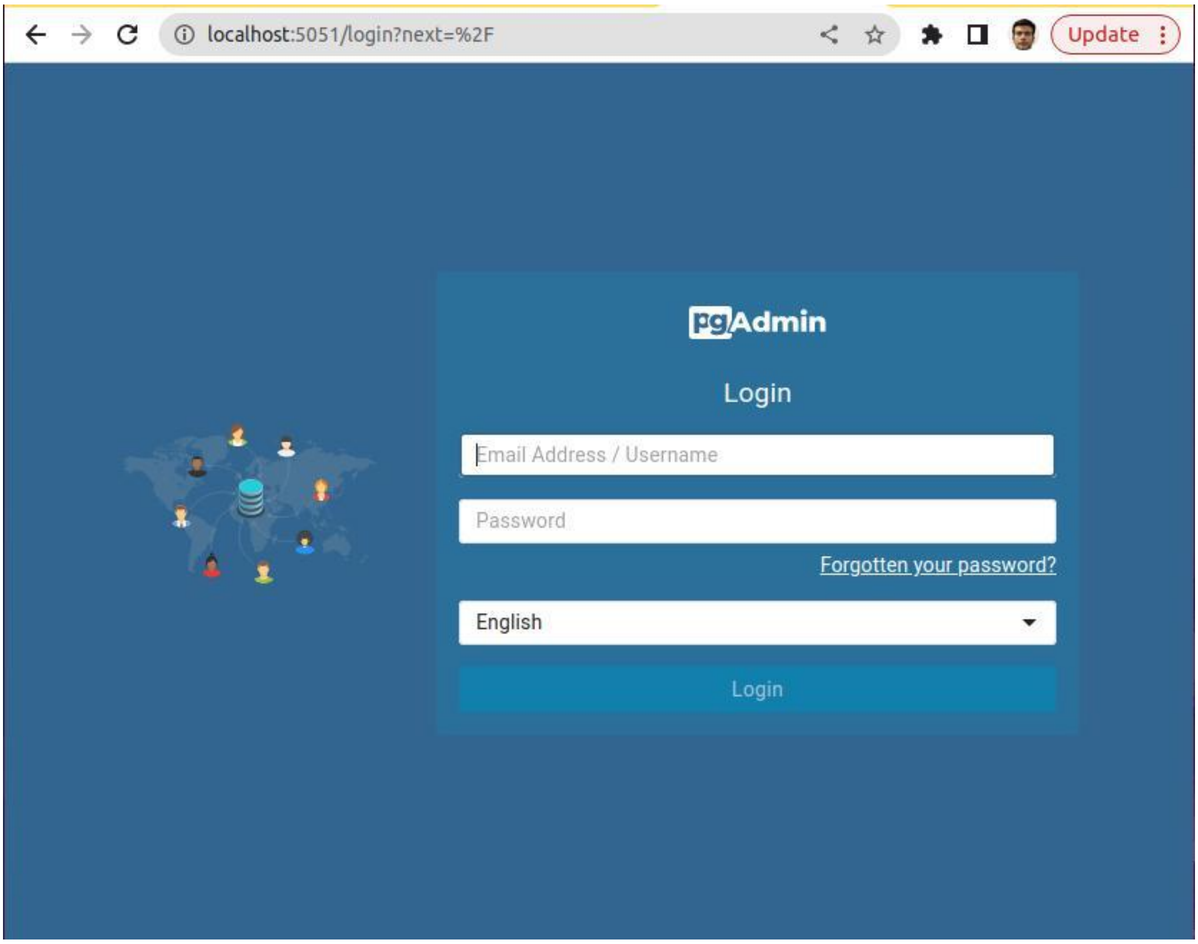
# Appendix K: Programming Excerpt (Backend)



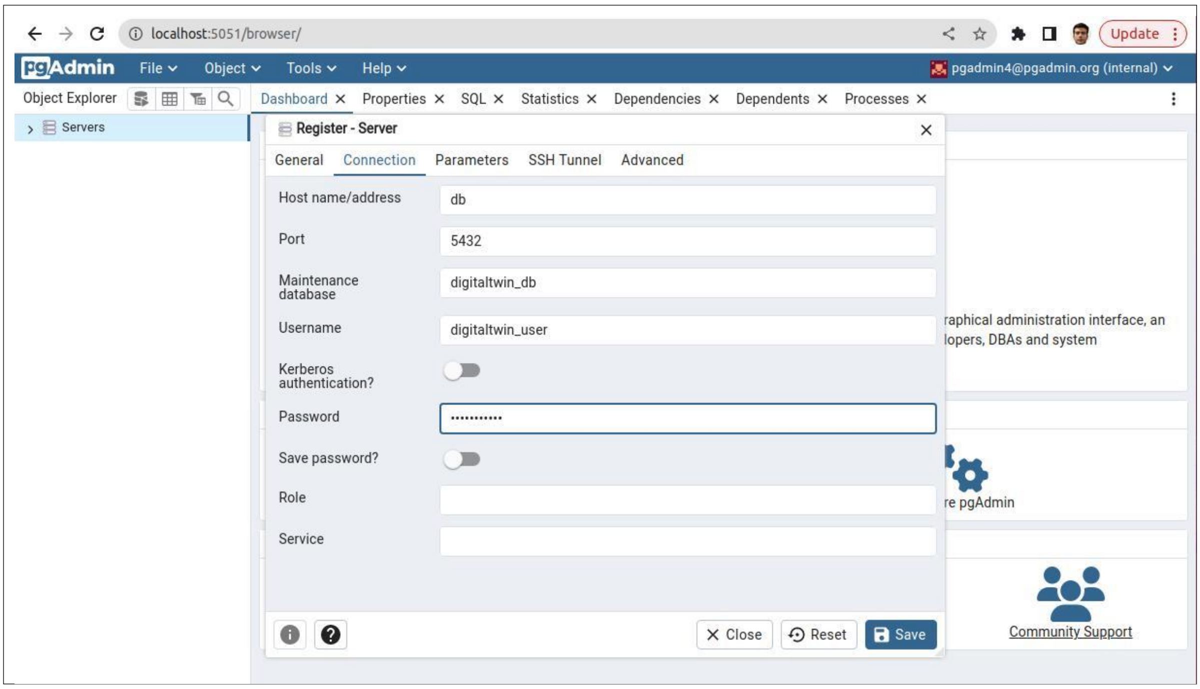
# Appendix L: Programming Excerpt (Frontend)



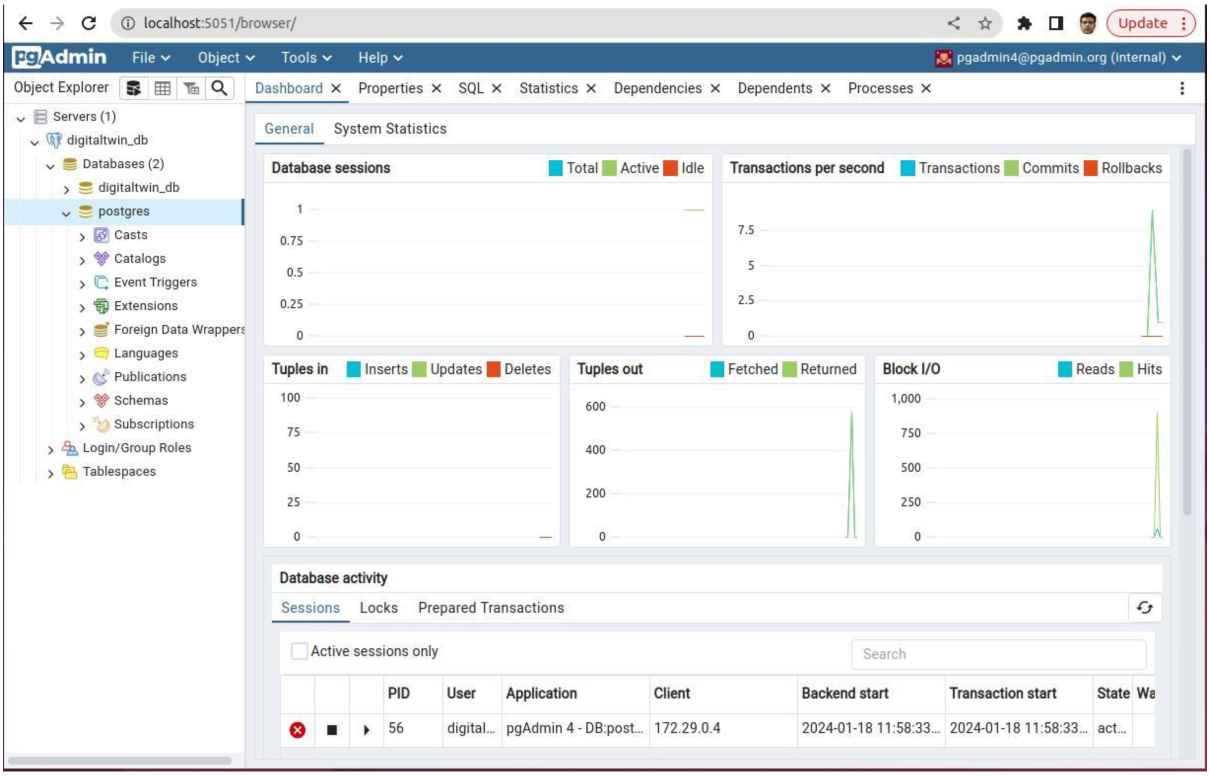
## Appendix M: PgAdmin Login Interface



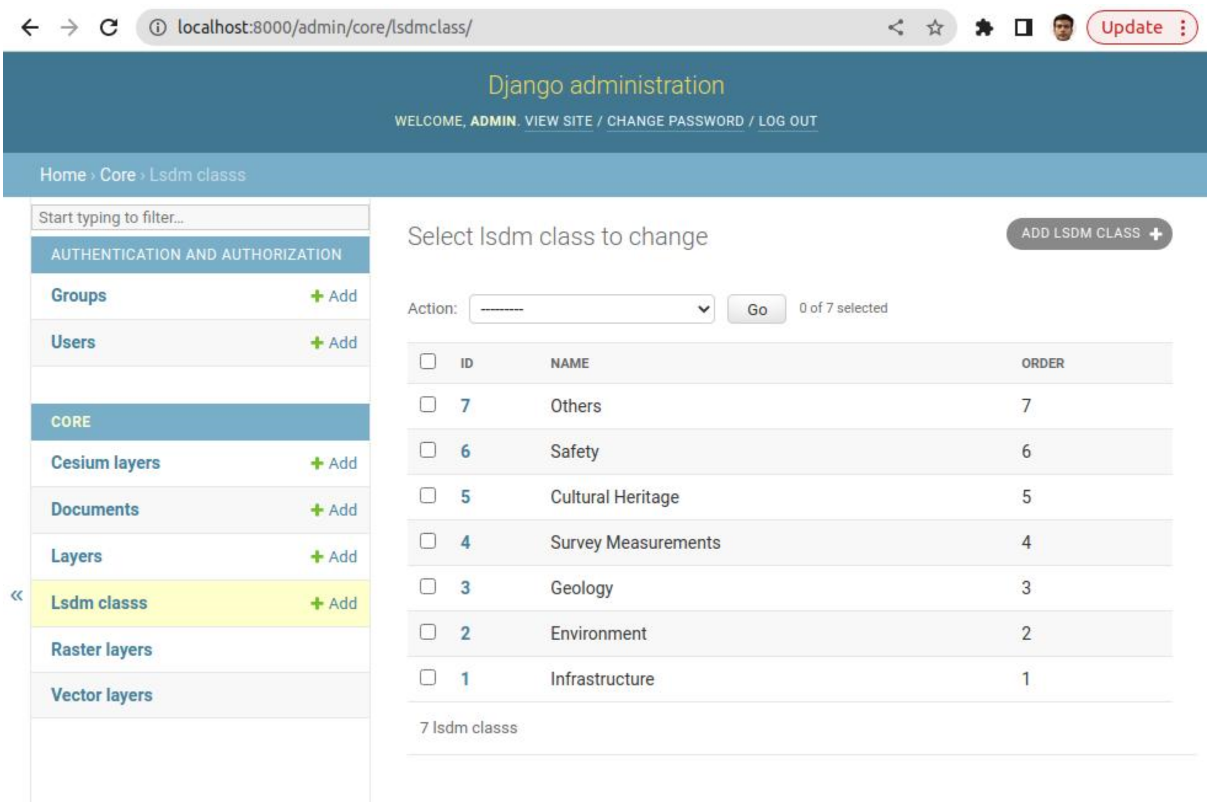

## Appendix N: PgAdmin Register Server



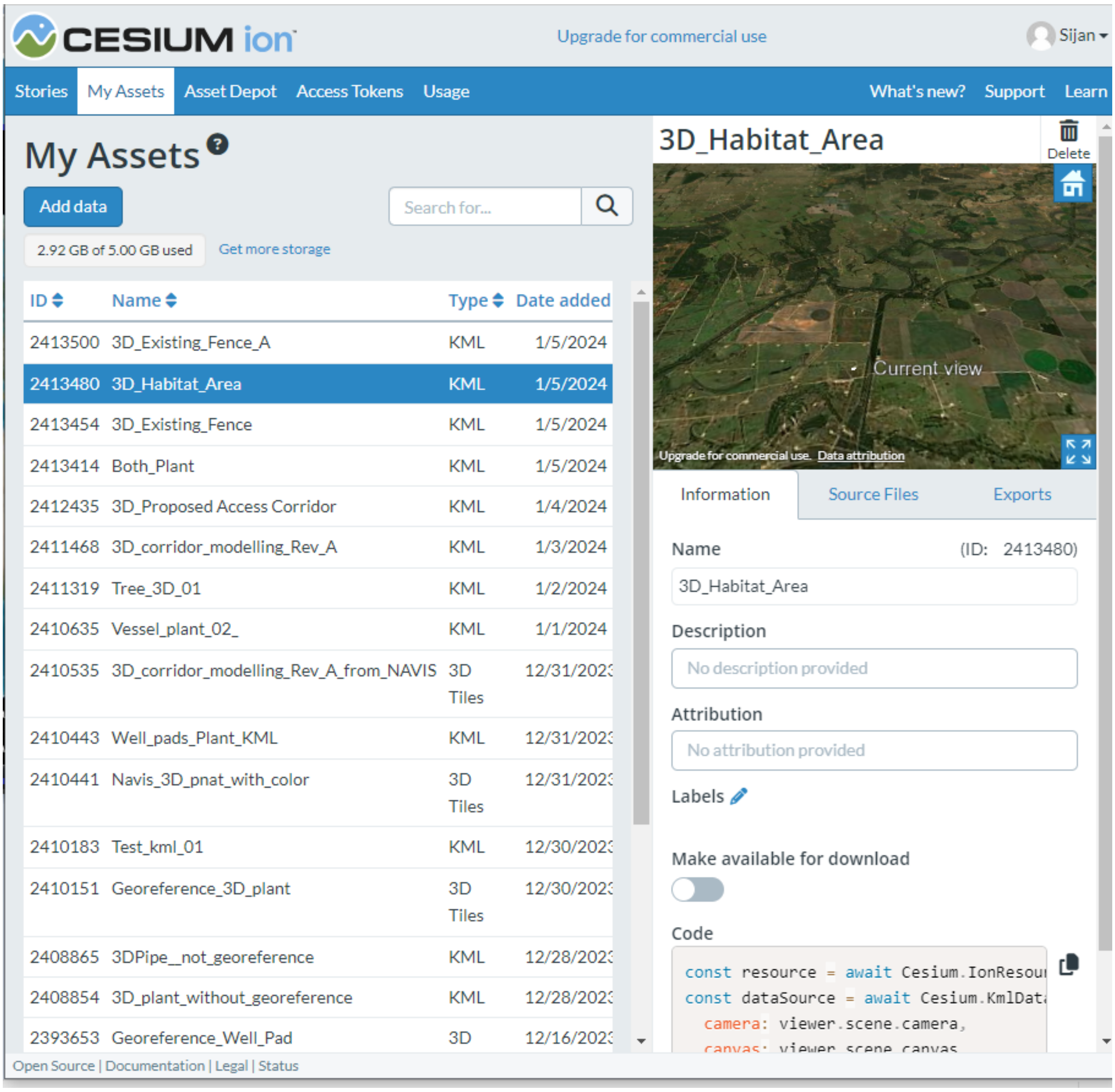
# Appendix O: PgAdmin Running Dashboard



# Appendix P: Django LSDM Layers



# Appendix Q: Cesium Ion Interface



# Appendix R: Design Standard (APGA, 2022)

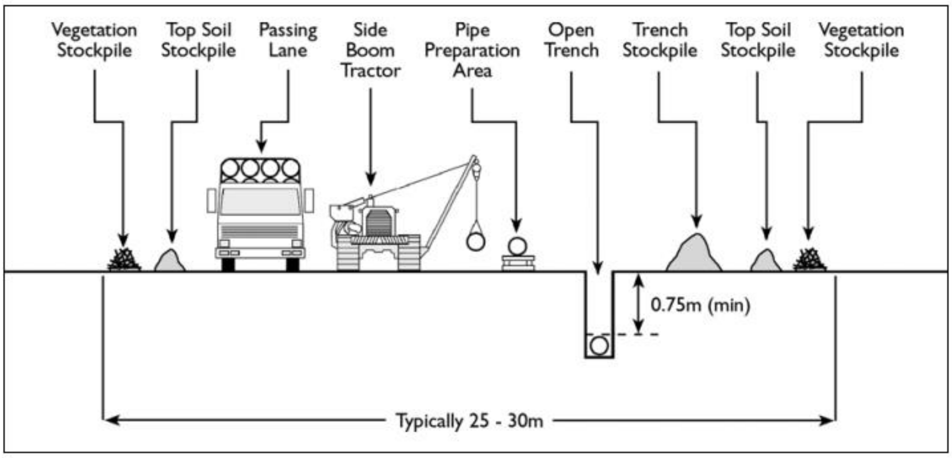
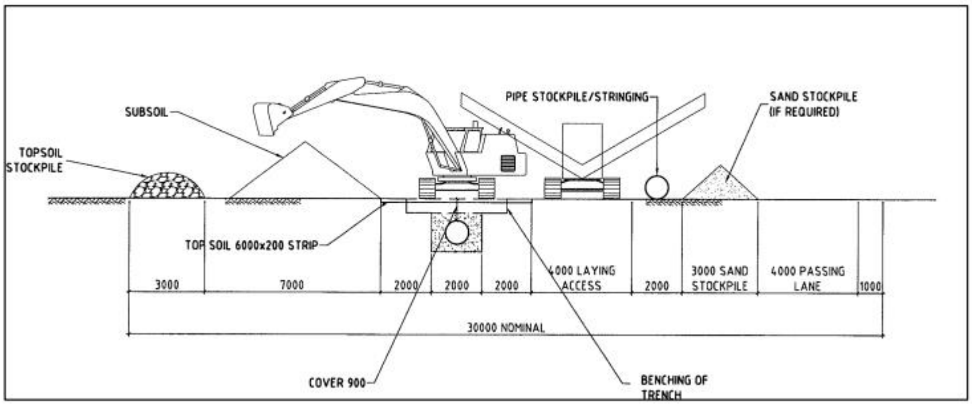
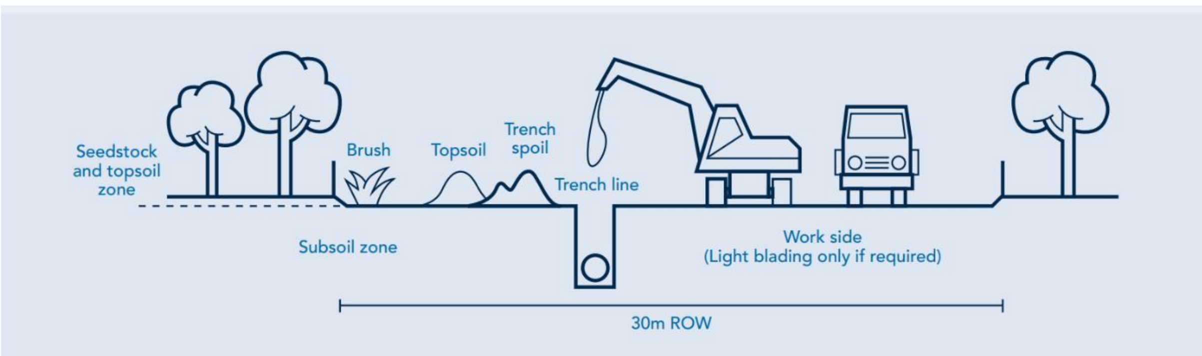



**Figure 4: Typical construction corridor layout for small diameter pipeline construction**




# Appendix S: Design Standard (VIVA Energy,2020)



## Appendix T: GCP Painted Marker

## Appendix U: GCP Surveying

# Appendix V: Camera Calibration Parameters

## Camera Calibration

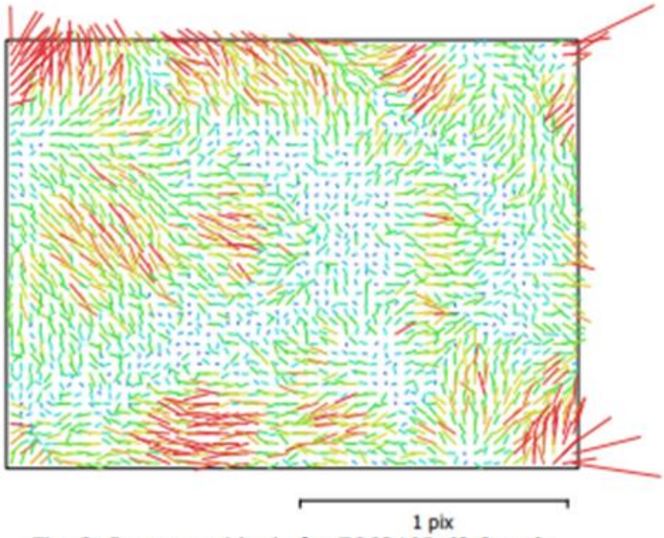



Fig. 2. Image residuals for FC6310R (8.8mm).

**FC6310R (8.8mm)**

511 images, precalibrated

| Type | Resolution | Focal Length | Pixel Size |
|---|---|---|---|
| **Frame** | **4864 x 3648** | **8.8 mm** | **2.61 x 2.61 µm** |

| | Value | Error | F | Cx | Cy | B1 | B2 | K1 | K2 | K3 | K4 | P1 | P2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **F** | **3709.51** | 0.31 | 1.00 | -0.01 | -0.11 | -0.02 | 0.03 | -0.92 | 0.52 | -0.30 | 0.22 | 0.01 | 0.10 |
| **Cx** | **-48.9772** | 0.039 | | 1.00 | 0.07 | -0.02 | 0.08 | 0.00 | 0.01 | -0.03 | 0.05 | -0.93 | -0.08 |
| **Cy** | **5.4791** | 0.037 | | | 1.00 | -0.07 | -0.00 | 0.10 | -0.06 | 0.04 | -0.03 | -0.09 | -0.95 |
| **B1** | **-0.0446682** | 0.0047 | | | | 1.00 | -0.01 | 0.03 | -0.04 | 0.04 | -0.04 | 0.03 | 0.08 |
| **B2** | **0.186327** | 0.0045 | | | | | 1.00 | -0.03 | 0.02 | -0.01 | 0.01 | -0.09 | 0.01 |
| **K1** | **-0.292041** | 5.4e-05 | | | | | | 1.00 | -0.80 | 0.62 | -0.53 | -0.00 | -0.09 |
| **K2** | **0.157062** | 0.0001 | | | | | | | 1.00 | -0.96 | 0.91 | -0.01 | 0.06 |
| **K3** | **-0.0819729** | 0.00015 | | | | | | | | 1.00 | -0.99 | 0.03 | -0.04 |
| **K4** | **0.0229489** | 7.7e-05 | | | | | | | | | 1.00 | -0.05 | 0.03 |
| **P1** | **2.26676e-05** | 1.9e-06 | | | | | | | | | | 1.00 | 0.10 |
| **P2** | **-0.000138216** | 1.9e-06 | | | | | | | | | | | 1.00 |

Table 2. Calibration coefficients and correlation matrix.

# Appendix W: UAV Processing Report

## Ground Control Points


Fig. 5. GCP locations and error estimates.
Z error is represented by ellipse color. X,Y errors are represented by ellipse shape.
Estimated GCP locations are marked with a dot or crossing.

| Count | X error (mm) | Y error (mm) | Z error (mm) | XY error (mm) | Total (mm) |
|---|---|---|---|---|---|
| 11 | 2.81411 | 3.52051 | 3.94444 | 4.50702 | 5.98931 |

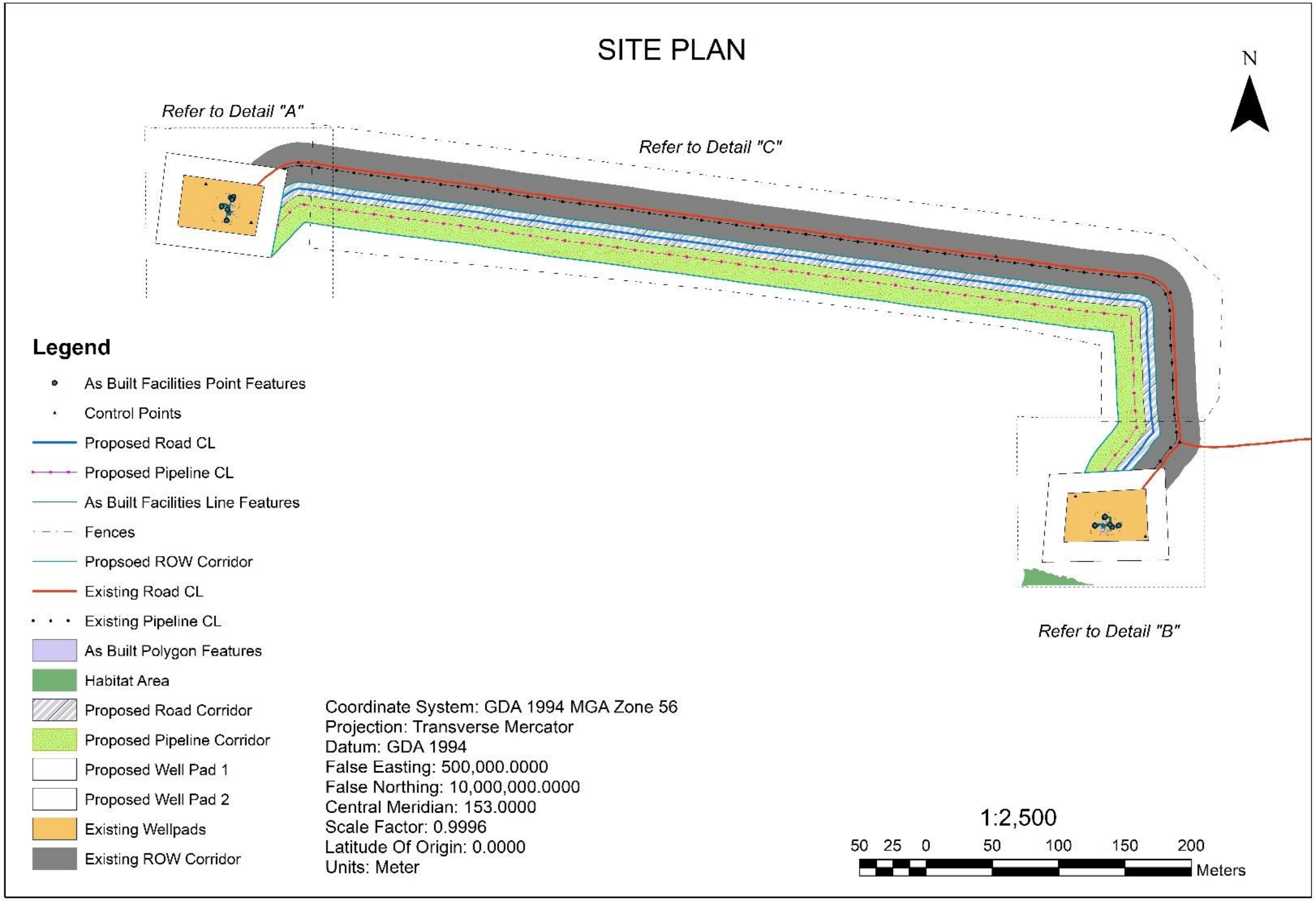
Table 5. Control points RMSE.
X - Easting, Y - Northing, Z - Altitude.

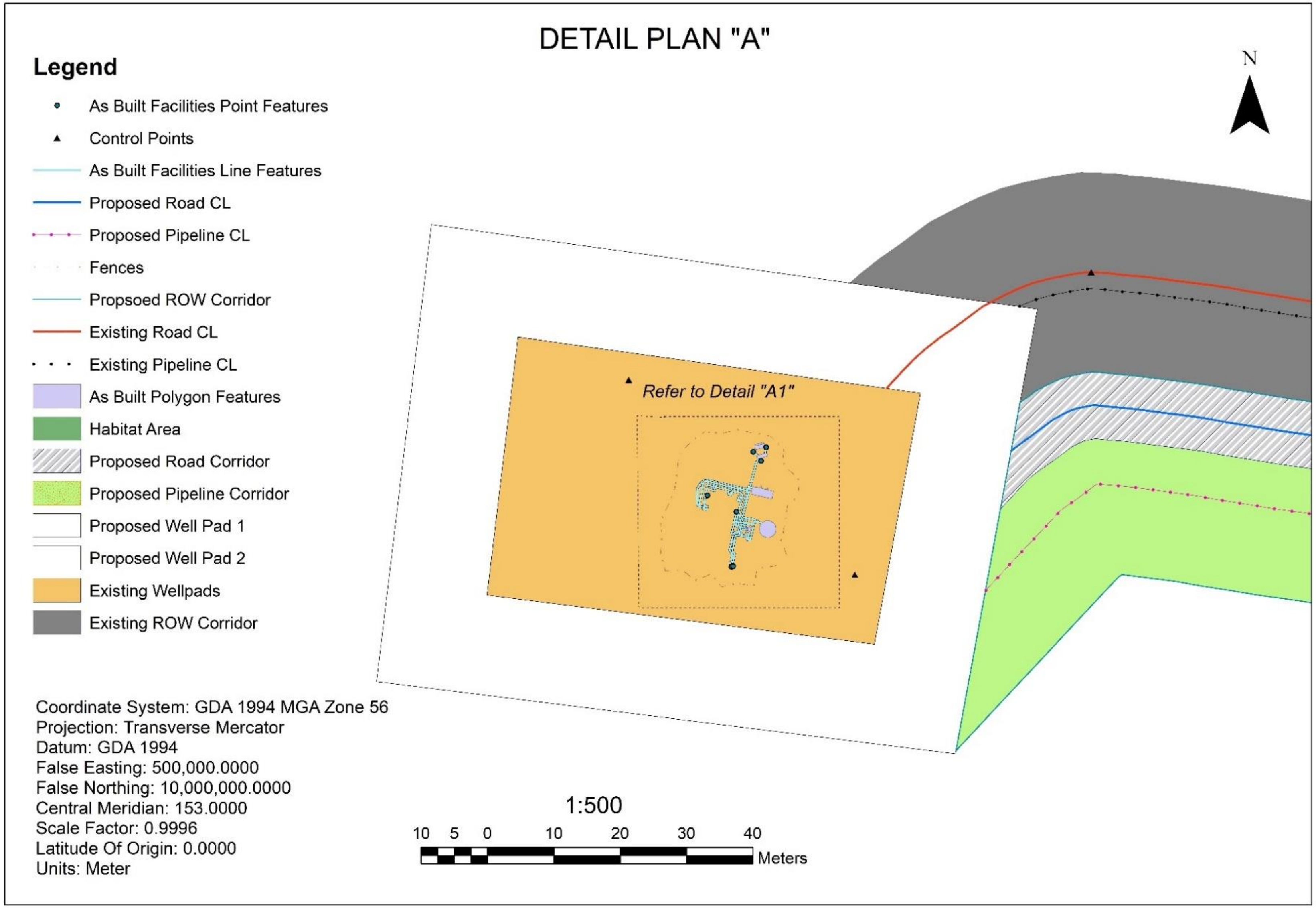
# Processing Parameters

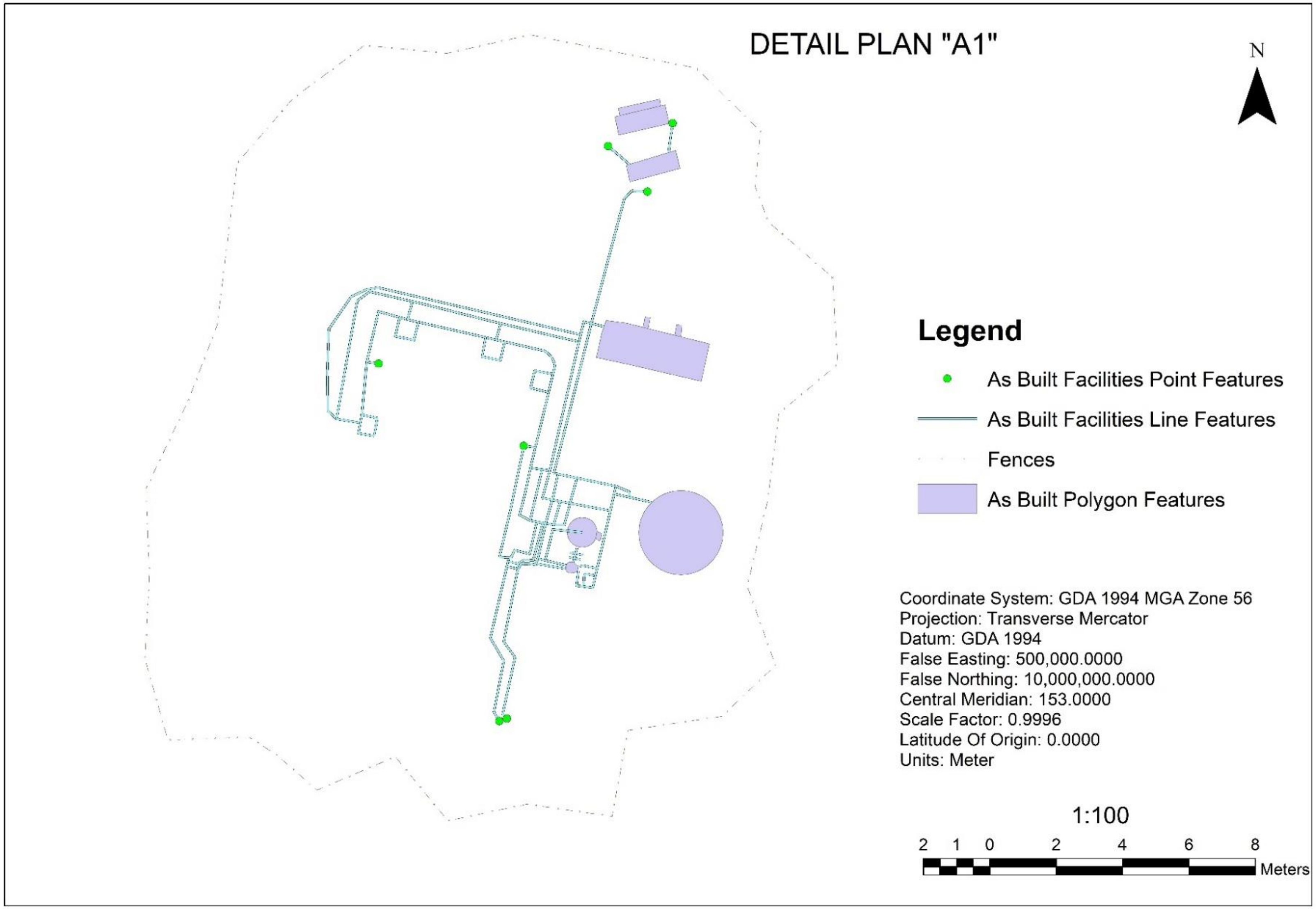
| | |
|---|---|
| **General** | |
| Cameras | 617 |
| Aligned cameras | 617 |
| Markers | 11 |
| **Shapes** | |
| Polygon | 1 |
| Coordinate system | GDA94 / MGA zone 56 (EPSG::28356) |
| Rotation angles | Yaw, Pitch, Roll |
| **Tie Points** | |
| Points | 544,592 of 562,597 |
| RMS reprojection error | 0.210966 (0.667252 pix) |
| Max reprojection error | 2.78624 (37.9403 pix) |
| Mean key point size | 2.86414 pix |
| Point colors | 3 bands, uint8 |
| Key points | No |
| Average tie point multiplicity | 4.75522 |
| **Alignment parameters** | |
| Accuracy | High |
| Generic preselection | Yes |
| Reference preselection | Source |
| Key point limit | 40,000 |
| Key point limit per Mpx | 1,000 |
| Tie point limit | 4,000 |
| Exclude stationary tie points | Yes |
| Guided image matching | No |
| Adaptive camera model fitting | Yes |
| Matching time | 5 minutes 38 seconds |
| Matching memory usage | 860.39 MB |
| Alignment time | 8 minutes 31 seconds |
| Alignment memory usage | 363.55 MB |
| **Optimization parameters** | |
| Parameters | f, cx, cy, k1-k3, p1, p2 |
| Adaptive camera model fitting | Yes |
| Optimization time | 53 seconds |
| Date created | 2023:05:04 04:24:57 |
| Software version | 2.0.1.16069 |
| File size | 75.31 MB |
| **Depth Maps** | |
| Count | 617 |
| **Depth maps generation parameters** | |
| Quality | High |
| Filtering mode | Moderate |
| Max neighbors | 16 |
| Processing time | 34 minutes 48 seconds |
| Memory usage | 4.63 GB |

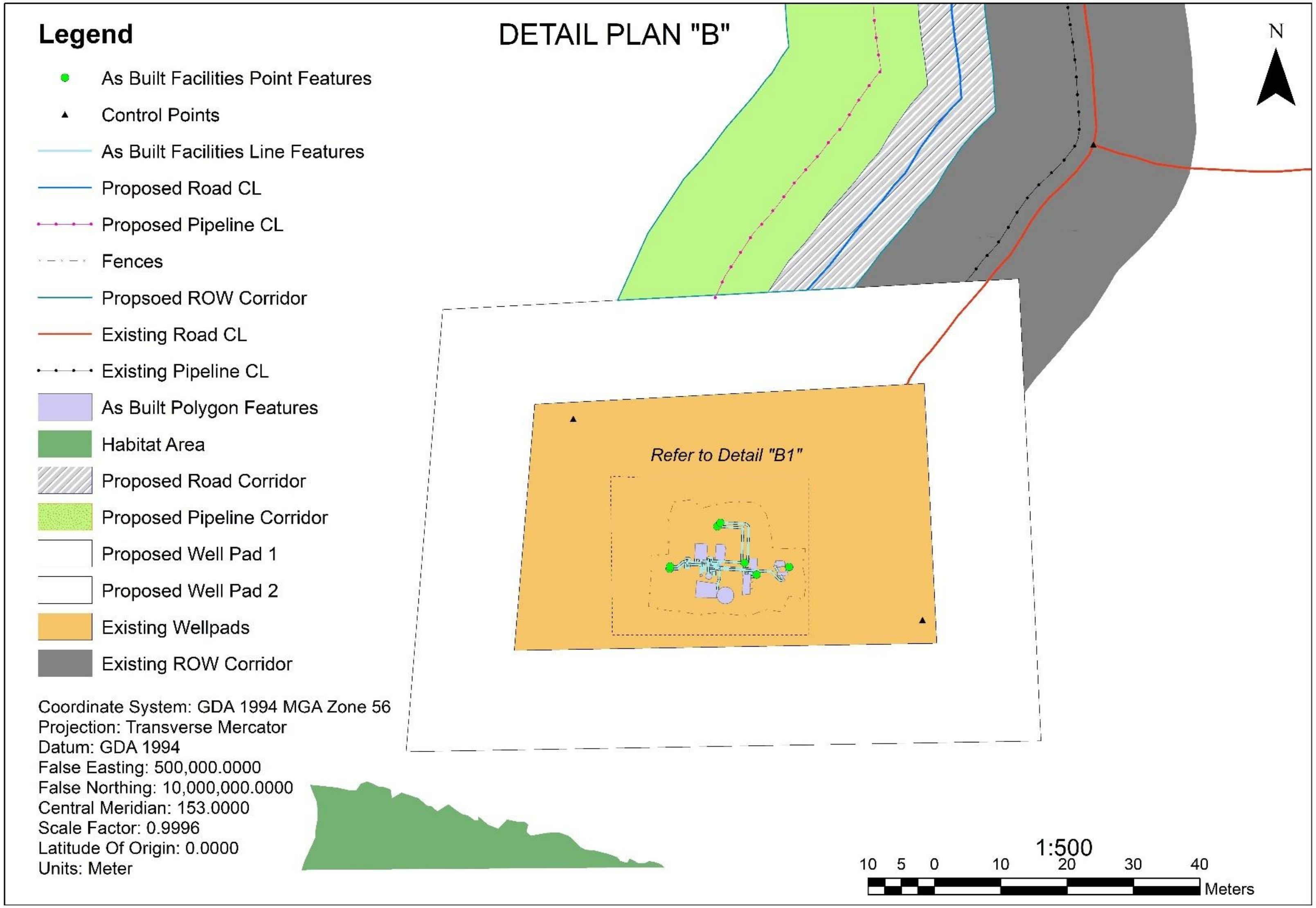
| | |
|---|---|
| **Point attributes** | |
| Position | |
| Color | 3 bands, uint8 |
| Normal | |
| Confidence | |
| **Point classes** | |
| Created (never classified) | 276,897,975 |
| **Depth maps generation parameters** | |
| Quality | High |
| Filtering mode | Moderate |
| Max neighbors | 16 |
| Processing time | 34 minutes 48 seconds |
| Memory usage | 4.63 GB |
| **Point cloud generation parameters** | |
| Processing time | 1 hours 22 minutes |
| Memory usage | 9.08 GB |
| Date created | 2023:05:04 07:19:03 |
| Software version | 2.0.1.16069 |
| File size | 3.93 GB |
| **DEM** | |
| Size | 42,238 x 17,845 |
| Coordinate system | GDA94 / MGA zone 56 (EPSG::28356) |
| **Reconstruction parameters** | |
| Source data | Point cloud |
| Interpolation | Enabled |
| Processing time | 4 minutes 8 seconds |
| Memory usage | 310.62 MB |
| Date created | 2023:05:04 07:30:51 |
| Software version | 2.0.1.16069 |
| File size | 830.26 MB |
| **Orthomosaic** | |
| Size | 73,482 x 31,045 |
| Coordinate system | GDA94 / MGA zone 56 (EPSG::28356) |
| Colors | 3 bands, uint8 |
| **Reconstruction parameters** | |
| Blending mode | Mosaic |
| Surface | DEM |
| Enable hole filling | Yes |
| Enable ghosting filter | No |
| Processing time | 12 minutes 34 seconds |
| Memory usage | 2.15 GB |
| Date created | 2023:05:04 07:39:40 |
| Software version | 2.0.1.16069 |
| File size | 15.76 GB |
| **System** | |
| Software name | Agisoft Metashape Professional |
| Software version | 2.0.1 build 16069 |
| OS | Windows 64 bit |
| RAM | 31.78 GB |
| CPU | Intel(R) Core(TM) i7-9700K CPU @ 3.60GHz |
| GPU(s) | NVIDIA GeForce RTX 2080 |

## Appendix X: 2D Plan and Associated Spatial Information

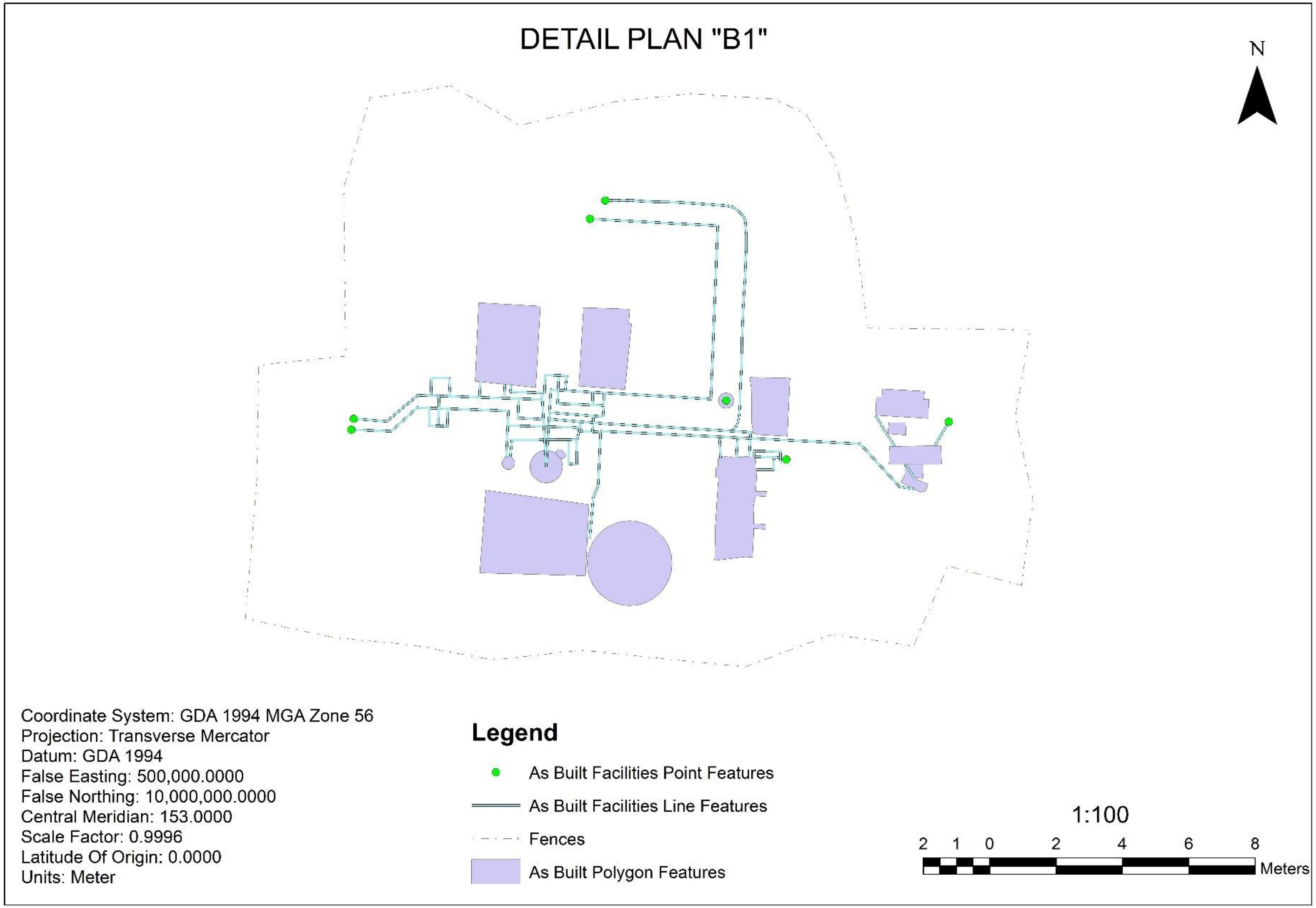



DETAIL PLAN "A"
Legend
As Built Facilities Point Features
Control Points
As Built Facilities Line Features
Proposed Road CL
Proposed Pipeline CL
Fences
Propsoed ROW Corridor
Existing Road CL
Existing Pipeline CL
As Built Polygon Features
Habitat Area
Proposed Road Corridor
Proposed Pipeline Corridor
Proposed Well Pad 1
Proposed Well Pad 2
Existing Wellpads
Existing ROW Corridor
N
Refer to Detail "A1"
Coordinate System: GDA 1994 MGA Zone 56
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000.0000
False Northing: 10,000,000.0000
Central Meridian: 153.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter
1:500
10 5 0 10 20 30 40
Meters


DETAIL PLAN "A1"
N
Legend
As Built Facilities Point Features
As Built Facilities Line Features
Fences
As Built Polygon Features
Coordinate System: GDA 1994 MGA Zone 56
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000.0000
False Northing: 10,000,000.0000
Central Meridian: 153.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter
1:100
2 1 0 2 4 6 8
Meters

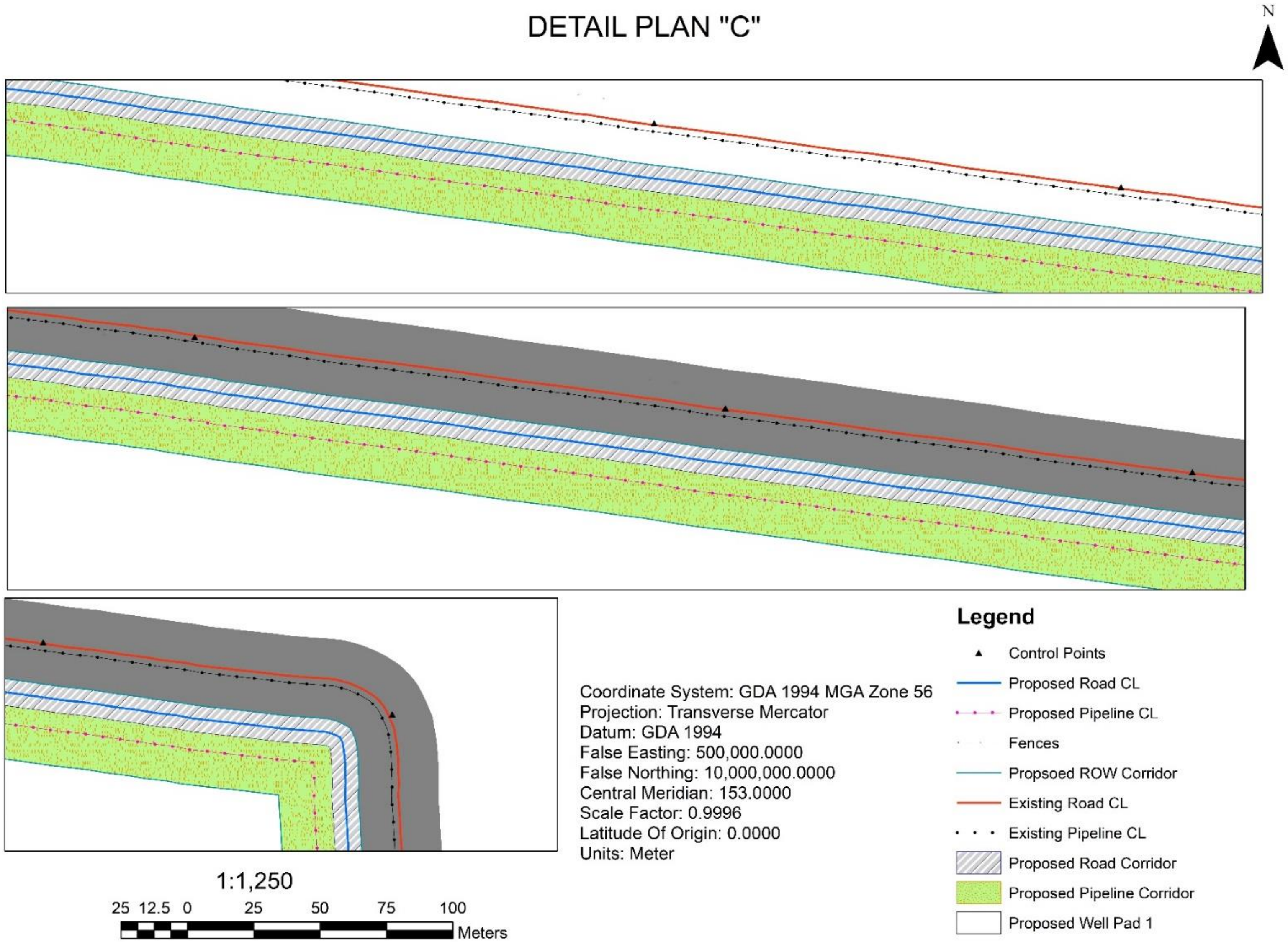


Legend
DETAIL PLAN "B"
N
As Built Facilities Point Features
Control Points
As Built Facilities Line Features
Proposed Road CL
Proposed Pipeline CL
Fences
Propsoed ROW Corridor
Existing Road CL
Existing Pipeline CL
As Built Polygon Features
Habitat Area
Proposed Road Corridor
Proposed Pipeline Corridor
Proposed Well Pad 1
Proposed Well Pad 2
Existing Wellpads
Existing ROW Corridor
Refer to Detail "B1"
Coordinate System: GDA 1994 MGA Zone 56
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000.0000
False Northing: 10,000,000.0000
Central Meridian: 153.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter
1:500
10 5 0 10 20 30 40
Meters



DETAIL PLAN "B1"
N
Coordinate System: GDA 1994 MGA Zone 56
Projection: Transverse Mercator
Datum: GDA 1994
False Easting: 500,000.0000
False Northing: 10,000,000.0000
Central Meridian: 153.0000
Scale Factor: 0.9996
Latitude Of Origin: 0.0000
Units: Meter
Legend
As Built Facilities Point Features
As Built Facilities Line Features
Fences
As Built Polygon Features
1:100
2 1 0 2 4 6 8
Meters

# DETAIL PLAN "C"



## Appendix Y: Georeferenced 3D Model