BIM and Game Engines Coupling for Digital Twin Implementation in the AEC Industry: a use-case analysis.

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Preface

Completing this thesis has been a tough and gratifying journey, and I am glad to express my deepest gratitude to everyone who has played a part in making it a reality. This academic endeavour would have been significantly more difficult without their unfailing support, patience, and encouragement.

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I'd like to extend my heartfelt appreciation to my family, particularly my mother and sister. Your everlasting love and support have been the foundation of my strength. Your faith in my talents, even from afar, has given me the confidence to face challenges and pursue my objectives with zeal. Your sacrifices and persistent support have been the driving force behind my achievement, and I will be eternally grateful for your unending love and care.

Finally, my thesis is a monument to the joint efforts and support of many people who have had a great impact on my life. Their belief in my ability has been the foundation of my success. I send my profound gratitude to all those mentioned above, as well as those whose names may not appear on these pages but whose imprint is everlasting in my heart. This thesis is a reflection of both your contributions and my own work. Thank you for being such an important part of this incredible adventure.

Sincere appreciation,

Luisa Caporalini,
Amsterdam, Netherlands
Friday 28th of July, 2023

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Executive Summary

Introduction and Problem Statement:

The construction industry has seen a transformative shift with Digital Twin (DT) technology, providing virtual representations of real-world objects for improved project design and management (Sacks et al., 2020). Integrating Building Information Modelling (BIM) with Game Engines (GEs) like Unity3D is crucial for successful DT implementation in construction (Wang et al., 2022). However, research in this area is still in its early stages, and challenges remain in finding effective data exchange methods and workflows to transfer BIM data to GEs seamlessly (Khajavi et al., 2019). Addressing these gaps is essential for ensuring successful DT implementation in the industry as technology continues to evolve.

Purpose of the Research:

This research aims to bridge knowledge gaps in integrating BIM and GEs for DTs in construction projects. It evaluates synchronous and asynchronous Autodesk Revit to Unity3D data exchange methods from current literature, including commercial software applications, for various DT applications. The goal is to identify optimised workflows for each DT use case, improving efficiency and decision-making throughout the construction lifecycle. The findings will provide valuable insights and guidelines for successful BIM and GE integration, enabling more efficient project design, construction, and maintenance, leading to sustainable and innovative buildings and infrastructure.

Research Question:

The main research question is formulated below:

For each different DT use case, what are the data exchange methods that would allow for consistent and useful BIM data retrieval?

This main question is answered through the following two sub-questions:

- **SRQ1:** What is the level of information required by each DT use case in terms of BIM data?
- **SRQ2:** To what extent do these exchange methods allow for Autodesk Revit BIM data visualization and manipulation in Unity3D Game Engine?

Research Steps:

The research development consists of four branches, each with a specific purpose related to the research objectives. Figure 1 graphically shows the methodology construction process.

Literature Review: The first branch conducts a comprehensive literature review to establish the data requirements for DT use cases in construction. By synthesizing existing knowledge, this branch identifies the essential data types needed for successful DT implementation in the construction industry.

Evaluation of Software Pipelines: The second branch evaluates existing software pipelines by analyzing documented ones in the literature and conducting a desktop search for relevant pipelines. The aim is to assess the capabilities and limitations of these pipelines in facilitating data exchange between Autodesk Revit and Unity3D, considering their suitability for DT implementation.

Comparative Analysis of Data Exchange Methods: The third branch focuses on comparing and evaluating the data exchange methods identified in the previous branch. Using the requirements established in the literature review, this branch aims to identify the most suitable approaches for effective and efficient data transfer between Autodesk Revit and Unity3D for DT implementation in construction.

Development of a Prototypical Data Exchange Method: The fourth branch involves creating a practical and functional solution for exporting data from Autodesk Revit to Unity3D. Utilizing Dynamo, a visual programming platform, this branch aims to demonstrate a viable approach for seamless data transfer and integration between the two software tools.

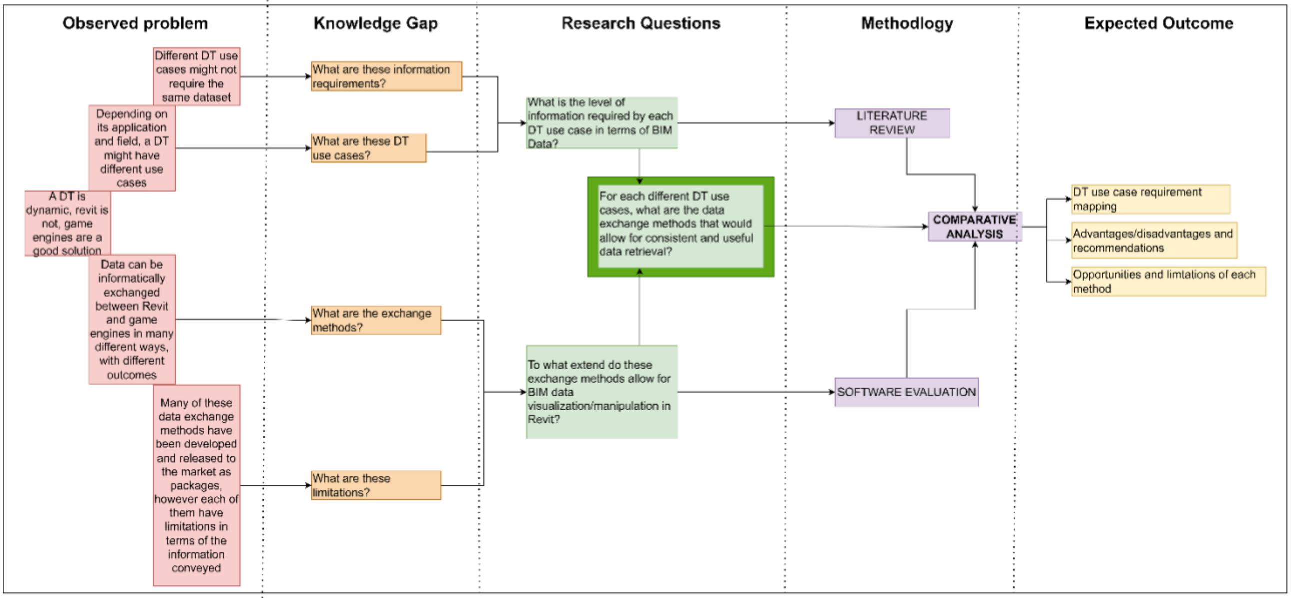

Figure 1 - Methodology Overview

Main results:

The main results for this thesis concerned:

- A thorough **analysis** of construction Digital Twin use cases requirements.
- An extensive list of **advantages, disadvantages** of each data exchange methods based both on method type and file format.
- Future **recommendations** for the virtual development of DTs in the construction industry.
- A **prototypical data exchange method** based on a sample model.

Conclusions & Recommendations

In conclusion, the discussion highlights strategies for enhancing the data exchange process to achieve effective DT implementation in construction. Bi-directional and real-time data exchange methods are recommended to ensure synchronisation with the physical counterpart, enabling accurate monitoring, analysis, and simulation. Proposed improvements for data exchange between Autodesk Revit BIM and Unity3D involve selecting appropriate file formats and incorporating polygon reduction techniques for efficient and seamless data transfer.

The consideration of emerging technologies like object behaviour data, sensor data, and environmental data offers new possibilities for realistic simulations and comprehensive monitoring within the DT environment. The contributions made in this research provide valuable insights for researchers, practitioners, and stakeholders, identifying DT use cases and analysing required data types. This understanding supports the development of tailored DT applications to optimise their effectiveness in the construction industry.

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List of Abbreviations

AEC(O) – Architecture, Engineering and Construction (and Operation)

AR – Augmented Reality

BAS – Building Automation System

BIM – Building Information Modelling

CAD – Computer-Aided Design

(c)MMS – Computerized Maintenance and Management Systems

CPS – Cyber-Physical Systems

CNN – Convolutional Neural Network

DBMS – Database Management Systems

DES – Discrete Event Simulation

DT(s) – Digital Twin(s)

ERP – Enterprise Resource Planning

ETF – EuroTube Foundation

FM – Facility Management

GE(s) – Game Engine(s)

GIS – Geographical Information System

IoT – Internet of Things

LBS – Location Breakdown Structure

MCDM – Multi-Criteria Decision Making

MEP – Mechanical, Electrical and Plumbing

MR – Mixed Reality

O&M – Operation and Maintenance

SDK – Software Developer Kit

SMF – Smart Mobile Factory

VR – Virtual Reality

VDC – Virtual Design and Construction

WBS – Work Breakdown Structure

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1. Introduction

1.1 Research background

In recent years, the development of Digital Twin (DT) technology has revolutionized the way that architects, engineers, and construction professionals design and manage building projects (Caramia et al., 2021), representing a step in the evolution of manufacturing, being capable of facilitating the implementation of Industry 4.0 principles (Sacks et al., 2020). By collecting real-world data through simulation technology, DTs create a digital representation that accurately reflects the object. They enable real-time observation of the digital entity's operation, monitoring of operational parameters, and further simulation of the virtual world using accumulated data and artificial intelligence (Wang et al., 2022).

Building Information Modelling (BIM), a well-established technology in the construction industry, provides a comprehensive 3D model-based approach for project design, coordination, and management (Shahat et al., 2021). However, there is a need to extend the capabilities of BIM to enable the creation and utilization of digital twins in construction projects. This extension requires seamless data exchange and integration between BIM platforms and Game Engines (GEs), such as Unity3D, which offer interactive visualization and simulation capabilities (Khajavi et al., 2019).

While the potential benefits of integrating BIM and game engines for digital twin implementation in construction are evident, the research and development in this area are still at an early stage. There is a lack of comprehensive understanding regarding the most effective data exchange methods, workflows, and tools to enable the seamless transfer of BIM data to game engines for digital twin applications (Khajavi et al., 2019).

1.2 Research Gap & Motivation of the Study

Despite being in its early stages, research on DT development has seen significant progress, with numerous scholars contributing to the field. One notable area of focus has been the development of frameworks that provide a holistic view of the DT, incorporating diverse data sources and enabling comprehensive asset monitoring and analysis (Sacks et al., 2020). Additionally, scholars have also explored detailed methods to overcome technical barriers associated with DT implementation, such as polygon reduction techniques to optimize computational efficiency and the development of efficient BIM data exchange methods to ensure seamless integration with existing workflows (Chen et al., 2020).

Furthermore, the implementation of DTs in the construction industry has been explored across multiple application areas, commonly referred to as use cases. These use cases encompass diverse functionalities, extending beyond mere visualization to encompass simulation, analysis, and even building control. Moreover, DTs have shown promise in building control, facilitating remote monitoring and management of various systems, including HVAC, lighting, and energy consumption. Through comprehensive research and experimentation, scholars have demonstrated the versatility and potential of DTs in addressing various construction challenges, enhancing efficiency, and improving overall project outcomes (Li et al., 2020).

The coupling of BIM with GEs in the construction field is applied to similar use cases as DTs. GEs, considered a key technology in DT implementation, provide interactive visualization, simulation, and analysis capabilities. By merging BIM with GE, researchers have explored applications such as simulating and evaluating construction processes, performing discrete event simulations, and supporting asset management (Edwards et al., 2015). This integration leverages the data-rich nature of BIM and the dynamic capabilities of GEs, enabling enhanced construction workflows and decision-making.

While data exchange processes between BIM and GE have already been tested, developed and proven possible in several different studies, developers might come to an impasse when faced with the choice of the most suitable data exchange method to fit their specific needs. Almost a decade ago, (Bille et al., 2014b) overviewed the conversion from BIM to GE and specifically from the BIM tool Autodesk Revit to the Unity3D3D game engine in a case study. Again in a second paper, (Bille et al., 2014b) overviews virtual environment development issues and outlines conversion pipelines from BIM to virtual environment via GE from the current literature, clustering the findings by the end goal for which the conversion was applied. This approach is very similar to categorization by use cases presented by this research. However, the fast pace in which technologies advance has caused both the papers presented by (Bille et al., 2014a; Bille et al., 2014b) to be outdated. Additionally, the research they proposed specifically focused on data file formats and specifically the transmission of geometrical, material and informational BIM data transfer, while nowadays uncertainty of methods encompasses more aspects such as software used and other BIM data types. The present research focuses on the latter, to fill the gap that involves the choice of data exchange methods among the suitable software commercially available, in relation to the file format used and the purpose of the DT, hence its use case.

1.3 Research scope, objectives, and questions

A construction project surely requires an extensive and comprehensive dataset, especially during the design phase (Liu et al., 2019). In current average practice, the dataset related to a construction project in the design phase almost entirely resides in BIM (Liu et al., 2019). However, in this phase, the digital model cannot be considered as a DT just yet, because it lacks the fundamental element of the physical counterpart (Sacks et al., 2020). This research hypothesizes that not all data within the BIM model remains relevant or useful in subsequent stages, such as the operation and maintenance of the constructed asset. In these phases, for example, a DT would extend the capability of a simple BIM model to include dynamic data for simulation or monitoring purposes. Irrelevant or excessive data can burden the DT, which is a virtual representation of the physical asset, and impede the smooth functioning of associated systems (Yu et al., 2023). One of the critical concerns arising from the presence of excessive data is the delay in data transfer between the physical asset and its virtual twin, causing lag in real-time monitoring and decision-making processes (Havard et al., 2019).

To mitigate the negative consequences of excessive data, strategies that focus on data optimization and information management within the BIM model should be adopted. This involves identifying and prioritizing the necessary data elements for specific applications, eliminating redundant or irrelevant information, and establishing efficient data exchange mechanisms, as different data exchange methods allow different degrees of data manipulation and extraction. The construct of a data exchange method, also called data exchange "workflow" or "pipeline", offers different features depending on file formats, software, and semantic definitions used. The features extent and the limitations that these data exchange methods are subject to, can hinder the development of the DT, and restrain its implementation. Regarding this aspect, this research also hypothesizes that the measurement of the extent of data extraction and manipulation that each data exchange method can be shaped to the requirements of a specific DT use case. In other words, DT use cases rarely use all data types that reside in a BIM model to fulfill its specific use case purpose.

In summary, this research hypothesizes that specific requirements of each DT use cases can benefit more from specific characteristics of the data exchange workflows between BIM and GE, resulting in easier manipulation of the DT architecture by allowing for partial application of BIM models in DT use. Therefore, the aim of this thesis is to evaluate and compare the different synchronous and asynchronous Autodesk Revit to Unity3D data exchange method proposed by current literature, including available commercial software applications, for different DT applications, with the goal of identifying the suitable workflows for each application.

To reach the stated objectives, the research will pursue the answering of the following research question and sub-questions:

RQ: For each different DT use case, what are the data exchange methods that would allow for consistent and useful BIM data retrieval?

> **SRQ1:** What is the level of information required by each DT use case in terms of BIM data?
>
> **SRQ2:** To what extent do these exchange methods allow for Autodesk Revit BIM data visualization and manipulation in Unity3D Game Engine?

2. Literature Review

In this chapter, a thorough literature review on DT technology within the Architecture, Engineering, and Construction (AEC) industry is presented. The following key areas are covered:

Firstly, the concept and characteristics of DTs are introduced, providing a foundational understanding, and establishing a framework for further exploration. Next, a wide range of use cases for DTs are examined, showcasing their practical applications and the benefits they bring to decision-making, operational optimization, and fostering innovation.

The chapter then delves into the various implementation technologies used in creating and maintaining DTs. These technologies encompass data acquisition, integration, visualization, and simulation tools, which form the backbone of DT development.

Furthermore, the integration of BIM and GEs is explored as an effective approach to enhance visualization, simulation, and collaboration within the AEC industry. This coupling offers new possibilities for improving design, analysis, and communication processes. Finally, the chapter concludes by summarizing the key findings derived from the literature review. It identifies gaps in current research and suggests potential avenues for future investigation, aiming to contribute to the ongoing discourse surrounding DT technologies in the AEC industry.

By conducting an extensive review of existing literature, this chapter provides a comprehensive understanding of DT technology, its applications, implementation technologies, and its integration with BIM and GE. This knowledge serves as a solid foundation for subsequent chapters and contributes to the overall comprehension of DT technology within the AEC domain.

2.1 Overview of the Digital Twin Concept

DTs have been a rising technological trend in the AEC industry for at least a decade. These models have been referred to as “Digital Twins” or “Digital Replicas” of buildings, and their role in simulating physical objects in real-time using sensors has been addressed by specialists (Nour El-Din et al., 2022). By collecting real-world data through simulation technology, DTs create a digital representation that accurately reflects the object. This technology enables real-time observation of the digital entity's operation, monitoring of operational parameters, and further simulation of the virtual world using accumulated data and artificial intelligence (Wang et al., 2022). (Nour El-Din et al., 2022) define DTs as the connection between technologies in the form of a digitized model of a physical asset, transmitting data in at least one direction, and monitoring the physical asset in real-time. In addition to this definition, it’s worth highlighting how the three main components of a DT are a physical artifact, a digital counterpart, and data that connects them (Kořínek et al., 2021).
However many more researchers expand the concept definition to a more comprehensive level of detail. For example, (Zhang et al., 2022) define DTs as visual and digital models of physical objects that facilitate ongoing and bi-directional dynamic data exchange between the physical and digital realms, enabling real-time monitoring, updating, simulating, analysing, controlling, predicting, and optimizing processes as well as validating and seamlessly coordinating activities throughout the life cycle of the object. To comply with this highly demanding definition, DTs utilize various data sources, including physical models, sensor updates, and operating history, to integrate simulation processes across multiple disciplines, physical aspects, scales, and probabilities. These simulations are performed in a virtual space to encompass the complete life cycle of the corresponding physical equipment (Wang et al., 2022). Chapter 2.3 will elaborate more on the DT implementation technologies.

2.1.1 Digital Twin, Digital Shadow, and Digital Model

There is a significant difference between DTs and current digital 3D models and 3D systems (Sepasgozar, 2021). Current literature defines three levels of integration between physical and digital assets, namely DT, Digital Shadow and Digital Model (El Jazzar et al., 2020). This difference between them can be understood based on the flow of data and the level of interaction between the physical and digital objects (Kim & Kim, 2020). A DT enables bi-directional communication between the physical and digital assets, allowing for automatic data exchange and synchronization (Rasheed et al., 2020). Instead, a digital shadow involves an automated one-way data flow from the physical to the digital object, where changes in the physical object result in corresponding changes in the digital object. It represents a one-sided reflection of the physical system in the digital realm (Wei et al., 2022). Lastly, a digital model refers to a virtual representation of a physical system with manual data flow between the two objects (Douglas et al., 2021). It represents a static representation of the physical system without the dynamic interaction and synchronization capabilities of a DT (Sepasgozar, 2020). The distinction between these concepts is crucial in understanding the level of data integration, interaction, and automation between the physical and digital realms in the context of DTs in the AEC-FM industry.

2.2 Digital Twin use cases in the AEC industry

The DT technology involves the creation of a digital representation of a physical construction project, which can take various forms and serve different purposes throughout the many stages of the project life cycle. Predicting maintenance needs, real-time asset visualization, behaviour and performance monitoring, and operation simulation and optimization (Lee & Lee, 2021) are all examples of different purposes for which a DT digital representation is required for the performance and monitoring phase. Similarly, in the Implementation phase, DTs can be employed to simulate construction (Bourlon & Boton, 2019) and Discrete Event Simulation (Sandoval et al., 2018). These DTs purposes will hereby be referred to as DT use cases.

When considering DT representations, it is important to recognize that their required level of information may vary depending on the specific use case at hand. DTs are not a one-size-fits-all solution, and their use cases can influence the extent of information they encompass.

In the context of construction, a DT use case refers to the application of DT technology to enhance and optimize different aspects of the construction process (Guo & Lv, 2022). In some use cases applications, such analysis and simulation of specific aspects of a DT virtual model, a simplified representation of the DT may be sufficient to analyse and optimize specific aspects. This might involve focusing on key parameters or variables rather than encompassing the entire breadth of information. On the other hand, for use cases that involve more realistic interpretation of the virtual model, a more comprehensive spectrum of data needs to be integrated. Therefore, the level of information required for a DT can vary depending on the specific construction use case and its corresponding required data integration level.

With a focus on BIM capabilities towards real-time sensing data for building environment monitoring and management, (Menassa, 2021) identified several research domains, highlighting their relevance and support towards DT applications. These research domains are: (1) Construction Process Monitoring; (2) Energy Performance Management; (3) Indoor Environment Monitoring; (4) Indoor Thermal Comfort; (5) Space Management; (6) Hazard Monitoring and (7) CommUnity3D Monitoring.

(Caramia et al., 2021) identified six mainstream DT research fields in which the AEC-FM industry is studied. These are: (1) DT in Facility Lifecycle Management; (2) DT-Information Integration Standards; (3) DT-Based Occupants-Centric Building Design; (4)DT-Based Predictive Maintenance; (5) Semantic DT for Facility Maintenance; (6) DT-Based Human Knowledge. However, the methodology used for the scientometric and clustering analysis is found to be unadaptable to the purpose of this research as overlapping keywords were found to be overriding DT applications that could be considered DT use-cases themselves. For example, maintenance management, energy management, space management, asset management, building performance, control management, sustainability management, emergency management, and other building management tasks are all included in Facility management (FM) (Caramia et al., 2021).

In their paper, (Jiang et al., 2021) identified the research clusters of DT in the Civil Engineering sector dividing them by project phase, namely Design, Construction, and Operations & Maintenance (O&M). However, it is argued in the article that, in the absence of a physical counterpart, a DT can only be built partially, therefore only at the full completion of a project, hence the O&M phase, a DT can have a realistic application. For this reason, this paper will only take into consideration the following DT applications on operation and maintenance, identified by (Jiang et al., 2021). These applications are: (1) Defect detection; (2) Asset Monitoring; (3) Analysis and diagnosis; (4) Decision Making; (5) Automatic Control; (6) Retrofitting and Demolishing; (7) Comprehensive Asset Management.

Similarly, (Boje et al., 2020) discussed the DT uses from across engineering fields and revealed disparate potential methods and technologies to be considered for DTs. The study further simplified the DT use cases into 3 main use cases: (1) Sensing, (2) Monitoring, (3) Life Cycle.

Other scholars also clustered use cases of DTs in Construction. In the literature review section of previous scholars' research, it is noticeable how clusters of research fields often align with the definition of DT use case. An overview of the DT use cases found in the literature can be seen in Table 1, proposing a clustering method for the use cases found in literature under 7 main categories. These are (1) Construction Progress Monitoring, (2) Construction Process Management, (3) Safety Management & Hazard Monitoring, (4) Facility Management, (5) Energy Performance Assessment & Management, (6) Building Operation Control and Condition Monitoring, and (7) Space & People Management. It needs to be noted that the Space & People Management use case is not further considered for the remainder of this research as no sufficient technical information was found in current literature supporting BIM and GEs integration for DT development.

Table 1 - DT Use Cases Clusterization

Construction Progress Monitoring

Construction Progress Monitoring and Management	(Jiang et al., 2021)
Automated Site Progress Monitoring	(Boje et al., 2020)
Enhanced Site Sensing	(Boje et al., 2020)
Construction Process Monitoring	(Menassa, 2021)

Construction Process Management

Materials Monitoring and Management	(Jiang et al., 2021)
Machinery Monitoring and Management	(Jiang et al., 2021)
Optimized Construction Logistics and Scheduling	(Boje et al., 2020)
Construction Management	(Nour El-Din et al., 2022)2022)

Safety Management & Hazard Monitoring

Real-time Site Safety Detection	(Boje et al., 2020)
Construction Safety Monitoring and Management	(Jiang et al., 2021)
Hazard Monitoring	(Menassa, 2021)
Infrastructure Risk Management	(Zhang et al., 2022)

Facility Management

Asset Monitoring	(Jiang et al., 2021)
Facility Management	(Nour El-Din et al., 2022)
Operations and Maintenance	(Jiang et al., 2021)
Predictive Maintenance	(Khajavi et al., 2019)
Comprehensive Asset Management	(Jiang et al., 2021)
Defect Detection	(Jiang et al., 2021)
Facility Monitoring	(Zhang et al., 2022)

Energy Performance Assessment & Management

Energy Performance Management	(Menassa, 2021)
Energy Performance Assessment and Management	(Zhang et al., 2022)

Building Operation Control & Condition Monitoring

Indoor Environment Monitoring	(Menassa, 2021)
Indoor Thermal Comfort	(Menassa, 2021)
Energy Use, Air Pollution, and Water Quality Analysis	(Zhang et al., 2022)
Tenant Comfort Enhancement	(Khajavi et al., 2019)
Resource Consumption Efficiency	(Khajavi et al., 2019)
Climate, Carbon, and Circular Economy Outcome Analysis	(Zhang et al., 2022)
Infrastructure Conditions Monitoring	(Zhang et al., 2022)
Structural Health Monitoring	(Nour El-Din et al., 2022)

Space & People Management

Construction Quality Monitoring and Management	(Jiang et al., 2021)
Space Management	(Menassa, 2021)
Workers Monitoring and Management	(Jiang et al., 2021)
CommUnity3D Monitoring	(Menassa, 2021)

2.3 AEC Digital Twin implementation technologies

In the AEC and FM industry, various technologies are utilized for the creation of DTs. A DT in construction can encompass 2D drawings, 3D models, point clouds, Augmented Reality (AR) or Virtual Reality (VR) simulations, and other data-driven visualizations (Sepasgozar, 2020). These representations can be used at different stages of the construction process, from initial design and planning to construction operations and facility management. These technologies can be categorized into virtual technologies and physical technologies.

Physical technologies provide the means to capture real-world data, while virtual technologies process and analyse this data, creating an accurate and dynamic virtual representation. This convergence of physical and virtual components establishes a powerful symbiotic relationship, enabling the DT to act as a digital surrogate of the physical entity (Wei et al., 2022). Hence, DT implementation involves a harmonious integration of both physical and virtual technologies, emphasizing that it is not solely reliant on a single software solution. Instead, the concept of a DT encompasses a diverse range of components from both the physical and virtual realms.

Figure 2 shows an example of DT architecture framework and a set of relatable implementation technologies.

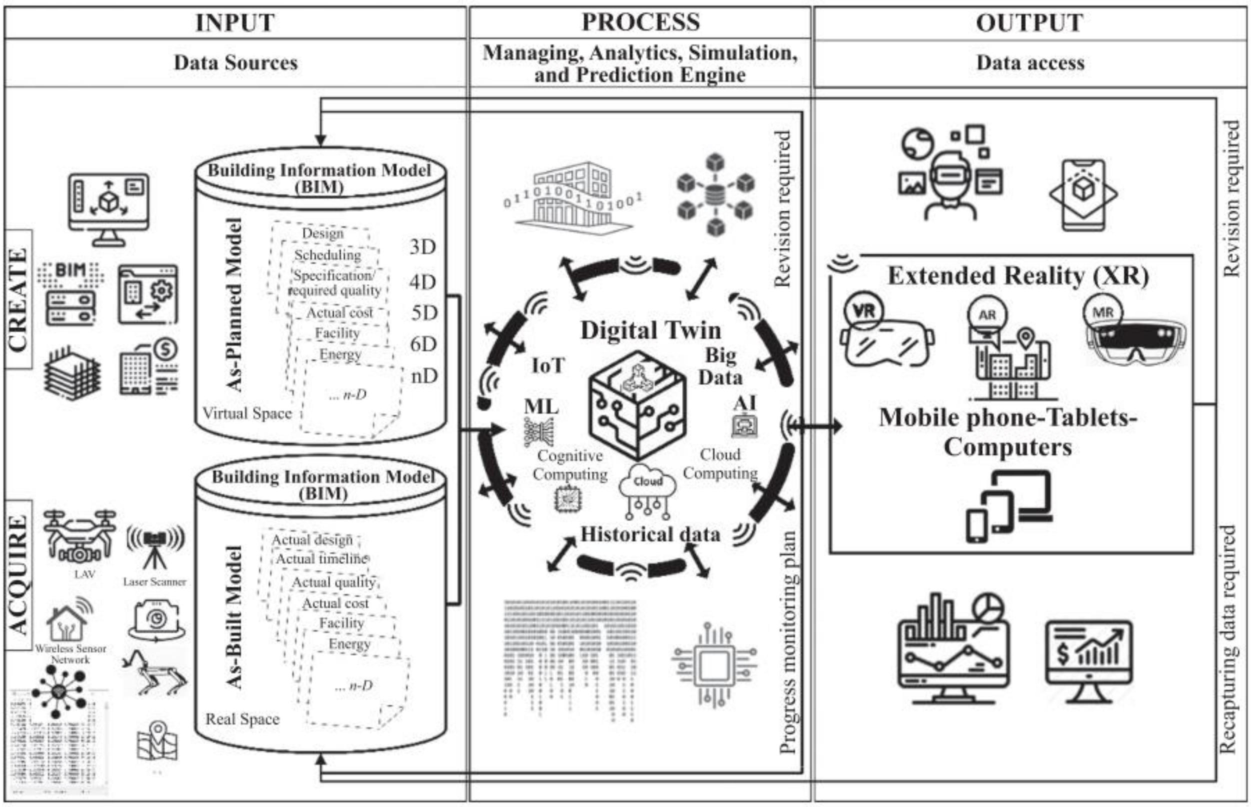

Figure 2 - DT Overview Example (Alizadehsalehi et al., 2020)

Virtual technologies play a crucial role in the development of DTs in the AEC-FM industry. VR and AR are widely used for immersive visualization and interaction with the DT (Sepasgozar, 2020). These technologies enable users to experience and manipulate the virtual representation of physical assets. Additionally, Mixed Reality (MR) combines virtual and physical elements, allowing users to interact with the DT in a real-world context (Sepasgozar, 2021).

DT technologies also rely on the integration of data from various sources. Building information modelling (BIM) is a key virtual technology that provides a digital representation of the physical asset, capturing its geometry, spatial relationships, and other relevant information (Liu et al., 2020). BIM serves as a foundation for the creation and management of the DT. Furthermore, semantic DTs utilize semantic technologies to enhance the understanding and interpretation of data within the DT (Hosamo et al., 2022).

On the other hand, the stream of monitored data that flows from the physical artefact to the digital processes are an essential component of the connection between physical and DTs (Sacks et al., 2020). The Internet of Things (IoT) plays a significant role in collecting data through sensors and devices embedded in the physical environment (Liu et al., 2020). These sensors can monitor various parameters such as temperature, humidity, occupancy, and energy consumption, providing valuable insights for the DT. Additionally, 3D scanning technologies are used to capture the physical asset's geometry and appearance, enabling accurate representation in the DT (Bosch-Sijtsema et al., 2021).

Other physical technologies that contribute to the creation of DTs in the AEC-FM industry include robotics and automation. Robots can be deployed for tasks such as inspection, maintenance, and construction, generating data that can be integrated into the DT. Furthermore, drones are utilized for aerial surveys and monitoring, capturing high-resolution imagery and generating 3D models of the physical asset (Bosch-Sijtsema et al., 2021).

In summary, the creation of DTs in the AEC-FM industry involves the use of various virtual and physical technologies. Virtual technologies such as VR, AR, and BIM enable immersive visualization and data integration, while physical technologies like IoT, 3D scanning, robotics, and drones facilitate real-time data capture from the physical asset. The combination of these technologies allows for the development and management of accurate and dynamic DTs in the AEC-FM industry.

2.3.1 Building Information Modelling (BIM)

BIM has played an increasingly central role in managing construction information throughout the lifecycle of a project, from the preparation and briefing to the use stage, which has helped to promote the digital transformation of the built environment (Nour El-Din et al., 2022). BIM is generally understood as an overarching term to describe a variety of activities in object-oriented Computer-Aided Design (CAD), which supports the representation of building elements in terms of their 3D geometric and functional attributes and relationships (Kořínek et al., 2021).

BIM can be defined as a functional, semantic and topological representation of any objects in an AEC project as virtual information (Safikhani et al., 2022). In other words, a BIM model is a digital representation of the physical and functional characteristics of a building or infrastructure asset, which can be used to analyse, optimize, and manage building performance in real-time by creating intelligent 3D models that integrate both geometric and non-geometric data, spatial, and semantic data, which can be used to support decision-making throughout the building lifecycle (Deng et al., 2021).

BIM has transformed the Architecture, Engineering, and Construction-Facility Management (AEC-FM) industry with its advanced technical capabilities. The adoption of BIM in the AEC industry has been driven by the recognition of its importance and the growing demands for exposure to BIM in built environment-related programs (Ding et al., 2015). BIM enables efficient data organization and management through BIM Database Management Systems (BIM-DBMS), facilitating the creation of detailed 3D models for accurate visualization and analysis of complex structures. Clash detection is another key capability of BIM, allowing potential conflicts between different building systems to be identified and resolved during the design phase, reducing errors during construction BIM also supports Virtual Design and Construction (VDC), enabling simulation-based analysis and decision-making to optimize construction processes and improve project outcomes (Song et al., 2017). The integration of Multi-Criteria Decision Making (MCDM) techniques with BIM further enhances its capabilities by optimizing multiple objectives and exploiting its benefits (Tan et al., 2021). Additionally, BIM has been recognized for its potential in promoting sustainable development in the AEC industry, with governments actively promoting its adoption through policy initiatives (Deng et al., 2021). Overall, BIM's technical capabilities in data management, visualization, clash detection, simulation, and decision-making have revolutionized the AEC-FM industry, improving efficiency and project outcomes (Merschbrock & Munkvold, 2012).

BIM plays a crucial role in the implementation of DTs in the AEC-FM industry. The integration of BIM with DTs enables the creation of accurate and detailed virtual representations of physical assets throughout their lifecycle (Shahat et al., 2021). BIM also provides the foundation for capturing and managing data and information during the design, construction, operation, and maintenance phases of assets (Yitmen et al., 2021).

The combination of BIM and DTs allows for the exchange, control, and utilization of data and information, facilitating effective asset management (Yitmen et al., 2021). BIM's capabilities in data management, visualization, clash detection, and simulation are instrumental in creating and maintaining DTs (Khan et al., 2021). The use of BIM in remote architectural practice and education also contributes to the implementation of DTs by supporting collaborative design processes (Lee et al., 2023) and the use cases levels of DTs in the AEC-FM industry are closely linked to the capabilities and utilization of BIM Data (Fuller et al., 2020).

BIM Data encompasses diverse multidisciplinary datasets within the model, enhancing projects with essential information (Lu et al., 2020). BIM Data is integral to the model, playing a crucial role in enriching the project throughout its various stages. Its primary objective is to comprehensively define key design elements, encompassing not only geometric aspects but also other dimensions facilitated by BIM such as time, costs, sustainability, facility management, and security (Harode et al., 2023).

In addition to geometric characteristics, a typical BIM model may include various types of data, such as material, design, planning (4D), cost (5D), structural, energy-related, environmental, production, on-site delivery, installation and assembly, health and safety, quality, commissioning, maintenance, and demolition-related data (Afsari et al., 2016).

However, it is not always advisable to include an excessive amount of information in the BIM model. Overloading the model with too much data can lead to confusion, difficulty in comprehension, redundancy, and challenges in production, utilization, and management (Afsari et al., 2016). On the other hand, including minimal amounts of information may reduce the BIM model to a basic three-dimensional representation of the building, lacking necessary details.

No clear definition and classification of BIM data was found in literature, therefore this research proposed a DT data classification that includes BIM data, as elements of the proposed dataset. Chapter 4.1 will elaborate more on the DT data type considered, their classification and its relative use case requirement assessment.

2.3.2 Game Engines (GE)

GEs are software platforms that provide the foundation for creating and developing interactive digital experiences, including games, simulations, and virtual environments. They offer capabilities for rendering graphics, managing input devices, and handling audio playback, among other fundamental subsystems. GEs are distinguished from graphics engines by their extensibility and ability to support a wide range of game development functionalities. They provide a flexible and reusable framework for managing large databases, facilitating the efficient use of GPUs and parallel processing techniques (Li et al., 2015).

GEs have gained attention in the AEC-FM industry for their potential applications. Their versatility and advanced visualizations make them valuable tools for various applications in the AEC-FM industry (Shahzad et al., 2022). So far, GEs have been utilized for various purposes, such as enhancing interactive building walkthroughs, visualizing complex environments, and facilitating training and education (Buhammood et al., 2020) and DT implementation (Shahzad et al., 2022). The use of GEs in DTs implementation provides a platform for interactive and engaging experiences, improving understanding, decision-making, and user engagement (Vichare et al., 2022). Also, GEs facilitate real-time data integration, allowing for the synchronization of the physical and digital assets in the DT (Segovia & Garcia-Alfaro, 2022).

2.3.3 Virtual Reality/ Augmented Reality

The integration of BIM with technologies such as IoT (Internet of Things) and VR further enhances the capabilities of DTs (Liu et al., 2020). Similarly, the integration of GE with technologies like VR has also been facilitating design visualization and improved the design review process (Wen & Gheisari, 2020).

AR is an innovative technology that can enable digital information to be over-laid on the real world to facilitate natural contact between users and their surroundings. AR was applied to the Architecture, Engineering, Construction and Operation (AECO) industry. AR makes user information readable and manipulable surrounding facilities by mixing virtual and the real world. However, currently, there are limited studies about implementing AR collaboration for FM (Alijani Mamaghani & Noorzai, 2023). Figure 3 clearly shows the role of VR and AR in relation to the virtual and real environment.

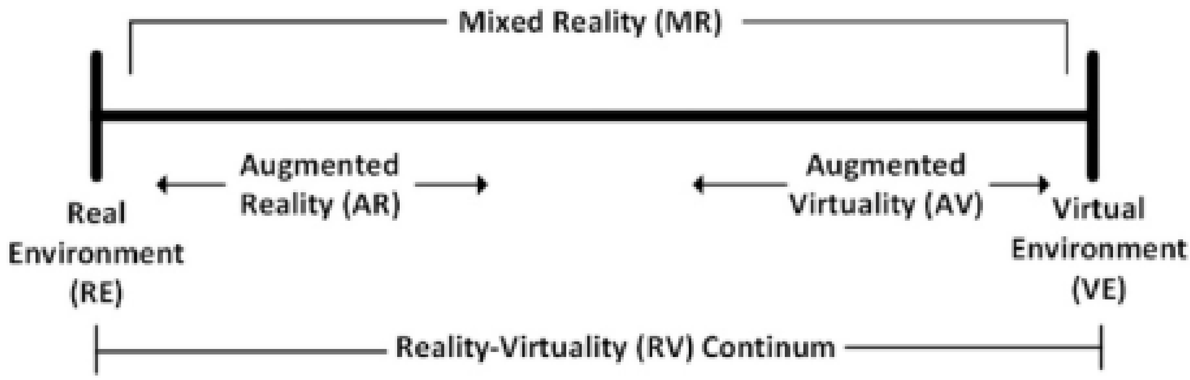

Figure 3 - Reality/Virtuality continum (Alizadehsalehi et al., 2020)

2.4 BIM and Game Engines coupling in the AEC industry

The coupling of GE with BIM in DTs implementation offers several benefits in the AEC-FM industry. By integrating GE with technologies like BIM and VR, DTs can be visualized and experienced in a realistic and engaging manner (Wen & Gheisari, 2020), enhancing interactive building walkthroughs and improving construction knowledge through the coupling of BIM and game engine technologies (Buhammood et al., 2020).

Lately, this coupling has been examined for its potential to improve data integration and decision-making in the AEC industry (Jiang et al., 2022) and for building performance analysis and optimization. (Lee & Lee, 2021) note that GEs can be used to create virtual replicas of physical structures, systems, or processes, providing AEC professionals with a tool for real-time monitoring, analysis, and optimization of building performance. (Kosse et al., 2022) and (Jiang et al., 2022) similarly suggest that GEs can enhance data integration and improve decision-making in the AEC industry. Other studies have explored the potential of GEs for building design and construction (Delbrugger et al., 2017) and for the creation of virtual environments in the AEC industry (Gerhard et al., 2020).

Furthermore, the research findings demonstrated that a universal data exchange pipeline solution does not exist. For instance, (Alijani Mamaghani & Noorzai, 2023) study utilized the IFC format for transferring geometry information, which is a common format for BIM data, but (Xiong et al., 2018) opted for the FBX format, which is a proprietary format developed by Autodesk. While both formats are capable of transferring data, the differences between them can lead to compatibility issues and a loss of precision.

On the other hand, (Bourlon & Boton, 2019) and (Osorio-Sandoval et al., 2022) both utilized the OBJ format for data exchange, but differed in their methods for transferring materials and textures. Bourlon's study used a separate material library to transfer materials, while Osorio-Sandoval's study utilized a custom method for transferring textures. Similarly, (Vincke, 2019) and (Buhammood et al., 2020) used the IFC format for metadata transfer, but (Khalili, 2021) utilized a custom format that was specific to his research.

A clear overview of the proposed data exchange solutions will be provided in Chapter 4.

Despite the potential benefits of coupling GE with DTs, there are also challenges associated with this approach. Further research and innovation in this area is necessary for the AEC industry to fully realize the potential of GE and DTs for building performance analysis and optimization.

(Yan et al., 2022) note that the integration of BIM and GE requires a comprehensive understanding of the different data models and formats used in different systems. They suggest that the use of semantic web technologies can facilitate data integration and interoperability. They propose a framework for semantic web-based BIM-game engine integration, which can enable the use of a single data model to represent the different data elements of BIM and GE. This approach can facilitate the creation of a unified data model that can be used for different applications, such as design visualization, construction simulation, and facility management.

(Wu & Kaushik, 2015) also highlight the importance of semantic web technologies for data integration in the AEC industry. Other challenges associated with BIM-game engine data integration include issues related to data privacy and security (Vincke, 2019), the lack of collaboration and communication among stakeholders (Lin et al., 2015; Nandavar et al., 2018), and the lack of standardization in the AEC industry (Anifowose et al., 2022; Du et al., 2016; Feng et al., 2022; Gueye & Boton, 2022; Motamedi et al., 2017; Shen et al., 2012).

Additionally, to what proposed to in the reviewed literature, some commercial solutions have been developed over the years to provide support for data exchange between BIM and GE. These solutions vary in terms of cost, ease of use, and technical capabilities. Some of the popular commercial solutions include Unity3D Reflect, A+T Sync, Tridify, Lumion Livesync, and PiXYZ. These solutions provide a more streamlined and standardized approach to data exchange, enabling DT developers to transfer BIM data to GEs with minimal effort. However, each solution has its own strengths and limitations, and it is important to evaluate them carefully before planning.

2.5 Conclusions of Literature Review

Although the literature review shows significant advancements in testing, developing, and establishing the feasibility of data exchange processes between BIM and GEs, developers often face challenges in selecting the most suitable data exchange method to meet their specific requirements. To clear connection, up to this date has been made in academics clearing announcing the differences in BIM data types of data exchange methods between construction software and use case requirements. This investigation considers the associated file formats and aligns them with the purpose of the DT in relation to its specific use case. By exploring these dimensions, this research aims to provide valuable insights into the decision-making process for selecting optimal data exchange methods for integrating BIM and GEs within the context of DT implementation in the construction sector.

The primary objective of this thesis is to comprehensively evaluate the various synchronous and asynchronous Autodesk Revit to Unity3D data exchange methods proposed in the existing literature and commercially available software applications. This evaluation aims to identify the most suitable workflows for different DT applications. To achieve these objectives, the research will address the research question and sub-questions stated in the Introduction.

Those are reported below for ease:

RQ: for each different DT use cases, what are the data exchange methods that would allow for consistent and useful BIM data retrieval?

> **SRQ1:** What is the level of information required by each DT use case in terms fo BIM data?
>
> **SRQ2:** To what extend do these exchange methods allow for BIM data visualization/ manipulation in Unity3D?

By delving into these research questions and sub-questions, this thesis aims to provide insights and recommendations regarding the most appropriate data exchange methods for different DT applications. The evaluation will consider the consistency and usefulness of BIM data retrieval, the specific information requirements for each use case, and the capabilities of the data exchange methods in terms of visualizing and manipulating BIM data within Unity3D.

3. Methodology

The research methodology for this master's thesis is provided in this chapter, with an emphasis on the methods for data exportation between Autodesk Revit and Unity3D for DT implementation in the construction sector. The approach consists of four distinct branches, each of which plays a specific role in achieving the objectives of the study. This introduction summarizes each branch in general terms and explains how each one advances the thesis.

In the first branch of the methodology, the first step is a thorough literature study. The primary objective of this branch is to define the standards for DT use cases in the construction industry, specifically with regard to the data types involved. This branch thoroughly examines significant literature to identify and synthesize the most recent knowledge regarding the essential data types required for successful DT implementation.

The first step of the methodology's first branch is a thorough literature study. This branch's primary objective is to establish the requirements for DT use cases in the construction sector, specifically with regard to the data types involved. By carefully examining applicable literature, this branch discovers and compiles the most recent knowledge regarding the essential data types required for successful DT implementation.

As we move to the second branch, the process entails a careful assessment of current software pipelines. In order to find other pertinent pipelines, a thorough desktop search will be conducted in addition to the analysis of pipelines that have been described in the literature. This branch's goal is to evaluate these pipelines' potential and limits in terms of easing data transfer between Autodesk Revit and Unity3D while taking the DT environment into account.

The comparative examination of the data sharing techniques described in the first branch is the primary goal of the methodology's third branch. The criteria for this analysis are the requirements set forth in the first branch. This branch attempts to determine the most appropriate techniques for providing effective and efficient data transfer between Autodesk Revit and Unity3D for DT implementation in construction by methodically comparing and assessing the discovered data exchange methods against the established requirements.

The fourth branch of the methodology entails creating a prototype data sharing technique utilizing Dynamo in Autodesk Revit's Built-In plugin. This branch attempts to develop a workable and effective method for exporting data from Autodesk Revit to Unity3D by drawing on the knowledge learned from the earlier branches. This branch attempts to show a workable method for establishing seamless data transfer and integration between these two software products through the use of Dynamo, a visual programming platform.

3.1 Literature Review for requirements analysis

The first portion of the research consists of a comprehensive literature evaluation to find DT application cases and their corresponding requirements. In completing the literature evaluation for this study, it is essential to remember that only a subset of the examined studies contributed directly to the achievement of the research objective. These individual studies were selected and analysed with care to provide insights and support the study's stated goals. However, a substantial percentage of the evaluated literature was included in order to examine the broader phenomenon of DTs. The search strategy and data collection procedures were applied strictly to the category of publications directly connected to the research objective, allowing for a concentrated analysis of the pertinent materials. Using this targeted strategy, the literature review intended to collect the pertinent data while preserving a full grasp of the DT phenomena.

This study's search technique was tailored to concentrate on DT applications in the AEC industry. Therefore, the search was restricted to publications pertinent to the AEC industry. To guarantee an exhaustive evaluation, numerous sources, including journal articles, conference papers, and editorial publications, were considered. These types of publications were thought beneficial for documenting a variety of opinions and research breakthroughs in the subject. Google Scholar, renowned for its comprehensive coverage of scholarly literature across fields, was the major search engine employed. Using these search parameters and Google Scholar as the primary resource, the objective was to collect a varied and representative sample of literature on DT applications throughout the AEC industry.

This study's search technique included the use of specific keywords, like "DT" and "AEC-FM" (Architecture, Engineering, and Construction - Facilities Management), to discover relevant literature. The purpose of the search was to identify material that addressed the application of DTs in the construction industry. By limiting the scope in this way, the objective was to collect literature that directly addressed the topic of interest. Data collection consisted mostly of extracting pertinent ideas and results from the conclusion and discussion portions of the papers in order to glean pertinent information from the selected literature. These parts were deemed to be the most likely origins of crucial observations and results pertaining to the application of DT in the construction sector. By employing this search technique and data gathering method, the study aimed to collect all previously investigated DT application cases that were previously described.

On the basis of the results of the literature review, an exhaustive list of criteria for each use case will be compiled. This is accomplished by a comprehensive examination of each use case provided in the literature. will serve as a baseline for assessing the technical analysis of the exportation operations. These needs will be defined and articulated in terms of the data type integration that the techniques for data exchange should incorporate. This method provides for a more specific and thorough examination of the potential benefits and drawbacks of connecting BIM and a gaming engine for DT implementation, as it concentrates on the most relevant use cases.

In relation to the objective of the research, the goal of this phase is to answer SRQ1.

3.2 Software Evaluation

The second component of the process is an evaluation of software. This phase intended to review and evaluate the available data exportation methods described in the current literature at the time the research was conducted, as well as identify and test the various software alternatives that facilitate the interchange of data between BIM and GEs. The research assumes that the DT structure is wholly managed in Unity3D and that backlog with the BIM authoring platform is a supporting function that is not required for the DT purpose to achieve simultaneous and bi-directional BIM Data interchange. For finding and analyzing literature data sharing methods, a literature review was conducted, while a desktop search was chosen as the search strategy for this phase. This explanation of data collection methods will be further subdivided into (a) Literature study for Customized data exchange methods and Custom-built software literature, and (b) Desktop search for Commercial exportation solutions, in order to describe the search process utilized for each method.

3.2.1 Literature Review for Software Evaluation

Specific considerations guided the search approach applied to choose data exchange pipelines between BIM and GEs. The search terms "BIM", "Game Engine", and "BIM and Game Engine connection" were utilized. Since the majority of literature studying the coupling of BIM and GE was identified in the context of VR and AR applications, only research that adheres to use cases pertinent to DTs in the AEC industry is considered, regardless of whether or not the DT concept was examined. Only studies with a defined data interchange structure in terms of file formats, software, and implementation methodologies were considered for inclusion in the review. The scope of this study is restricted to data sharing methods that use Autodesk Revit as the BIM authoring platform and Unity3D as the Game Engine platform. The data was gathered by analyzing the comments contained within the case studies offered in the chosen papers, which focused on the BIM data types that the presented data sharing technique regarded to be integrated. By adhering to these factors in the search strategy and data collection procedure, the study sought to find and assess appropriate data exchange pipelines between BIM and GE, particularly in the context of construction use cases.

3.2.2 Desktop Search for Software Evaluation

The desktop search approach involved utilizing search engines or dedicated software to gather information on the available software solutions. This method enabled the exploration of a wide range of options, considering factors such as features, functionality, and compatibility with specific requirements. By utilizing a desktop search, the research phase sought to identify and evaluate the most suitable software options, considering various criteria and considerations relevant to the research objectives. The selection criteria for commercial solutions that provide support for data exchange between BIM and GEs encompassed several key considerations. First, the availability of use, including free trials, demos, or demo videos, was an important factor in assessing the usability and functionality of the solutions. This allowed for a preliminary evaluation of the features and capabilities before making a purchase decision. Second, the requirement for the solution to be published ensured that the chosen solution had undergone scrutiny, review, and dissemination in the public domain, enhancing its credibility and reliability. By employing these selection criteria, the study aimed to identify viable commercial solutions that facilitate seamless data exchange between BIM and GE, promoting efficient collaboration and integration between the two platforms.

It is important to note that some of the software identified in the desktop approach are used by researchers analysed in the literature review for the software evaluation part, while some of them are not. Commercial solutions should be considered to have a comprehensive view of the available data exchange methods, regardless of their use in academics.

This phase of the methodology contributes to the findings of the first part of the methodology, but specifically addresses the research question SRQ2.

3.3 Comparative analysis

As a data analysis technique for establishing technical requirements for BIM to GE data exchange pipelines in DT use scenarios, a comparative analysis of existing data exchange workflows was used. The comparative study will collect results from previous phases and discuss the advantages and disadvantages of each data interchange method in relation to the adoption of DTs in the construction industry for each identified DT use case. This phase's findings will be used to address the primary research question (RQ).

This data analysis method was chosen because it permits a more targeted and exhaustive examination of the potential benefits and cons of connecting BIM and game engines for DT deployment in the AEC industry. Through a detailed assessment of each DT use case identified in the literature review, this study seeks to produce a comprehensive list of requirements for each DT use case, which will serve as a standard for evaluating the technical analysis of the exportation procedures.

In the comparison analysis, existing data exchange methods are compared by identifying their shared characteristics and any limits or drawbacks connected with each workflow. Each customized and commercial data exchange method will be evaluated against the requirements established in the preceding phase, with a particular focus on the various virtual data kinds and their respective data category. A discussion of the findings will evaluate the potential of data interchange techniques for various data kinds in relation to the desired use case and recommend the use of certain methods and solutions to facilitate the seamless integration of BIM data into GE.

By applying this data analysis method, it is possible to acquire useful insights into the strengths and shortcomings of existing data exchange procedures, and this knowledge may be utilized to inform the development of more effective and efficient BIM to Unity3D data sharing techniques for DT use scenarios.

3.4 Prototype Development

The research approach will also involve the development of a prototype to implement a custom data exchange method to export BIM data types from a sample Autodesk Revit model. This will provide a practical demonstration of the benefits and challenges associated with BIM and game engine coupling for DT implementation in the AEC industry. The prototype will be based on a sample project that will be made of 3 geometrically modelled elements taken from an under-development academic research project called SMF4INFRA, which stands for Smart Mobile Factory for Infrastructure. Paragraph 3.4.2 will introduce further the academic research used for the Prototype development.

3.4.1 Choice of Tools

Autodesk Revit and Unity3D have been chosen among the various BIM platforms and game engine platforms for their exceptional features and capabilities that are particularly relevant to the Architecture, Engineering, and Construction (AEC) industry.

Autodesk Revit by Autodesk stands out as a leading BIM authoring platform that has gained widespread adoption in the AEC industry (Alizadehsalehi et al., 2020). Its intelligent 3D modelling capabilities, seamless integration of geometric and non-geometric data, and emphasis on collaboration make it a go-to choice for architects, engineers, and construction professionals (Bille et al., 2014b). Autodesk Revit is also able to directly integrate structural, electrical, and mechanical graphic elements into the same architectural model (Gueye & Boton, 2022). Furthermore, Autodesk Revit provides several tools for processing graphical and numerical data. There are tools for tabular view and data processing. Based on the known parameters of the model, the new settings can be created and calculated (generated) (Ignatova et al., 2018). With its robust parametric modelling, extensive library of pre-built components, and strong interoperability, Autodesk Revit provides a comprehensive solution for creating DTs that accurately represent real-world buildings and facilitate efficient project management (Edwards et al., 2015). Besides the widespread capabilities that Autodesk Autodesk Revit has, accessibility, free trial and 3-years student license, and availability of several plugins for this tool (Safikhani et al., 2022) were the main reason for choosing this BIM Authoring platform over the others.

On the other hand, Unity3D has emerged as a powerful and versatile platform that initially gained popularity as a game engine. However, its capabilities go beyond gaming, and it has become an invaluable tool in the AEC industry (Buhammood et al., 2020). Unity3D 3D provides a visual editor, full and robust scripting and an animation system, and supports multiple platforms (Xiong et al., 2018). The choice for Unity3D was based on its quick, high-quality renders (Zhao et al., 2019), the ability for customization, and its user-friendly interface (Ghoneim, 2021) along with its short learning curve (Zou et al., 2018). Unity3D's ability to render real-time, high-fidelity visuals and support interactive simulations has made it an ideal choice for creating immersive experiences and virtual environment, hence empowering AEC actors to engage with DTs in a dynamic and intuitive manner, enabling better decision-making, communication, and understanding throughout the project lifecycle (Deng et al., 2021). At the time of the research, Unity3D3D comes in both free and commercial forms. Unity3D also recently announced a collaboration with Autodesk, to support and enable models produced using

Autodesk BIM tools (Autodesk Revit, 3DS Max, Maya) to be imported seamlessly into the game engine where they can be visualized and experienced in real-time (Buhammood et al., 2020).

Both Autodesk Revit and Unity3D offer unique advantages that address specific needs of the AEC industry. While Autodesk Revit excels in intelligent 3D modelling, data integration, and collaboration, Unity3D shines in real-time visualization, interactive experiences, and immersive simulations. By leveraging the strengths of these platforms, professionals in the AEC industry can harness the power of DTs to enhance productivity, streamline workflows, and deliver successful projects.

Lastly, Dynamo for Autodesk Revit is a powerful visual programming tool that enhances the parametric modelling capabilities of Autodesk Revit software. Built as a standalone application but integrated seamlessly with Autodesk Revit, Dynamo empowers users to automate repetitive tasks, create complex geometric forms, and establish custom workflows within the Autodesk Revit environment. At its core, Dynamo utilizes a node-based interface where users can connect pre-built nodes to define relationships and logic. These nodes represent specific functions, such as geometry creation, data manipulation, or Autodesk Revit element operations. By connecting and configuring these nodes, users can generate sophisticated parametric models, manipulate data, extract information, or perform complex analyses. Dynamo offers extensive capabilities for computational design, enabling users to create generative designs, explore design iterations, and optimize performance parameters. Furthermore, Dynamo facilitates seamless data exchange with other software tools through a variety of import and export options, enhancing interoperability and facilitating interdisciplinary collaboration.

3.4.2 Introduction to the SMF4INFRA case study

The research prototype will be conducted in collaboration with EuroTube Foundation (ETF), a recently established research institute with the mission of establishing cutting-edge test and development infrastructure for sustainable ultra-high-speed vacuum ground transportation, also known as the "hyperloop." A specific form of infrastructure project, vacuum transportation has the possibility for high-speed travel at cheaper costs and with fewer greenhouse gas emissions. As ETF has began to design for a prototype test track, they have identified the need for more mobile and digital manufacturing processes than are currently utilized in the supply chain.

The primary purpose of this research project is to envision, design, and develop a prototype of a Smart Mobile Factory (SMF) DT that will be used to sustainably provide the development of infrastructure projects by linking BIM with a gaming engine.

A mobile factory is a distributed production facility comprised of reconfigurable and mobile production systems that allow for the on-site modification of production capacity and functionality. A smart factory, on the other hand, is a DT of physical manufacturing systems, requiring a bidirectional data flow for advanced planning, modelling, and on-demand production. The SMF will be digitized to intelligently equip the mobile factory. This involves modelling the digital representation of the product, factory (considering both the facility and manufacturing processes), and on-site building. The integration of various representations will yield a DT for the mobile factory, enabling bidirectional data flow. Important production data, such as the precise concrete batch, will be transmitted automatically to the product DT, enhancing supply chain traceability.

3.4.3 Prototype Implementation steps

In the initial phase, parameters were allocated to various elements of a Autodesk Revit sample model in order to capture pertinent information. Consequently, within the Dynamo visual programming environment, a pipeline was constructed. This pipeline was developed to export both geometrical and non-geometrical information from the Autodesk Revit model, assuring Unity3D compatibility by leveraging the right file formats. To validate the efficacy of the pipeline, a script for a Unity3D component was provided. This script was designed to evaluate the visibility of exported non-geometrical data within Unity3D. The ETF academic researchers provided a simple script in order to reconstruct the data in Unity3D. On the sample model, tests were conducted using Autodesk Revit 2024 and Unity3D 22.1 as the relevant software versions.

4. FINDINGS

4.1 Use Case Requirements Analysis

This chapter presents an analysis of the data exchange methods required for implementing DTs in construction, based on an extensive literature review.

The initial phase of the research involved conducting a comprehensive literature review to identify the DT use cases relevant to the AEC-FM sector. Six research papers were carefully reviewed, resulting in the identification of 44 distinct DT use cases. To streamline the analysis, these use cases were clustered into eight main categories:

1. **Construction Progress Monitoring**
   Construction Progress Monitoring is the tracking and evaluation of construction operations on a project site in real time. It includes automated site progress monitoring, which use advanced sensing technology and data analytics to monitor construction progress and compare it to the intended schedule. In addition, increased site sensing comprises the use of modern sensors and imaging techniques to collect comprehensive data about the site's conditions and development progress. In addition, Construction Process Monitoring entails the constant monitoring and analysis of construction processes in order to find inefficiencies and potential enhancements for maximizing project delivery.

2. **Construction Process Monitoring**
   Construction Process Management emphasizes the management and coordination of diverse construction processes. It entails materials monitoring and management, which involves tracking the availability, utilization, and storage of building materials to ensure timely acquisition and utilization. Monitoring and management of machinery are also essential, utilizing sensor and equipment data to monitor machinery performance and schedule maintenance. The objective of optimized construction logistics and scheduling is to expedite the building process by improving resource allocation and task scheduling. Construction management entails the entire supervision and control of construction projects, including the planning, execution, and monitoring of all project activities.

3. **Safety Management and Hazard Monitoring**
   Safety Management & Hazard Monitoring is committed to delivering a secure building site environment. Using sensors and cameras to monitor possible safety hazards and detect unsafe practices in real-time constitutes real-time site safety detection. Monitoring and managing construction safety involves ongoing surveillance and administration of safety rules, training, and compliance. To adopt effective safety measures, monitoring hazards requires the recording and analysis of numerous dangers, such as environmental threats. Infrastructure risk management focuses on identifying and reducing risks connected with infrastructure building in order to reduce the likelihood of accidents and losses.

4. **Facility Management**
   Facility Management is concerned with the efficient operation and upkeep of man-made structures. It entails monitoring and tracking the condition and performance of the facility's numerous assets. Operations and maintenance in facility management involve the routine management and maintenance of the facility's operational components to maintain their proper functioning. Predictive maintenance use data analysis and machine learning to forecast possible faults and proactively plan maintenance. Comprehensive asset management entails managing all facility assets holistically throughout their existence. The purpose of defect detection is to identify and address any issues or flaws inside a facility

in order to maintain its optimal state. Continuously monitoring facility metrics and conditions to ensure adherence to operating requirements is facility monitoring.

5. **Energy Performance Assessment and Management**
   Energy Performance Assessment & Management focuses on optimizing energy consumption and performance within a building. It entails energy performance management, which entails monitoring and analyzing energy consumption to identify improvement opportunities. Assessment and management of energy performance emphasize continual assessment of energy performance in order to apply energy-efficient solutions and accomplish sustainability objectives.

6. **Building Operations & Building Condition Monitoring**
   Building Operation Control & Condition Monitoring focuses on guaranteeing optimal building operation and monitoring the condition of diverse building components. It comprises interior environment monitoring, which monitors indoor air quality, temperature, and humidity to create a healthy and comfortable indoor environment. Thermal comfort involves the monitoring and maintenance of indoor temperature settings to ensure the comfort of occupants. The purpose of analyzing energy consumption, air pollution, and water quality is to evaluate and optimize resource usage and indoor environmental quality. Tenant comfort enhancement focuses on enhancing tenant happiness and comfort within the building. Optimizing resource usage for electricity, water, and other utilities is integral to resource consumption efficiency. The analysis of climate, carbon, and circular economy outcomes evaluates the building's environmental impact and sustainability performance. Infrastructure condition monitoring is continual monitoring of building infrastructure parts in order to detect any structural concerns. Utilizing sensors and innovative techniques to evaluate and maintain the structural integrity of a structure constitutes structural health monitoring.

7. **Space And People Management**
   Space & People Management is focused with optimizing the use of space on construction sites and managing the labour. It consists of construction quality monitoring and management, which entails monitoring and ensuring the quality of construction activities. The objective of space management on a construction site is the efficient exploitation and allocation of available space. Workers monitoring and management entails the surveillance and management of the employees, including their attendance, safety, and performance. CommUnity3D monitoring entails evaluating the impact of building works on the surrounding commUnity3D and applying strategies to reduce interruptions.

Each of these clusters represents a group of DT use cases that share similar objectives and requirements within the construction industry.

Further analysis was conducted to examine the specific data types necessary to support each DT use case. Through an in-depth review of research papers focused on individual use cases, a comprehensive list of data types was compiled. These data types encompassed various formats, including informational data, geometric data, sensor data, and schedule data. Informational data typically consists of numerical and textual information, while geometric data includes meshes, 3D models, and objects. Table 2 shows the data type identified for each DT use case.

The identifies data types were categorized into cluster according to their format within the DT architecture. The sections below describe what they encompass individually.

Table 2 - Data Types Identification Table

Data Type	Construction Progress Monitoring		Construction Process Management		Safety Management & Hazard Monitoring		Facility Management		Energy Performance Assessment & Management		Building Operations & Condition Monitoring	
	Data	Reference	Data	Reference	Data	Reference	Data	Reference	Data	Reference	Data	Reference
Geometrical Data	Geometrical Data	(Alizadehsalehi et al., 2020; Rahimian et al., 2020)	Geometric Data	(Hasan et al., 2022)	Geometic Data	(Liu et al., 2021)	Geometric Data	(Nour El-Din et al., 2022)	Geometric Data	(Schweigkofler et al., 2022)	Geometric Data	(Kertai, 2021)
	Clash Detection Data	(Alizadehsalehi et al., 2020)							Graphical Information	(Woo et al., 2016)		
Informational Data			Cost Data	(Jiang et al., 2022)	Structural Data	(Liu et al., 2021)	Inventory Data	(Lu, 2020)			Building Data	(Alijani Mamaghani & Noorzai, 2023)
			Quantity Data	(Zhang et al., 2022)	Behavioural Data	(Liu et al., 2021)	Maintenance Data	(Lu, 2020)			Systems Data	(Kertai, 2021)
			Occupancy Data	(Zhang et al., 2022)							Equipment Data	(Kertai, 2021)
			Identity Data	(Jiang et al., 2022)								
Material Data			Material Data	(Ospina-Bohórquez et al., 2023)	Material Data	(Liu et al., 2020)	Texture Data	(Zou et al., 2018)	Material Definition Data	(Woo, 2016)	Material Data	(Fürst et al., 2014)
							Material Data	(Zou et al., 2018)			Metadata	(Zou, 108)
Zone And Areas Data			Location Data	(Ratajczak et al., 2019)	Hazard Zone Data	(Zhang et al., 2022)	Spatial Data	(Ghoneim, 2021)	Sensors Location Data	(Schweigkofler et al., 2022)	Asset Location Data	(Kertai, 2021)
Linked Data	Photographical Data	(Alizadehsalehi et al., 2020))	Installation Data	(Ratajczak et al., 2019)	Management Records	(Liu et al., 2021)	Installation Data	(Lu, 2020)			Documented Data	(Kertai, 2021)
							Warranty Data	(Lu, 2020)				
							Maintenance Data	(Ghoneim, 2021)				
Schedule Data	Schedule Data	(Alizadehsalehi et al., 2020)	Time Schedule Data	(Zhang et al., 2022)								
Geographical Data	Location Data	(Rahimian et al., 2020)	Geodata	(Bliznyuk, 2022)					Geographical Data	(Woo et al., 2016)		
			Objects Placement Data	(Bliznyuk, 2022)								
			Materials Placement Data	(Bliznyuk, 2022)								
			Transportation Logistic Data	(Zhang et al., 2022)								
			Collision Conflict Data	(Zhang et al., 2022)								
			Distance Data	(Zhang et al., 2022)								
Sensor Data	Big Data	(Alizadehsalehi et al., 2020)	Light Sensor Data	(Zhang et al., 2022)	Smoke Sensor Data	(Liu et al., 2021)	Operational Data	(Lu, 2020)	Humidity Data	(Schweigkofler et al., 2022)	Operational Building Data	(Alijani Mamaghani & Noorzai, 2023)
	Machine Learning and Artificial Intelligence Data	(Alizadehsalehi et al., 2020)	Energy Consumption Data	(Zhang et al., 2022)	Temperature Data	(Liu et al., 2021)			CO2 Concentration Data	(Woo et al., 2016)	HVAC System Data	(Kertai, 2021)
	Image Data	(Rahimian et al., 2020)	Machinery Operational Data	(Kosse et al., 2022)	Humidity Data	(Liu et al., 2021)			Illumination Data	(Schweigkofler et al., 2022)	Temperature Data	(Alijani Mamaghani & Noorzai, 2023)
			Construction Progress Data	(Kosse et al., 2022)	Oxygen Concentration Data	(Liu et al., 2021)			Temperature Data	(Woo et al., 2016)	CO2 Concentration Data	(Alijani Mamaghani & Noorzai, 2023)
			Workers Data	(Jiang et al., 2022)	Carbon Monoxide Data	(Liu et al., 2021)					Humidity Data	(Alijani Mamaghani & Noorzai, 2023)
					Controlled Access Data	(Liu et al., 2021)					Outside Air Data,	(Kertai, 2021)
											Condition Data	(Alijani Mamaghani & Noorzai, 2023)
											AHU Sensors Data	(Kertai, 2021)
Environmental Data	Environmental Quality Data	(Alizadehsalehi et al., 2020)	Soil Condition Data	(Bliznyuk, 2022)	Wind Speed	(Liu et al., 2021)			Environmental Data	(Schweigkofler et al., 2022)	External Environmental Data	(Hämäläinen, 2021)
			Weather Data	(Zhang et al., 2022)								

frequently created. It provides insight into the project's progress, identifies obstacles, and helps the DT coordinate its actions.

4.1.8 Geographical Data

Geographical data is spatial information that pertains to the physical location of assets, structures, or sites. This data type consists of geographical coordinates, topography data, maps, aerial images, and geographic information system (GIS) data. Geographical data offers context and allows the DT to incorporate external environmental considerations, such as topographical analysis, solar exposure, and accessibility to services and infrastructure.

4.1.9 Sensor Data

Sensor data consists of real-time or archived measurements collected from physical sensors installed in the built environment. This data type consists of information gathered from sensors such as temperature sensors, humidity sensors, occupancy sensors, motion sensors, and other monitoring equipment. Within a physical place, sensor data provides significant insights into operational performance, energy consumption, ambient variables, and occupant behavior. It is essential for real-time monitoring, anomaly detection, predictive analytics, and optimization of building systems and is often captured in numerical representations.

4.1.10 Environmental Data

Environmental data includes information regarding external elements and conditions that have an effect on the built environment. This data type contains meteorological data, data on air quality, noise levels, and other environmental characteristics. The most common sources of environmental data are weather stations, environmental monitoring systems, and public databases. It is essential for evaluating the effects of weather, air quality, and noise on building performance, occupant comfort, and sustainability. Typically, environmental data is collected numerically and can be incorporated into the DT for performance analysis and simulations.

The various data types considered in the context of DT implementation in the construction industry have diverse forms and properties. Geometrical, informational, material, and zone and area data are called BIM data, as they are generated by BIM systems and represent the virtual components of the built environment. In addition to being virtual data, linked data and scheduling data are received from external software systems, so augmenting the DT with additional information and capability. Sensor data and environmental data, on the other hand, pertain to the physical realm, gathering measurements from sensors and environmental monitoring systems in real time or as recordings.

Assessment of the interoperability of DT use cases and BIM data interchange methods required categorizing the data kinds based on their formats. By comparing each use case to the necessary data types, it became clear that not all use cases required the same set of data types. The results are presented in Table 3.

Table 3 - Use Case data type Requirements Analysis

	Virtual Data						Physical Data		
Digital Twin use case	Geometrical Data	Informational Data	Material Data	Zone and Areas Data	Linked Data	Schedule Data	Geographical Data	Sensor Data	Environmental Data
Construction Progress Monitoring	✓				✓	✓	✓	✓	✓
Construction Process Management	✓	✓	✓	✓	✓	✓	✓	✓	✓
Safety Management & Hazard Monitoring	✓	✓	✓	✓	✓	✓	✓	✓	✓
Facility Management	✓	✓	✓	✓	✓			✓	
Energy Performance Assessment & Management	✓		✓	✓			✓	✓	✓
Building Operation Control & Conditions Monitoring	✓	✓	✓	✓				✓	✓

During the implementation of DTs in construction projects, the analysis of DT use cases and their associated data types provides useful insights for determining the most effective data interchange methods. Recognizing the specific requirements of each use case enables the creation of customized data exchange mechanisms, hence increasing the efficacy and efficiency of DT systems. This conclusion established the framework for the core hypothesis of this thesis: different DT use cases in the construction sector can benefit to variable degrees from various BIM data interchange protocols.

In conclusion, this chapter has provided an in-depth review of DT use cases in the construction industry, categorizing them into eight primary groups. The chapter lays the groundwork for analysing BIM data transmission techniques by identifying and classifying the data types necessary for each use case. In order to realize the full potential of DT technology in the construction industry, specific data sharing strategies are required, according to this study's conclusions.

4.2 Software Evaluation

Autodesk Revit BIM and GEs are widely utilized software applications in the AEC sector. Several research have investigated the coupling of BIM with GEs, and several data exchange pipelines have been developed, as emphasized in the literature review.

This chapter contains a software evaluation that groups the results of the literature study and desktop search data interchange methods into three unique solution types: commercial solutions, customized pipelines, and custom-built software. This classification was intended to give a detailed study of the existing alternatives for exchanging BIM data with gaming engines.

4.2.1 Commercial solutions

This category includes commercial software products intended specifically for exchanging BIM data with game engines. These commercially available solutions are created by well-known firms and provide a variety of features and functionalities designed to enable the transfer of data between BIM software and GEs. The review assessed the advantages and disadvantages of these commercial solutions, taking into account variables such as compatibility, usability, and support availability.

Personalized software: In contrast to the preceding categories, custom software refers to solutions that are created from scratch, typically in-house or by specialist development teams. These solutions are designed to fulfil specific project requirements and address unique data transmission difficulties between BIM and game engines. The examination of custom-built software assessed their amount of customization, scalability, and compatibility with project workflows and data needs. Some scholars have offered bespoke pipelines for merging BIM and GEs data, while other scholars have produced their own custom-built software, and other solutions are commercially available and freely accessible to the public, either for free or by subscription. All these pipelines and custom-built solutions, however, demonstrate the necessity for bespoke solutions that match the specific needs of each use case.

For each selected commercial or research-related data sharing method, a thorough analysis of the applicable methods and given features will be done. The anticipated outcome of this study is an evaluation of the transfer capabilities of each data type from Autodesk Revit to Unity3D. Table 4 provides a summary of the software evaluation analysis performed on the commercial solutions discovered via desktop search. The following list will detail each individual commercial solution. The presence of an asterisk (*) indicates that the file was modified in an external program prior to use.

Table 4 - Commercial Solutions software Evaluation

Reference	Author and Year	Name	Data Flow	Real-time	Geometrical Data	Informational Data	Material Data	Zone and Areas Data	Schedule Data
https://apps.autodesk.com/RVT/en/Detail/HelpDoc?appId=3759955758891315427&appLang=en&os=Win64	Efavreu, 2022	Export to Unity3D	Uni-Directional	no	OBJ	.cs script	MTL	no	no
https://Unity3D.com/products/Unity3D-reflect	Unity3D Technologies, 2022	Unity3D Reflect	Bi-Directional	yes	file format not specified	file format not specified	file format not specified	no	no
https://apps.autodesk.com/RVT/en/Detail/HelpDoc?appId=4892322793396128687&appLang=en&os=Win64	AmbiensVR, 2021	A+T Sync	Uni-Directional	yes	AVRO	AVRO	AVRO	no	no
https://support.lumion.com/hc/en-us/articles/360007538494-Download-Lumion-LiveSync-for-Autodesk Revit	Lumion, 2024	Lumion Livesync	Uni-Directional	no	DAE	DAE	DAE	no	no
https://www.pixyz-software.com/documentations/html/2022.1/plugin4Unity3D/	Unity3D Technologies, 2022	PiXYZ	Bi-Directional	yes	IFC	IFC	IFC	IFC	IFC
https://assetstore.Unity3D.com/packages/tools/utilities/ifc-importer-162502	Arcventure, 2020	IFC importer	Bi-Directional	no	IFC	IFC	IFC	IFC	IFC
https://www.simlab-soft.com/3d-plugins/Autodesk Revit_Plugins.aspx	SimLab soft, 2023	SimLab	Uni-Directional	no	FBX*	no	FBC*	no	no

Export to Unity3D: The "Export to Unity3D" Autodesk Revit plugin allows direct export of BIM models from Autodesk Autodesk Revit, a popular BIM authoring tool, to various GE. The plugin supports the exportation of geometrical data, material data and informational data, allowing the visual representation of the BIM model and its BIM objects (families) parameters information in Unity3D. Zones, spaces and scheduling data will require additional steps or custom scripting to be transferred effectively.

The plugin consists in two buttons in the Autodesk Revit ribbon: one will export the geometry in .obj giving the user a choice of de-structuring the geometry by materials, to keep the geometry structure intact or to export a one single entity; the second button will export the materials into a .mtl file. Both buttons allow the user to select the exportation folder path. This can turn useful because, by selecting the Unity3D project asset folder, the additional step of manually importing assets into the game engine project can be avoided. Additionally, by clicking the geometry exportation button, the plugin automatically downloads in the folder a component script, which will contain the metadata associated to the BIM objects and their relative values. Once the project is imported in Unity3D, the script will have to be attached to each game engine object and, after entering the "play" mode, this data will become visible by simply placing the mouse pointer to the object.

Export to Unity3D is free and working on Autodesk Revit versions 2018 to 2022. The features that tis plugin provides are limited to uni-directional and asynchronous data exchange. While this commercial solution allows for geometry and materials alterations to be done in the Unity3D environment, it does not allow for manipulation of the informational data.

Unity3D Reflect: Unity3D Reflect is a comprehensive BIM-to-Unity3D solution that enables bidirectional data exchange between BIM software and Unity3D. It provides a live link between the two platforms, allowing changes made in either environment to be synchronized and reflected in real-time. Unity3D Reflect supports multiple BIM file formats, such as Autodesk Revit, Rhino, and SketchUp, and provides rich geometric, informational, and metadata transfer capabilities. It also supports zone and space information, as well as materials and textures. Reflect offers a high level of DT maturity by facilitating bidirectional and synchronous data exchange and manipulation within Unity3D.

This commercial solution is deemed to be particularly costly, and it consists of two plug-ins, one for Autodesk Revit and one for Unity3D. This commercial solution is developed by Unity3D itself and offers a selection between two packages with different costs and features. Both packages offer basic features for visualization and manipulation of the BIM model in the Unity3D environment, whit the difference that the Unity3D Reflect Develop package allows for multiplayer and annotations features.

A+T Sync: A+T Sync is a plugin designed for synchronizing BIM data from Autodesk Autodesk Revit to Unity3D. It allows the export of Autodesk Revit models into Unity3D while preserving the BIM hierarchy and properties. The plugin focuses on geometrical and informational data transfer, including metadata and material assignments. It supports unidirectional data flow, meaning changes made in Unity3D will not be reflected to the Autodesk Revit model without additional steps. To run this application, both plugins, one in Autodesk Revit and one in Unity3D, need to be installed.

Lumion Livesync: Lumion Livesync is a plugin that enables real-time visualization and synchronization between Lumion, a popular architectural visualization software, and Unity3D. While Lumion itself is external software, Livesync establishes a seamless connection between Lumion and Unity3D, allowing live updates of the architectural model. It primarily focuses on geometrical data transfer, including materials and textures. Lumion Livesync provides unidirectional data flow from Lumion to Unity3D, meaning changes made in Unity3D won't affect the Lumion model. The principle of this export application is based on the file format named Collada

(.DAE), which is supported by the Unity3D application. Collada, which stands for "COLLAborative Design Activity," is an XML-based file format used for the exchange of digital assets between different 3D modelling and graphics software applications. It is an open standard developed by the Khronos Group, an industry consortium focused on the creation of open, royalty-free standards for 3D graphics, augmented reality, and parallel computing.

Testbeds of this export application show how the geometry structure in the Unity3D editor is not kept but rather de-structured and re-structured by materials. The object in Unity3D will then be seen as selectable groups of geometries that belong to a certain material. In other words, multiple geometries belonging to different Autodesk Revit families would be grouped by material after the export and components, locations and other types of manipulations would be simultaneously applied to each object that is made of that material.

PiXYZ: PiXYZ is a Unity3D-based plugin suite that offers advanced CAD data preparation and optimization features for Unity3D. It allows the import of CAD data from various sources, including BIM software, and provides tools to clean up, optimize, and refine the imported models for real-time visualization. PiXYZ focuses on geometrical data, but it also supports material and texture conversion. This application converts and imports IFC files making the model and its properties visible and modifiable in the Unity3D editor. The Industry Foundation Class (IFC) is the most used neutral data format for BIM (Chen et al., 2020) as it semantically describes the components of a building, their properties and their relations and contains definitions of geometries in the widespread EXPRESS format (Delbrugger et al., 2017) an ISO standard language (Du et al., 2018). While this commercial solution doesn't provide direct bidirectional synchronization or live data exchange, it offers powerful options for preparing BIM data for Unity3D.

IFC Importer: Like PiXYZ, IFC Importer is a plugin specifically designed to import Industry Foundation Classes (IFC) files into Unity3D. IFC is an open and neutral file format widely used in the BIM industry for interoperability. The plugin primarily focuses on geometrical data transfer and supports importing BIM elements and their properties into Unity3D. It may require additional customization or scripting to handle metadata, zones, spaces, and materials beyond the basic geometric representation.

4.2.2 Customized pipelines

This category includes pipelines that are tailored and configured based on specific project requirements by utilizing a combination of existing software tools and plugins. These customized pipelines leverage pre-existing components and integrate them in a way that addresses the unique needs of the project. The evaluation of customized pipelines focused on assessing their adaptability, flexibility, and efficiency in transferring BIM data to GE while considering project-specific constraints and objectives.

It is important to mention that only pipelines that apply to Autodesk Revit BIM authoring platform and Unity3D Game Engine platform were taken into consideration. Also, only pipelines that refer to use cases that contribute to the development of a DT and associate to DT use cases were considered. For example, pipelines implemented for the development of Cultural Heritage re-construction and visualization in VR were not taken into consideration.

During the review process, a comprehensive analysis was conducted on a total of 11 pipelines, each designed to cater to specific use cases within the realm of DTs. Out of these pipelines, a significant majority, accounting for 10 out of the 11, were identified as customized solutions for three prominent use cases: Facility Management, Construction Process Management, and Construction Progress Monitoring. These customized pipelines were specifically developed to address the unique requirements and challenges associated with these use cases, ensuring their effectiveness and applicability in real-world scenarios.

The level of BIM data integration exhibited variations across the different pipelines, with the extent of integration being contingent upon the specific research scope of each study. This finding suggests that researchers have adopted diverse approaches to incorporate BIM data into their DT pipelines, tailoring them to suit their objectives and analytical needs. By adapting the level of BIM integration, researchers can customize the DT experience to provide optimal insights and functionality for the respective use cases.

Nevertheless, it is important to note that certain limitations and gaps were identified within the reviewed pipelines. Some of the pipelines lacked comprehensive descriptions of their application methods, failing to provide detailed insights into the specific techniques employed to achieve their intended outcomes. This lack of transparency regarding the application methods could pose challenges for other researchers and practitioners seeking to replicate or build upon the work. Additionally, a few of the pipelines did not specify the file formats utilized within their implementation, which could potentially hinder interoperability and compatibility with other systems and tools.

For ease, the following pipeline will be individually described below, and the limitations will be also discussed in the individual sections.

In (Sandoval et al., 2018) research on Game Engine application for construction site Discrete Event Simulation (DES), The BIM model was exported as an FBX file and directly imported into Unity3D. Each model element becomes a separate game object. Externally developed Material library files (mat) are applied to Unity3D's game objects, and their properties are adjusted in the inspector for the desired texture. Unity3D processes the model materials to enhance realism. Non-geometrical meta-data lost during FBX export is assigned to specific model elements through scripting, if needed. This approach was used to assign distinct tags to individual walls for differentiation. The main limitation in this pipeline is the impossibility to modify of the input parameters of the DES model before the construction activity is completed.

In their paper, (Zou et al., 2018) exported the BIM model as an IFC file however it doesn't fully describe the methods of exportation nor the limitations encountered. The solution involved exporting the IFC file from the BIM authoring tool and using the globally unique IDs of each component to map their information in the gaming environment. Each component instance in the IFC file has a unique ID, which is stored in the gaming environment within brackets at the end of the object's name. To automate this process, scripts were written in C#, Javascript, and Python to process IFC files into a database and dynamically pull data for respective components into the game engine.

(Xiong et al., 2018) presented a pipeline in which The Autodesk Revit model is exported as an .FBX file and imported into Unity3D 3D for asset development in the game. To reduce file size, the Autodesk Revit models (Architectural and MEP) are split into different parts, such as Arch_1st floor for the first level of the architectural model. The original .FBX file is optimized using 3Ds Max, which reduces the number of polygons by approximately 30% while maintaining satisfactory performance (Xiong et al., 2018). Simple textures are added to the assets in Unity3D 3D to conserve system resources. Temperature data from room sensors is uploaded and manually saved on a MySQL server. Unity3D 3D offers a scripting API to connect to the MySQL server and generate form data. In this pipeline, the data exchange process between BIM tools and GE work, but the main challenge are the geometric complexities in architectural models and the building scale involved. The prototype game can achieve real-time data, but it is still a very early attempt at using the game to manage a multitude of building operation data.

The identified limitations emphasize the significance of comprehensive documentation and standardization in the development of DT pipelines for the construction industry. Transparent and detailed descriptions of the application methods employed can enhance the reproducibility and knowledge transferability of DT research. Similarly, specifying the file formats used can facilitate seamless data exchange and interoperability, enabling integration with existing construction workflows and software tools.

(Schweigkofler et al., 2018) explains how to import a BIM model into Unity3D, it needs to be in either .obj or .fbx format. Since the project file was created in Autodesk Revit, it must be passed through 3DSMax® to convert it to FBX format to maintain the ID that links to the 3D elements. This is proven to be inaccurate by other scholars. In Unity3D, a camera captures and displays the user's view. The ""Location Listener"" plugin informs the virtual camera of the user's initial location, aligning it to display the 3D building components the user is looking at. The device, utilizing Tango's motion tracking capabilities, tracks the user's movement, ensuring the cameras stay aligned. The 3D model alone doesn't provide all the necessary information to the user. The ACCEPT plugin, a custom-made plugin for Autodesk Revit, extracts parameter information about each component in an XML format. The "Clickable"" script in Unity3D allows interaction with each component of the model, displaying this information with a double click. By exporting a gbXML file from Autodesk Revit®, information about project areas can also be captured. Areas represent subdivisions of space within the building model. This file enables the extraction of bounding coordinates for all areas, allowing identification of the user's current location within an area.

(Bourlon & Boton, 2019) exports the BIM model as an FBX file from Navisworks, which offers easier tree management compared to 3dsMax FBX. Sub-objects are not classified into subgroups. With this method the GameObjects' "child" elements are directly placed at level 1, considering the main GameObject as step 0. This simplifies the code retrieval process, eliminating the need for different path loops to find the elements matching those in the imported construction schedule. However, it should be noted that the rendering of textures is not optimal.

The construction schedule is imported into Unity3D from an Excel file in .csv format. This facilitates the integration of the schedule data into the Unity3D environment.

From Autodesk Autodesk Revit, two files are exported in (Ratajczak et al., 2019) pipeline: a 3D model as an .fbx file and its metadata as an .xml file using the ACCEPT XML plugin. The .fbx file is imported into Autodesk 3ds Max to organize the model entities, ensuring the same IDs for 3D objects in Unity3D as in Autodesk Revit. The geometry is then exported as another .fbx file and directly imported into Unity3D.

In Unity3D, the 3D model's geometry is set up, including positioning, scaling, materials, and physical characteristics such as rigidbody and colliders to prevent walking through walls. The metadata in the .xml file is also imported into Unity3D. It contains information like object geometry (length, width, height), materials, object IDs, and WBS/LBS codes.

The necessary data is parsed from the .xml file using layers and XML Parser scripts. These scripts extract data from the 'Elements' and 'Types' sections of the file, transforming them into more suitable data structures for application management. The 'Elements' section provides IDs and geometrical data (width, height, type) for 3D objects in Autodesk Revit, and the IDs of building components in Unity3D correspond to 'Elements' IDs in the .xml file.

The 'Types' section contains product-related information, technical data, and WBS/LBS codes. To link this data to building components in Unity3D, the 'TypeID' code is used. Many limitations are associated to this pipeline as components related to construction project controls are stand-alone components and have yet to be integrated. The testing utilized a definition of the starting point (x, y, z) for the application in the real world. The same position was applied to a Tango camera in Unity3D. Such an approach should allow the perfect alignment of both real and virtual worlds. However, the results of this testing showed several alignment errors of the 3D building model in AR. The model was not always perfectly superimposed onto the real building.

(Rahimian et al., 2020) presented a pipeline that involves the building's structural design exportation as an Autodesk Navisworks (NWD) file, while the architectural model was saved in IFC format for seamless data exchange between different BIM software applications. Daily construction site images were captured using a depth camera and replicated within the BIM model using the same camera settings and location. These images, along with the BIM model, were stored in cloud-based storage.

To identify objects and building components in the images, Convolutional Neural Network (CNN), a machine learning classification technique, was employed. Image processing techniques were then applied to remove unwanted objects for clarity. The recognized and classified elements were linked to actionable tasks from the time schedules associated with the BIM model. These extracted details were superimposed onto the as-planned BIM models to enable comparison.

The construction status data, overlaid on the BIM models, was transferred to the game engine through scripting or exporting the IFC file to FBX format. This integration with the virtual environment enhanced immersion, visualization, and interaction, providing a more immersive experience. Although this pipeline looks promising, no new release of twinmotion plugin after Autodesk Revit 20202 was found at the time of the current research.

In their study, (Buhammood et al., 2020) The IFC format and the Tridify plugin were utilized to facilitate the export/import process between Autodesk Revit and Unity3D. Tridify BIM tools, acting as a Unity3D plugin, support the exchange of models in IFC format between the two software (Tridify, 2019). The Autodesk Revit model is converted into IFC and then loaded into Tridify.

Once the model is successfully loaded and validated, the IFC Autodesk Revit model undergoes a conversion process to become compatible with Unity3D's format. This conversion enables the model to be seamlessly integrated into the Unity3D environment. However, The file capacity in the free version of Tridify is limited to 30 MB (Tridify, 2019) hence using larger size models was not possible. Also, Tridify was removed from the market so not applicable in the current research.

In (Ghoneim, 2021) pipeline, The 3D model can be exported into Unity3D using the Twinmotion plug-in. This plug-in allows for the direct export of the rendered view from Autodesk Revit to Unity3D, preserving all materials and textures. When exporting with Twinmotion, the grouping of elements by families is already a built-in feature that can be selected, simplifying the import process into Unity3D. The export interface and this feature are illustrated in the accompanying figure. Upon selecting the export option, the model is automatically saved in the accepted (.fbx) format for Unity3D. To reduce the file size, vegetation is excluded by unticking the corresponding option in the Twinmotion interface, as it is not deemed essential. However, no new release of twinmotion plugin after Autodesk Revit 20202 was found.

Lastly, (Alijani Mamaghani & Noorzai, 2023) presented a pipeline where the graphical model was obtained from the BIM model and exported as an .FBX file prior to importing the model into the Unity3D engine. A part of the non-graphical information was extracted from the BIM model using a visual programming extension for Autodesk Autodesk Revit, Dynamo, while the other part of the non-graphical information was obtained from the Computerized Maintenance Management System (CMMS). The non-graphical data was then stored in an SQL server database. However, Navisworks can display only offline and outdated data. To display instantaneous data, the Navisworks model should be connected to an online database. Also, the hardware data from sensors should be represented in the model; this is carried out in the third function. In the fourth function, the AR platform is incorporated into the BIM, and the system is integrated with sensors. As a result, the operation and maintenance of mechanical facilities can be performed in a short time, implementing intelligent FM.

There is no information in the document about any other middleware or file formats used in the export/import pipeline.

A comprehensive overview of each customized pipeline examined during the review process can be accessed in Table 5. This table offers valuable insights into the data exchange methods utilized and provides specific information regarding the file formats employed for each transferred data type. In instances where a particular data type was deemed non-applicable, meaning it was not extracted from the BIM model, the corresponding cell in the table is filled with "N/A". It is important to note that asterisks accompanying certain file formats in the table indicate specific conditions. An asterisk denotes that the file underwent refinement in an external software before being used (*), a double asterisk signifies that the file was not imported but instead rebuilt within the Unity3D software platform (**), and a triple asterisk indicates that the file was entirely generated using an external software (***). The inclusion of this detailed information in the table facilitates a clearer understanding of the data exchange methods and file format considerations employed within each customized pipeline.

Table 5 - Customized Pipelines Software Evaluation

Authors	Use Case	Data Flow and Sync	Real Time	Geometrical Data	Informational Data	Material Data	Zone and Areas Data	Schedule Data
(Sandoval et al., 2018)	Construction Process Management	Uni-directional	no	FBX	no**	mat***	no	no
(Zou et al., 2018)	Facility Management	Uni-directional	no	IFC	IFC or CSV	IFC	no	no
(Xiong et al., 2018)	Facility Management	Uni-directional	no	IFC or FBX (3dsMax)	no*	FBX (3dsMax)	no	no
(Schweigkofler et al., 2018)	Construction Process Management	Uni-directional	no	FBX (3dsMax)	XML	FBX (3dsMax)	gbXML	no
(Bourlon & Boton, 2019)	Construction Progress Monitoring	Uni-directional	no	Naviswork FBX*	no	Naviswork FBX*	no	.CSV***
(Ratajczak et al., 2019)	Construction Progress Monitoring	Uni-directional	no	3dsMax FBX	XML	3dsMax FBX	no	XML***
(Rahimian et al., 2020)	Construction Progress Monitoring	Uni-directional	no	Twinmotion FBX	no	Twinmotion FBX	no	no
(Buhammood et al., 2020)	Construction Process Management	Uni-directional	no	IFC*	IFC*	IFC*	no	no
(Ghoneim, 2021)	Facility Management	Uni-directional	no	Twinmotion FBX	no	Twinmotion FBX	no	no
(Alijani Mamaghani & Noorzai, 2023)	Facility Management	Uni-directional	yes	Naviswork FBX*	Not specified	Naviswork FBX*	no	no

4.2.3 Custom Built Software

A total of four custom-built software applications were subject to review. Surprisingly, none of these software solutions were found to be associated with any specific DT use case, nonetheless related to construction DT use cases previously mentioned. Furthermore, there were limitations identified in the reviewed software, specifically regarding the lack of comprehensive process descriptions. The research articles detailing these custom-built software applications did not provide sufficient information regarding the underlying processes and methodologies employed. Additionally, there were instances where the disclosure of file format usage was absent, making it unclear which file formats were utilized within the software. Despite these limitations, the research articles presented promising results regarding the custom-built software's capabilities. However, due to the lack of reproducibility and testing, the validity and reliability of these results remain uncertain. Thus, further investigation and validation of these custom-built software applications are necessary to evaluate their practical applicability within the context of DT development.

BUSICO 3D, developed by (Fürst et al., 2014), imports a CAD architectural model of the building that is created in a BIM program of choice, from which the structure of the physical building is derived. BUSICO 3D uses Unity3D 3D as an execution environment for which it is entirely written in C#. The middleware sMAP acts as a hardware abstraction layer on top of various physical devices. sMAP drivers abstract away the particulars of sensors and actuators and expose a uniform REST interface. BUSICO 3D reads this REST application programming interface of sensors and actuators and maps it by means of sMAP metadata to the CAD model, creating automatically objects for each found sensor or actuator including GUI, programming logic and renderer.

(Nandavar et al., 2018) developed a custom program using the xBIM Toolkit, an open-source SDK for handling IFC files. This program parses the entire BIM model and generates a customized XML file with encoded geometric and meta-data. This XML file, called IFC_VRXML, serves as the communication bridge from the BIM system to the VR system. In Unity3D, the 3D geometry is reconstructed using a custom C# class, maintaining the same hierarchical structure as the BIM model. Another set of C# classes handle user system interfacing, utilizing the IFC_VRXML file to query and retrieve object-specific data during runtime. An additional Unity3D class generates another XML file that summarizes all model manipulations. This file is then parsed by another xBIM-based program, which registers the changes to the original IFC file. As a result, a new IFC file is compiled with a version-tracking suffix appended to the original name, indicating the timestamp of changes made.

BVRS (BIMeVR Real-time Synchronization) is a real-time BIM to VR data synchronization Autodesk Revit plugin developed by (Du et al., 2018), that automatically and simultaneously updates BIM design changes in VR headsets. It utilizes a metadata interpretation and communication protocol with a cross-platform Cloud infrastructure. The system includes a Autodesk Revit plugin that gathers BIM metadata, a Cloud server that organizes and transfers metadata based on IFC, and a game engine that displays changes in VR headsets. The Autodesk Revit plugin scans all elements, saving their Element IDs in a list. Object properties are obtained by referencing these Element IDs, which are extracted from the FBX file. A mapping system matches Element IDs to corresponding object properties using a Hash Table as the underlying data structure. This choice allows for constant time searching of properties for a given ID. The project and relevant data are saved to Cloud servers, where the mapping system extracts and stores the building information in a pre-constructed data structure such as JSON. To achieve real-time data synchronization, Autodesk Revit continuously sends updated information to the Cloud server. Once the object information is acquired and stored in the Hash Table, the updated information is pushed to the Cloud servers and database using protocols like HTTP or HTTPS. The Cloud database receives and stores the updated information for further use.

Lastly, (May et al., 2022) developed a custom application using the xBIM Toolkit, an open-source SDK for handling IFC files. This plugin is called Unity3DRev and allows for the real-time bi-directional exchange of BIM data between Autodesk Revit and Unity3D. To achieve this, Unity3DRev uses a customized network based on a Transmission Control Protocol and Internet Protocol (TCP/IP) network architecture to facilitate the exchange of BIM data between Autodesk Revit and Unity3D. A local server is set up, hosted from the Unity3D software, with Autodesk Revit connecting to the server as a client. The process of transmitting data between the server and client consists of retrieving the element IDs, position, rotation, scale, metadata, and mesh data via the Autodesk Revit API and converting it into a byte array, which is then sent through a socket. This data is then decoded and parsed by the receiver to synchronize modifications within the corresponding software. Unity3DRev supports the transfer of BIM data in the IFC data format. IFC supports the transfer of BIM data by storing the metadata and geometric properties associated with a BIM into a single file format. However, modern game engines such as Unreal and Unity3D do not provide native support for IFC. To address this issue, third-party libraries have been released to support parsing IFC files into game engines. Additionally, Unity3DRev uses an XML-based approach to store manipulations that occurred to the BIM model within VR (i.e. Unity3D). The XML file could then be parsed back to the original IFC file using an open-source IFC management software: xBIM toolkit.

Table 6 shows an overview of the different custom-built software analysed.

Table 6 - Custom Built Solution Software Evaluation

Authors	**Software Name**	Data Flow and Sync	Real Time	Geometrical Data	Informational Data	Material Data	Zone and Areas Data	Schedule Data
(Fürst et al., 2014)	Busico3D	not specified	not specified	Not specified	no	Not specified	no	no
(Nandavar et al., 2018)	N/A	Bi-directional	not specified	IFC_VRXML	IFC_VRXML	IFC_VRXML	no	no
(Du et al., 2018)	BVRS	Bi-directional	yes	FBX	IFC	IFC	no	IFC
(May et al., 2022)	Unity3DRev	Bi-directional	yes	IFC (+ XML)	IFC (+ XML)	IFC (+ XML)	no	no

4.3 Comparative analysis

This chapter presents the findings of a comparative analysis conducted to evaluate different data exchange methods applicable for exchanging BIM data between Autodesk Revit and Unity3D in the implementation of Digital Twin (DT) use cases in the construction domain. The underlying hypothesis for this analysis is that, considering the specific construction DT use case and their respective requirements identified in the literature review (Chapter 2.2), the selection of suitable data exchange methods can significantly enhance the development of the construction DT.

The comparative analysis is centred around the virtual implementation of the Construction DT and utilizes DT use case requirements as the primary criteria for comparison. Two parallel grounds of comparison are examined. The first ground evaluates the type of data exchange method, encompassing commercial software solutions, customized pipelines, or custom-built programs, along with their respective advantages and constraints (Table 7). The second ground of comparison investigates the file extensions utilized for each Data Type identified in the use case requirements analysis (Chapter 4.1), outlining the relative advantages and limitations of each (Table 8, 9, 10).

Based on the assessments derived from both grounds of comparison, this chapter subsequently delves into a comprehensive examination of each DT use case individually. It identifies potential areas where the findings from the assessment of advantages and limitations can be strategically employed to maximize the efficiency and fulfilment of requirements in the virtual implementation of DTs. By pinpointing these key areas, this chapter seeks to provide actionable insights to optimize the integration of BIM data with Unity3D and enhance the overall effectiveness of DTs in the construction industry.

Table 7 - Data Exchange Methods Type Assessment

	Opportunities	Limitations
Commercial Software Solutions	• Synchronous and bi-directional data exchange capabilities for seamless integration. • Well-established interfaces with popular BIM platforms for ease of data transfer. • Ready-to-use solutions with extensive features for specific use cases. • Potentially faster implementation and lower development costs.	• Limited support for specific data exchange formats, potentially leading to data loss or format conversion issues. • May not fully cater to the unique requirements of certain DT use cases, limiting customization. • Some solutions may lack comprehensive support for all data types required in complex DT implementations. • Ongoing license costs and dependency on the software provider.
Customized Pipelines	• Tailored data exchange methods to address specific DT use case requirements. • Can be designed to optimize data transfer, performance, and accuracy. • Flexibility to incorporate multiple data types and adapt to changes in project needs. • Potential to leverage existing software infrastructure for efficiency.	• Higher development and maintenance costs compared to off-the-shelf solutions. • Require expertise in both BIM and game engine environments for proper implementation. • Time-consuming to develop and test, potentially delaying DT deployment. • Limited scalability if not designed with future expansion in mind.
Custom Built Programs	• Complete control over the data exchange mechanism to meet precise DT use case requirements. • Ability to integrate all relevant data types seamlessly for comprehensive DT implementation. • Potential for faster data transfer and real-time synchronization between BIM and game engine. • Scope for adding unique features and functionalities tailored to specific needs.	• Significantly higher development costs and longer implementation timelines. • Requires a team of skilled developers with expertise in BIM, game engines, and data exchange. • Challenges in maintaining and updating the program over time. • Dependency on internal development resources, which may not be available to all organizations.

Table 8 - File Formats Assessment - Part 1

<table>
<tr><th colspan="2"></th><th>Advantages</th><th>Constraints</th></tr>
<tr><td rowspan="4">Geometrical Data</td><td>FBX</td><td>• Widely supported format for 3D models in Unity3D
• Supports animations and skeletal meshes
• Allows hierarchical organization of objects
• Good compatibility for real-time rendering</td><td>• Limited support for parametric elements and BIM data
• Large file sizes for complex models
• Export settings may require finetuning for accuracy
• Preservation of materials and texture is allowed only by processing the model in an external software</td></tr>
<tr><td>OBJ</td><td>• Simple and widely supported format for 3D models
• Suitable for basic geometric data
• Lightweight file size
• Human readable and easily editable</td><td>• Loss of material and texture information
• No support for animations or parametric elements
• No hierarchy: all objects are exported as one group
• Limited support for complex geometries</td></tr>
<tr><td>IFC</td><td>• Industry standard format for BIM data exchange
• Preserves BIM data (e.g., objects, properties)
• Supports parametric elements and building data
• Suitable for interoperability with other BIM tools</td><td>• Limited direct support in Unity3D
• Requires third party plugins for Unity3D integration
• Complex IFC models may require manual cleanup
• Limited support for material and texture information</td></tr>
<tr><td>DAE</td><td>• Supports geometry, materials, and animations
• Good compatibility with Unity3D
• Allows embedding texture information</td><td>• Not all Collada features are supported in Unity3D
• Potential data loss during the export process
• Can be inefficient for very large models
• Does not allow hierarchical organization of objects</td></tr>
<tr><td rowspan="3">Informational Data</td><td>IFC</td><td>• Industry Foundation Classes (IFC) is a standard for BIM data exchange, ensuring compatibility across different BIM applications
• Preserves BIM-specific metadata, such as element types, properties, and classifications
• Supports both geometric and non-geometric information associated with BIM elements
• Enables the synchronization of metadata between Autodesk Revit and Unity3D, ensuring consistent data across platforms</td><td>• Allows the transfer of a wide range of BIM data, including object properties and relationships
• Unity3D may require third-party plugins or custom scripts to handle IFC data properly
• The IFC format can be complex and may require some understanding of the schema for customization
• Large IFC files can result in longer import times in Unity3D</td></tr>
<tr><td>CSV</td><td>• CSV files are simple and human-readable, making them easy to edit and modify if needed
• CSV format is widely supported and can be easily read by various applications, including Unity3D
• Suitable for exporting basic metadata like element names, categories, and property values
• Ideal for data backup, simple data manipulation, or quick data exchange between systems</td><td>• Limited support for complex data structures and hierarchical relationships
• Exporting metadata to CSV may require additional data processing or formatting
• CSV does not handle geometry or graphical information, limiting visualization capabilities</td></tr>
<tr><td>XML</td><td>• XML is a flexible and extensible format, allowing custom data structures and rich metadata representation
• Supports hierarchical data, making it suitable for organizing complex BIM metadata
• Allows encoding both geometric and non-geometric data, making it versatile for BIM data exchange
• Can be used to represent relationships and associations between different BIM elements</td><td>• Larger XML files can lead to increased loading times in Unity3D
• Requires parsing and processing to extract and interpret the data in Unity3D
• XML may be more challenging to read and edit directly compared to other formats
• Careful consideration needed for defining a clear XML schema for data consistency</td></tr>
</table>

Table 9 - File Formats Assessment - Part 2

		Advantages	Constraints
Material Data	IFC	• Industry Foundation Classes (IFC) supports material data and can store BIM-specific material properties • Enables the transfer of material names and basic properties, such as colour and transparency • Suitable for preserving BIM-specific material classifications and associations • Can be used to transfer material assignments to BIM elements in Unity3D	• Limited direct support for IFC material data in Unity3D • Unity3D may require additional custom scripts or plugins to handle IFC material data properly • Complex material properties in Autodesk Revit may not be fully compatible or accurately translated to Unity3D • Large IFC files can lead to longer import times and performance issues in Unity3D
	FBX	• FBX supports the transfer of material names, textures, and basic properties between Autodesk Revit and Unity3D • Preserves texture mappings, allowing textures to be applied to 3D models in Unity3D • Suitable for basic material representations, such as diffuse colour and basic textures • Provides a common format for exchanging 3D models and associated materials across applications	• Limited support for complex or advanced material properties in FBX • Unity3D may require additional adjustments to achieve visual parity with the original Autodesk Revit model • Large FBX files can result in increased loading times in Unity3D
	MTL	• MTL files are commonly used with OBJ files and can store basic material properties like colour and texture • Enables the transfer of basic material information from Autodesk Revit to Unity3D • Suitable for simple material representations, especially when using the OBJ format • Human-readable and easy to edit, making it accessible for manual adjustments if needed	• MTL files alone cannot fully represent complex material properties or hierarchies • Unity3D may require additional configuration to apply materials correctly • MTL does not handle advanced material features like transparency or reflection
	IFC_VRXML	• IFC_VRXML is an extension of IFC specifically designed to carry VR-related information • Enables the transfer of additional material data related to virtual reality and visualization • Suitable for exporting VR-specific material properties and settings from Autodesk Revit • Supports features like VR material types, shaders, and settings for enhanced visualization	• Limited support and adoption of IFC_VRXML in Unity3D • Unity3D may require custom implementation to interpret and use IFC_VRXML material data • Exporting IFC_VRXML may require additional setup and configuration in Autodesk Revit • Limited compatibility with other 3D modelling software and applications

Table 10 - File Formats Assessment - Part 3

		Opportunities	Limitations
Zone and Areas Data	ghXML	• ghXML (Grasshopper XML) is suitable for exporting custom data structures and geometric information • Enables the transfer of zones and areas with custom attributes and data defined in Grasshopper • Suitable for complex spatial data representations and custom geometries • Supports advanced data types and custom schemas for detailed spatial information	• Limited direct support for ghXML in Unity3D; custom parsing may be required • Unity3D may require additional scripts or plugins to interpret and use ghXML data • Exporting ghXML from Autodesk Revit may require additional steps or plugins for integration with Grasshopper • Complex ghXML files can lead to longer import times and performance issues in Unity3D
	IFC	• Industry Foundation Classes (IFC) supports zones and spaces for BIM data exchange • Enables the transfer of spatial data with standardized classifications and properties • Suitable for exchanging architectural spaces, such as rooms, with their properties • Provides a standard format for interoperability and data consistency between BIM and Unity3D	• Limited direct support for IFC zones and areas in Unity3D • Unity3D may require additional scripts or plugins to handle IFC zones and area data properly • Complex IFC files can lead to longer import times and potential performance issues in Unity3D • Some IFC data may require manual adjustments in Unity3D to achieve the desired visual representation
	CSV	• CSV files are simple and human-readable, making them easy to manage and modify • Enables the transfer of basic zone and area data, such as names, types, and properties • Suitable for quick data exchange and manual data management between Autodesk Revit and Unity3D • Ideal for managing and updating zone and area data independently of 3D models	• Limited support for complex data structures and spatial relationships in CSV • Unity3D may require additional parsing and organization of data from CSV files • CSV does not support 3D geometric information, limiting visualization capabilities • Spatial hierarchy and complex relationships may require special formatting in CSV files
	XML	• XML is a versatile format that supports custom data structures and hierarchical information • Enables the transfer of zones and areas with rich metadata and custom attributes • Suitable for exporting detailed information about zones, areas, and their properties • Supports flexible data organization and customizable schemas for diverse data types	• Unity3D may require additional custom scripts or plugins to handle XML data properly • Complex XML files can result in increased loading times and performance issues in Unity3D • Exporting XML from Autodesk Revit may require additional customization or filtering • XML files may require careful formatting to ensure compatibility between Autodesk Revit and Unity3D
Schedule Data	IFC	• Industry Foundation Classes (IFC) supports schedules and can store BIM-specific data • Enables the transfer of schedule data, including properties and quantities, to Unity3D • Suitable for exchanging building data related to quantities, material lists, and properties • Provides a standard format for interoperability and data consistency between BIM and Unity3D • Supports custom schedules and data structures defined in Autodesk Revit • Allows the synchronization of schedule data between Autodesk Revit and Unity3D for real-time project updates	• Limited direct support for IFC schedules in Unity3D • Unity3D may require additional custom scripts or plugins to handle IFC schedule data properly • Complex IFC files can lead to longer import times and potential performance issues in Unity3D • Some schedule data may require manual adjustments in Unity3D to achieve the desired representation • IFC schedules may need to be manually organized in Unity3D for visualization and interactivity • Limited support for dynamic or real-time schedule updates in Unity3D

4.3.1 Construction Progress Monitoring

For monitoring building progress, the direct or automatic exportation of geometry is a good method, as data on materials and zones may not be as pertinent. Therefore, compared to use cases that would necessitate a real-time exchange of geometric data, customized pipelines would effectively apply in this instance. The FBX file format is suggested because to its user-friendliness and capacity to preserve geometry and BIM object structure. In addition, the adoption of the Industry Foundation Classes (IFC) file format is proposed for attributing task development, as it facilitates the incorporation of task-related data into the DT. The efficient synchronization of informational data backlog is vital, but geometric data backlog may be of lesser importance. Implementing solid phase modelling in tools like Autodesk Revit can enable scheduling data, and integrating external apps like MS Project can assist with 4D simulations.

Focusing on geometry exports, it is suggested to use the IFC file format for task development attribution and to provide effective synchronization of informational data backlog.

4.3.2 Construction Process Management

The direct or automatic exportation of geometry is a good method for monitoring building progress, as data regarding materials and zones may not be as pertinent. In contrast to use cases that necessitate a real-time interchange of geometric data, therefore, customized pipelines are applicable here. The FBX file format is suggested because to its ease of use and capacity to preserve geometry and BIM object structure. In addition, the Industry Foundation Classes (IFC) file format is recommended for attributing task development, since it facilitates the incorporation of task-related data into the DT. The backlog of informative data must be effectively synchronized, whereas the backlog of geometric data may be of lower priority. Implementing solid phase modelling in software such as Autodesk Revit can support schedule data, and integrating external applications such as MS Project can assist with 4D simulations.

Focusing on geometry exports, it is suggested to use the IFC file format for task development attribution and ensuring effective synchronization of informational data backlog.

4.3.3 Safety Management & Hazard Monitoring

Safety and Hazard assessment use case covered the same range of Data Types as the construction process management use case; therefore, recommendation would be the same. However, the emphasis would shift towards linked data and Zone and Area data, which are, unfortunately the least explored in terms of data exchange methods.

4.3.4 Facility management

Several critical points emerge when examining data sharing mechanisms for DT applications in facility management. As with past use cases, it is essential to include essential data first. Consequently, the Industry Foundation Classes (IFC) file format continues to be suggested due to its capacity to accommodate a large variety of pertinent data. In this setting, however, the emphasis switches to the significance of backlog, especially for the collection of historical data like as inspection dates and maintenance records.

In addition, custom-built solutions are preferable in facility management scenarios for successfully managing and maintaining historical data and backlog. These solutions can be customized to ensure the efficient storage and retrieval of previous data, allowing for comprehensive facility management in the DT.

It plays an important function in terms of informational data in facility management. Although custom pipelines are an option, they are not advised since they may impose limits and data loss. Instead, it is recommended to utilize commercial solutions that strongly support the needed characteristics. Important to the successful application of DT in facility management is the selection of commercial software that enables bidirectional and real-time data sharing.

In conclusion, data interchange techniques for DT applications in facility management should emphasize the use of the IFC file format because of its capacity to capture critical data. In this scenario, backlog management becomes crucial for the storage and retrieval of past data. For efficient backlog management and historical data storage, custom-built solutions are preferred. Custom pipelines should be considered with caution when it comes to informational data, as they may bring restrictions and data loss. Commercial systems that provide bidirectional and real-time data transmission are recommended for facility management DT installations due to their powerful capabilities that support comprehensive facility management in a DT context.

4.3.5 Energy Performance Assessment and Management

When exploring data exchange methods for DT applications in Energy Performance Assessment and Management, several key considerations come to light. Firstly, there is a notable emphasis on zones and areas data, which has often been overlooked in existing research. This highlights the need for further attention and investigation into incorporating zones and areas data within the DT framework to enhance energy performance assessment and management capabilities.

Additionally, materials data play a significant role in this domain. To facilitate effective data exchange of materials information, a data pipeline utilizing the Industry Foundation Classes (IFC) or Collada (DAE) file formats is recommended. These formats offer compatibility and support for accurate representation and management of materials within the DT environment.

Furthermore, the implementation of automatic exportation methods can be programmed to streamline the exchange of data in energy performance assessment and management DTs. By automating the export process, the DT can receive updated information in a timely manner, enabling real-time monitoring and analysis of energy performance metrics.

It is important to note that information data for energy performance assessment and management DTs does not necessarily need to originate solely from software like Autodesk Revit. Sensor data can serve as a valuable source of information, providing real-time energy consumption and environmental data that can be integrated into the DT. This integration allows for accurate energy performance assessment and effective management based on sensor-derived insights.

In conclusion, when considering data exchange methods for DT applications in Energy Performance Assessment and Management, it is crucial to address the often-neglected zones and areas data. Utilizing data exchange pipelines that support the IFC or Collada file formats ensures efficient and accurate representation of materials data within the DT. Implementing automatic exportation methods enhances real-time monitoring and analysis of energy performance metrics. Additionally, integrating sensor data as a source of information enriches the DT's capabilities, enabling accurate energy performance assessment and effective management. By incorporating these aspects into data exchange methods, energy performance assessment and management within the DT framework can be optimized to drive more sustainable and efficient energy practices.

4.3.6 Building Operations

Several major findings emerge when analyzing data sharing mechanisms for DT applications in building operations. Priority is given to object behavior data in this domain, however it is frequently disregarded in the existing literature. This emphasizes the necessity for additional study and investigation into data interchange techniques that explicitly address object behavior data in order to improve building activities within the DT framework.

To successfully transmit data about object behavior, it is prudent to explore the creation of bespoke software solutions. The particular requirements and complexities of object behaviour data in building operations can be accommodated by tailor-made software. This strategy enables the development of a data exchange method that closely matches with the specific requirements and goals of building operations in a DT environment.

Alternatively, if custom software development is not viable, the object's behavioral model can be recreated within the Unity3D environment. Nonetheless, this method necessitates additional processing effort due to the manual reconstruction of the object's behavioral characteristics. Nonetheless, it provides a potential method for integrating data on object behavior into the DT for building processes.

In conclusion, data interchange mechanisms for DT applications in building operations should emphasize the incorporation of object behavior data, which is frequently ignored in the literature. To design a data interchange system specifically adapted to address the intricacies of object behavior in building processes, custom software development emerges as a preferred methodology. Alternately, it is possible to recreate the object's behavior model within the Unity3D environment, however this requires additional computational effort. By concentrating on object behaviour data interchange, the DT in building operations may efficiently simulate and optimize different elements of operational performance, thereby boosting efficiency and facilitating informed decision-making.

None of the aforementioned commercial solutions that support synchronous and bidirectional data flow offer an automatic data exchange that would permit the smooth integration of the entire BIM data spectrum between the two software. However, it might be claimed that DTs necessitate a flawless, synchronized, and bidirectional data flow between the virtual and physical realms, and not necessarily between two digital platforms.

4.4 Prototype Development

This chapter focuses on the integration of Autodesk Autodesk Revit, Dynamo, and Unity3D in the creation of a functional prototype. This chapter's major purpose is to provide a complete description of the prototype's design, implementation, and defining characteristics. By producing a tangible depiction of the intended process, this prototype serves as a key milestone in evaluating the viability and efficacy of the Autodesk Revit-Dynamo-Unity3D integration strategy for boosting the visualization and interaction capabilities of DTs.

The first section of the chapter establishes a clear framework for the prototype's creation by describing its modeling concepts and aims. The section then digs into the utilized approach, detailing the software tools, methodologies, and architectural concerns taken into account during the implementation process. The chapter shows the essential components and functions of the prototype through a step-by-step walkthrough, demonstrating how it facilitates the seamless transfer of data from Autodesk Revit to Unity3D and the subsequent association of parameters with Unity3D script components. The limitations of the scripts are then evaluated in light of the test results.

4.4.1 Modelling principles

The used BIM model was designed on the Eurotube SMF geometry model and re-built in Autodesk Autodesk Revit 2024 to enrich the model with additional data and prototype the model informational structure for optimal BIM model read in Unity3D. The BIM model was designed to display three components of the SMF, namely (1) a mobile crane, (2) a tube segment formwork, and (3) a pavement unit.

Autodesk Revit Families

Autodesk Revit families constitute a fundamental component of the software's modelling capabilities, allowing users to create and customize elements with specific properties and behaviours. Each family represents a particular object or component, such as doors, windows, furniture, or fixtures, and is categorized based on its functionality and characteristics. The categorization follows a hierarchical structure known as the category and type structure in Autodesk Revit.

The category and type structure organizes families into a logical framework, with categories serving as high-level groupings and types representing specific variations or configurations within each category. Categories encompass broad classifications, such as walls, roofs, or furniture, while types define more specific instances within those categories, such as concrete walls, sloped roofs, or dining chairs.

One of the notable capabilities of Autodesk Revit families is their ability to be nested within one another. This nesting feature allows for the creation of more complex and detailed elements by combining multiple families into a single cohesive unit. For example, a door family may include nested families for the frame, panels, handles, and other components.

The utilization of nested families becomes a crucial modelling principle in the development of the presented prototype for the purpose of assigning dynamic behaviours and visibility settings to specific parts of the object, rather than applying them to the entire object as a whole.

By leveraging nested families within the Autodesk Revit model, individual components or parts of an object can be encapsulated within nested families, each having its own set of parameters and properties. These nested families act as independent entities within the overall model, allowing for precise control over their behaviours and visibility settings in Unity3D. For instance, dynamic behaviours, such as physics simulations, can be assigned to specific nested families, enabling them to interact realistically within the Unity3D environment. By associating physics properties, collision detection, or motion constraints to these nested families, users can achieve accurate and lifelike simulations for those particular components, while other parts of the object remain unaffected by the dynamics.

Similarly, visibility settings can be finely tuned at the nested family level. By defining visibility parameters and conditions within the nested families, specific parts of the object can appear or disappear based on user interactions or object properties in Unity3D. This allows for dynamic visibility control, enhancing the interactive and immersive experience within the simulation.

By employing nested families in this manner, the Autodesk Revit-to-Unity3D exportation process offers a granular approach to assigning dynamic behaviours and visibility settings to specific components or parts of the object. This level of control ensures that simulations and dynamics are accurately applied only to the desired elements, while maintaining the integrity and stability of the overall model. Consequently, users can create engaging and interactive experiences in Unity3D, where different parts of the object exhibit distinct behaviours, respond to physics simulations, and dynamically appear or disappear based on the simulation's requirements or user interactions.

For this reason, it is extremely important that the geometry structure implemented in Autodesk Revit would be maintained in the Unity3D environment once imported.

Parameters and Constraints

Autodesk Revit parameters are an integral aspect of the software's parametric modelling capabilities, enabling precise control and manipulation of elements within a building model. Parameters in Autodesk Revit are defined properties associated with elements that govern their behaviour, appearance, and interaction with other elements. These parameters can be categorized into several types, including instance parameters, type parameters, shared parameters, and project parameters.

Instance parameters are specific to individual elements, allowing for unique values for each instance. They provide the flexibility to customize properties such as dimensions, material assignments, or positioning, providing granular control over element properties on a per-instance basis.

Type parameters, on the other hand, are associated with element types rather than individual instances. They define properties that are common to all instances of a particular element type. Modifying a type parameter will affect all instances of that type within the model, facilitating efficient global changes.

Shared parameters allow users to define custom parameters that can be shared and used across different families or projects. They provide a means to extend the built-in parameter options in Autodesk Revit and enhance interoperability between different models and disciplines.

Project parameters are global parameters that can be applied to multiple elements within a project. They are particularly useful for tracking and coordinating project-specific information, such as room numbers, equipment schedules, or project phases.

Autodesk Revit parameters can be accessed and modified through the software's user interface or programmatically using APIs like the Autodesk Revit API or Dynamo. This allows for automation and advanced customization, enabling users to create sophisticated parametric relationships between elements or drive element properties based on external data sources.

For the development of the BIM model, only type parameters were used. This originates from the fact that updating object type changes between Autodesk Revit and Unity3D was already successfully tested by previous scholars (Du, 2017).

4.4.2 Autodesk Revit Model

Figure 4 displays a snapshot of the test model for the smart mobile factory, which was designed to evaluate the effectiveness of BIM and game engine coupling for DT implementation in the AEC industry. The model includes multiple instances of each element throughout the virtual environment, providing an analysis of the instantiation of each element. This repetition is important for validating the exportation method, ensuring that every repeated element is recognized individually, rather than as a digital copy of a single element.

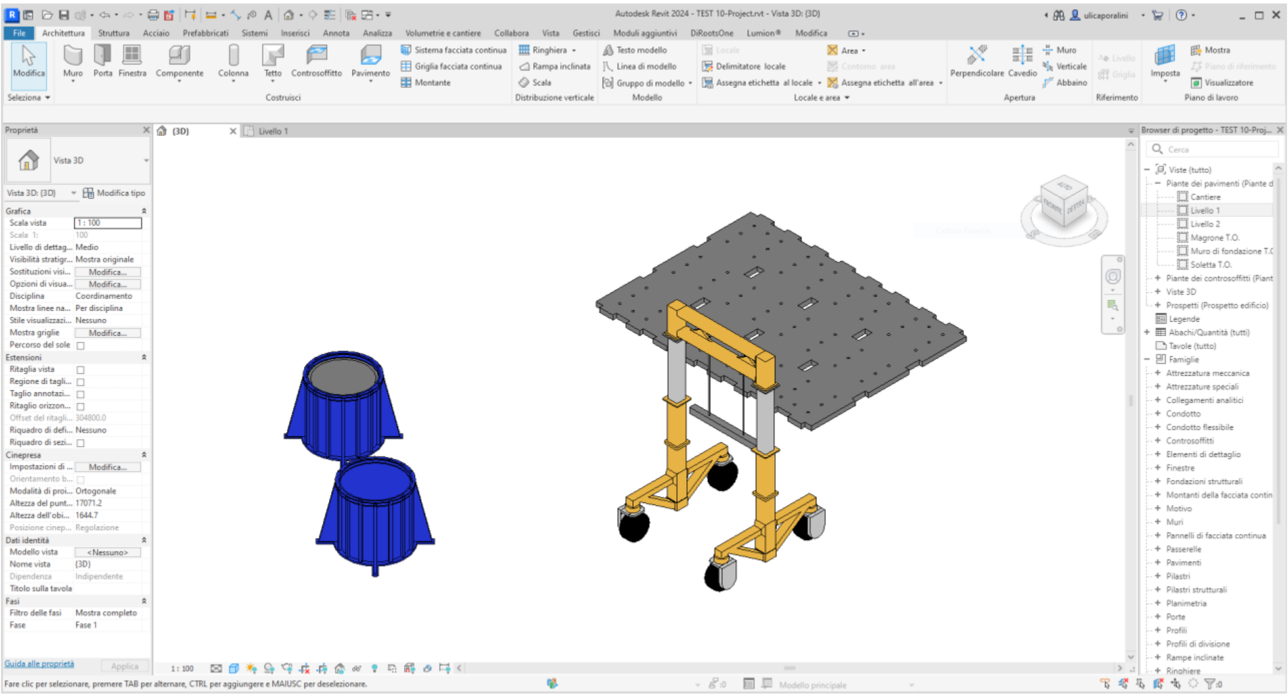

Figure 4 - Test Model in Autodesk Revit 2024

Mobile Crane Component

The mobile crane component was designed to have mobility parameters, which enabled it to move its built-in components and move geographically around the virtual environment. Figure 5 shows the Mobile Crane Component.

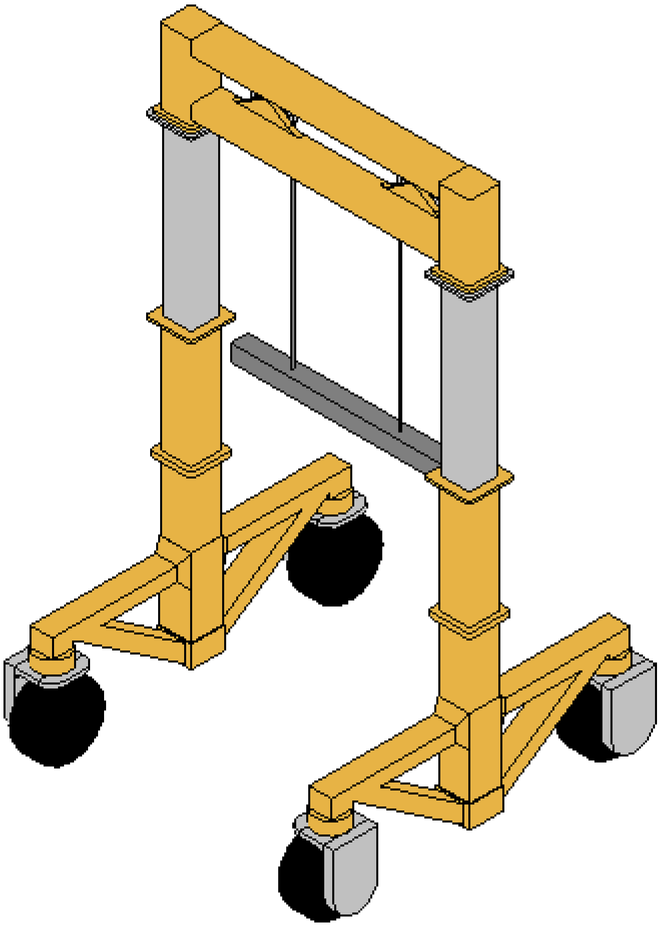

Figure 5 - Mobile Crane Component

The structure of the Mobile Crane model is made of sub-elements, called “movable elements”. These elements can be visualized in Figure 6, Figure 7 and Figure 8. Each movable element contains mobility parameters including movement type, referral axis and top/bottom constraint. The hosting element has parameters on its own that reflect the status of the machine itself. These parameters include Maintenance Period, Set Up Time, and Sate. In Unity3D, the mobile crane is then animated to move around the virtual environment, simulating its real-world behaviour.

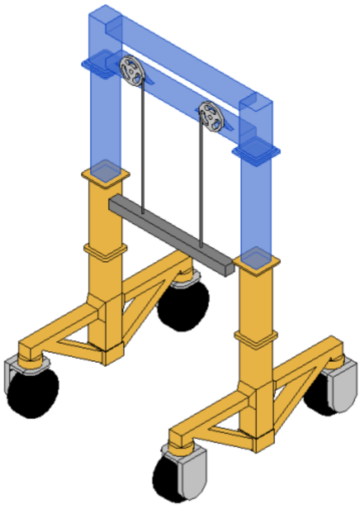

Figure 8 - Mobile Crane - Movable Element 1

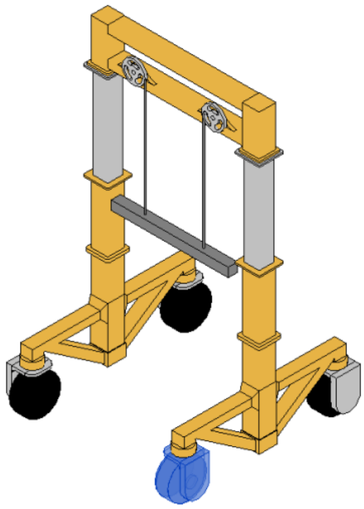

Figure 7 - Mobile Crane - Movable Element 2

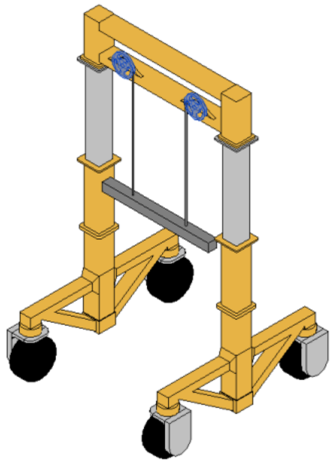

Figure 6 - Mobile Crane - Movable Element 3

The mobile crane component was chosen for the test model because it represents a critical element of the smart mobile factory, which needs to be monitored and controlled in real-time to ensure optimal performance and safety. By simulating the mobility parameters of the mobile crane in the virtual environment, stakeholders can evaluate and optimize its behaviour, reducing the risk of accidents and improving productivity. Similar components of the mobile factory would be Mechanical Equipment such as the concrete mixer, the load/offload truck, or any other component that operates by moving parts.

Tube Segment Formwork Component

The tube Segment Formwork component was designed to have visibility parameters, which enabled users to visualize the internal segment in the formwork according to the status of the formwork (Active/inactive). These visibility parameters are associated with the Family Type of the Tube Segment Formwork element. Figure 9 shows the Tube Segment Formwork component with its parameter dialog box.

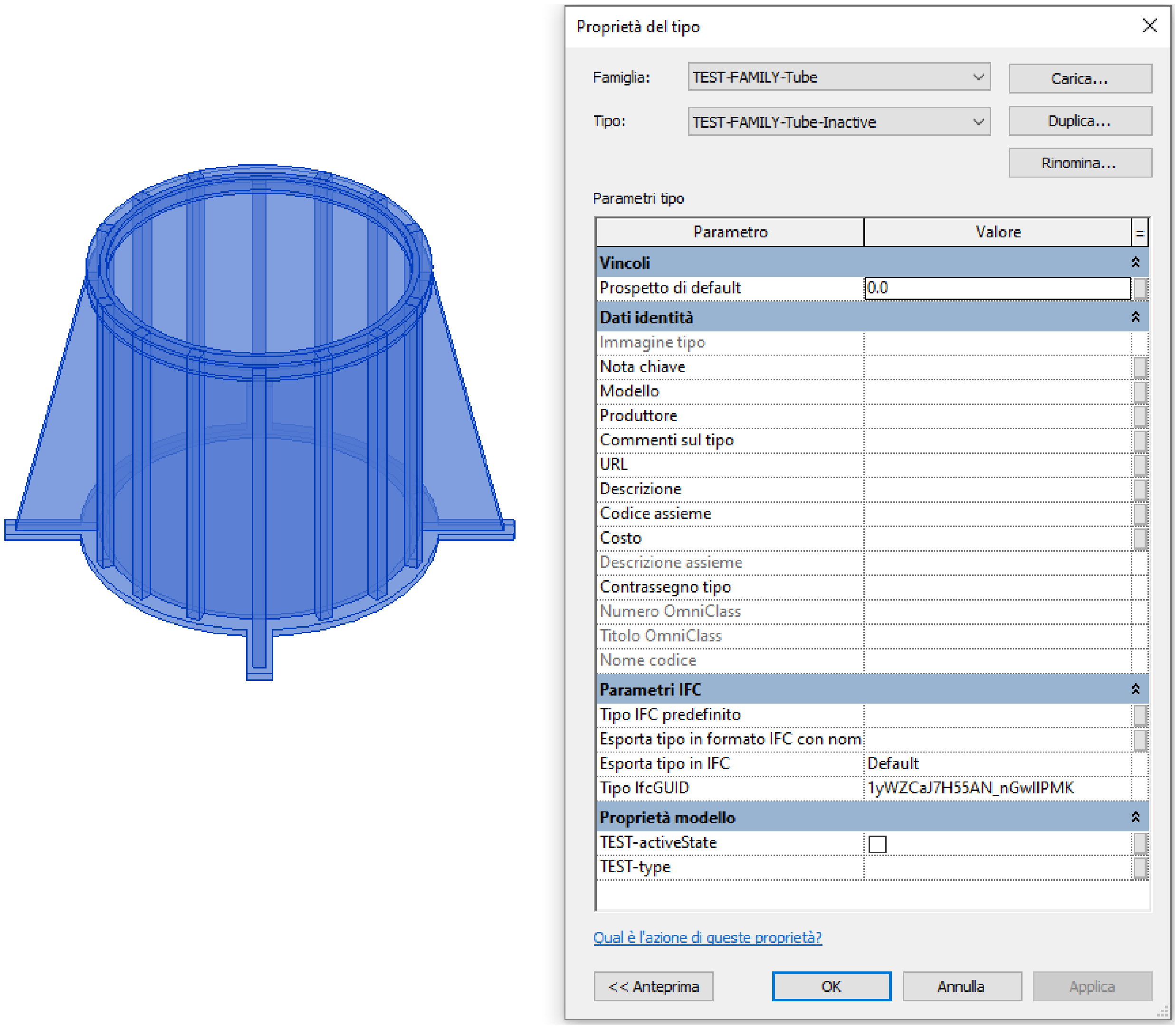

Figure 9 - Tube Segment Formwork Component

These nested families are considered in this research as temporary elements. The Temporary elements are characterized by their instantiation dependency to specific timeframes or state of the parent family. Thus, by changing the type in the model, the tube segment will become visible. Figure 10 and Figure 11 show the two model types.

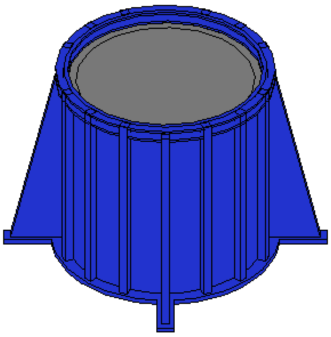

Figure 10 - Tube Segment Formwork - Active Type

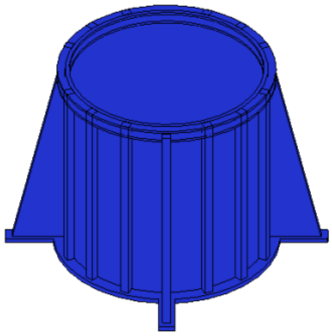

Figure 11 - Tube Segment Formwork - Inactive Type

The tube segment formwork component was selected for the test model because it represents a critical element of the Smart Mobile Factory. Monitoring and controlling this component in real-time are essential to ensure optimal performance and quality. By visualizing the internal structure and behaviour of the tube segment creation process in a virtual environment, users can evaluate and optimize its performance, reducing the risk of defects and improving product quality. For example, humidity levels.

Pavement Unity3D Component

The pavement Unity3D component was designed to be static, representing a stationary element of the smart mobile factory. In Unity3D, each pavement Unity3D instance will be visualized in the precise sequence in which they will be placed in every location of the Smart Mobile Factory. Figure 12 shows the model of a single Pavement Unit.

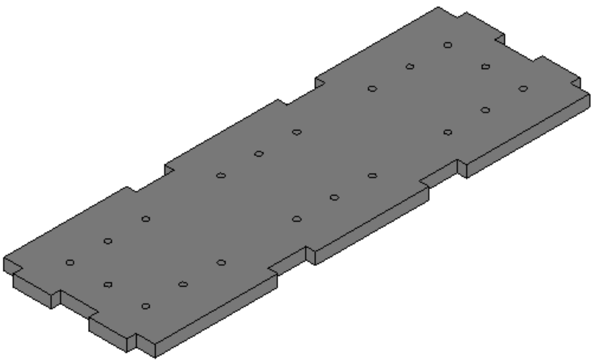

Figure 12 - Pavement Unit Component

The pavement Unity3D component was selected as the test model because it represents a critical element for demonstrating serial control of repeated elements in a dynamic virtual model. By visualizing the pavement Unity3D instance and its related parameters in the virtual environment, the DT can monitor the status of pavement assets and predict their performance and maintenance needs in real-time. For instance, by monitoring traffic patterns at a construction site, pavement unit instances can be placed in strategic locations to avoid repeatedly over-stressing a single element.

The chosen components of the test model were selected based on their relevance to the AEC industry. The different parameters evaluated for each component helped in assessing the accuracy of the test model.

This prototype would allow users to evaluate and optimize the behaviour and performance of critical components in real-time. For instance, by simulating the mobility parameters of the mobile crane, users can assess its behaviour and optimize its performance, reducing the risk of accidents and improving productivity. Similarly, by visualizing the internal structure and behaviour of the tube segment formwork, users can evaluate and optimize its performance, reducing the risk of defects and improving product quality. By accurately representing the pavement Unity3D component, users can monitor the status of pavement assets and predict their performance and maintenance needs in real-time.

4.4.3 Proposed Exportation pipeline objective

This paragraph focuses on the development of a comprehensive workflow that combines Autodesk Autodesk Revit, Dynamo, and Unity3D, aimed at enhancing the visualization and interaction capabilities of DTs. Specifically, the thesis proposes a two-module approach, where the first module leverages Autodesk Revit and Dynamo to export the geometry model and associated parameters into a JSON file, along with material information, and the second module employs Unity3D to parse the JSON data and dynamically associate it with the corresponding Unity3D script components. This introductory paragraph sets the stage for the subsequent discussion, highlighting the significance of DTs, the integration of multiple software tools, and the objectives of the proposed workflow, ultimately paving the way for an in-depth analysis of the developed Autodesk Revit-Dynamo-Unity3D integration approach.

The proposed prototype aims at successfully handle geometrical, informational, and material data exchange transfer between Autodesk Revit and Unity3D.

The Dynamo script offers several benefits in DT implementation in the AEC industry. First, it significantly reduces the time and effort required to transfer BIM data to Unity3D, making the data exchange process more efficient. Second, the script ensures data consistency and accuracy, reducing the potential for errors or discrepancies in the data. Finally, the script provides a standardized approach to data exchange, ensuring that all stakeholders are using the same process and format for data transfer.

Overall, the Dynamo script offers a streamlined and standardized approach to data exchange between BIM and Unity3D, facilitating the implementation of DTs in the AEC industry. By leveraging this technology, stakeholders can monitor, analyse, and optimize building performance in real-time, resulting in improved efficiency, reduced energy consumption, and enhanced sustainability.

4.4.4 Dynamo Script

A Dynamo script has been developed to optimize the data exchange between Autodesk Revit BIM and Unity3D for DT implementation in the AEC industry. The script integrates three Dynamo routines into one Dynamo file, streamlining the data exchange process.

The first routine exports an FBX file, which contains the 3D geometry information of the BIM model. The FBX file generated by the script contains the 3D geometry information of the BIM model, including the elements' structure and Id number (Figure 13). This information can be used to create a virtual replica of the physical building in Unity3D, allowing users to monitor and analyse building performance in real-time. However, dynamo alone, compared to the other pipeline solutions, does not allow the exportation of an FBX file that will retain materials. This is a big limitation and would require external effort in re-building the material properties in another way. However, the standard information exported can be read by Unity3D.

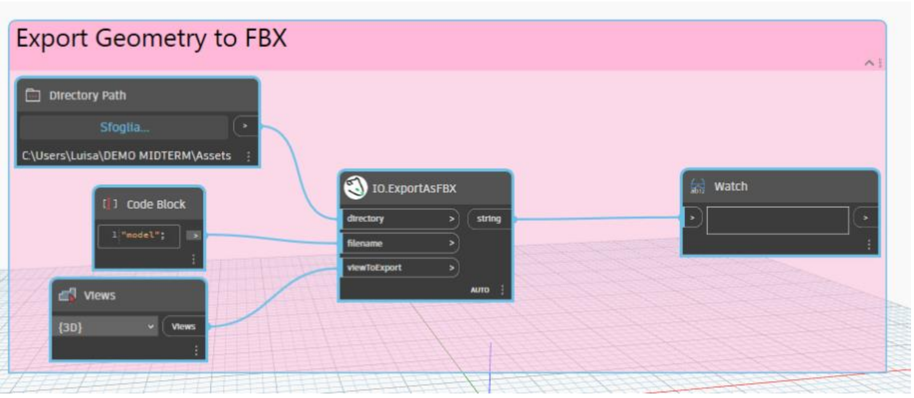

Figure 13 - Dynamo Script Snippet 1 - Geometry Export

The second routine exports metadata into a JSON file, which contains information about the BIM elements, such as their ID, name, and type. This information can be used to facilitate data management and analysis in Unity3D, allowing users to easily identify and analyse specific building elements. The JSON file structure consists of sub dictionaries assigned to each of the element's instances. The material data contained in the JSON file can then be reconstructed in Unity3D. Similarly, to the second routine, the third routine exports material data into a JSON file. The material data is de-constructed into Material Name, Colour in RGB scale and Texture File path.

Once all information is gathered, the data is merged as exported as 1 single unit. The sample prototype intentionally selected one one element out of the dictionary as it was difficult to atckle a complex JSON structure in Unity3D with the limited time givena and the restriscted programming knowledge of the Author (Figure 14).

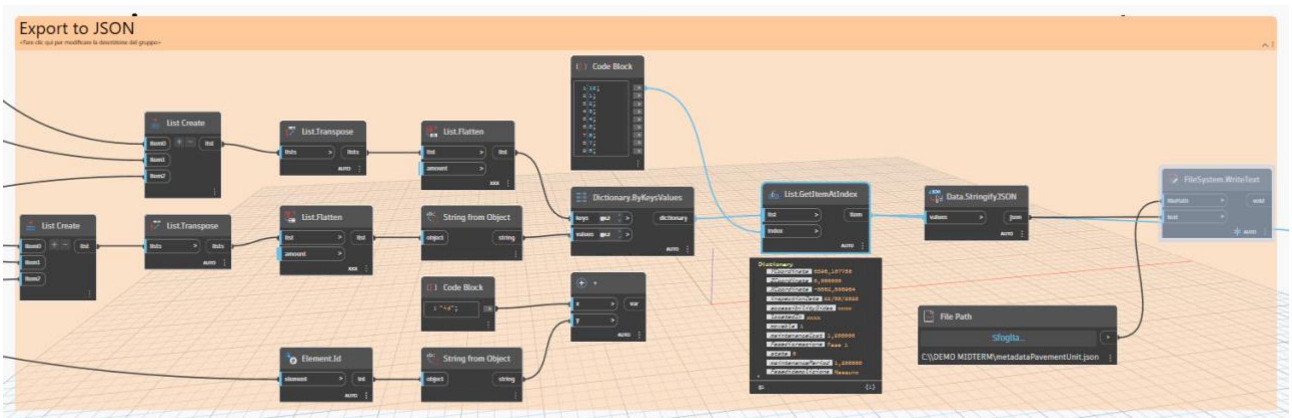

Figure 14 - Dynamo Scirpt Snippet - Export to JSON

Finally, the fourth routine is to write a .cs file that will be used in Unity3D to assign the parameters to the imported objects. Based on the metadata selected, the script exports a code that builds the class definition for the element (Figure 15). This is essential for seamless integration with Unity3D as all properties assigned to objects in Unity3D must be defined within the environment.

By combining these four routines, the Dynamo script provides a standardized approach to data exchange, enabling stakeholders to transfer BIM data to GE with minimal effort. Figure 16 show the Dynamo script in its entirety.

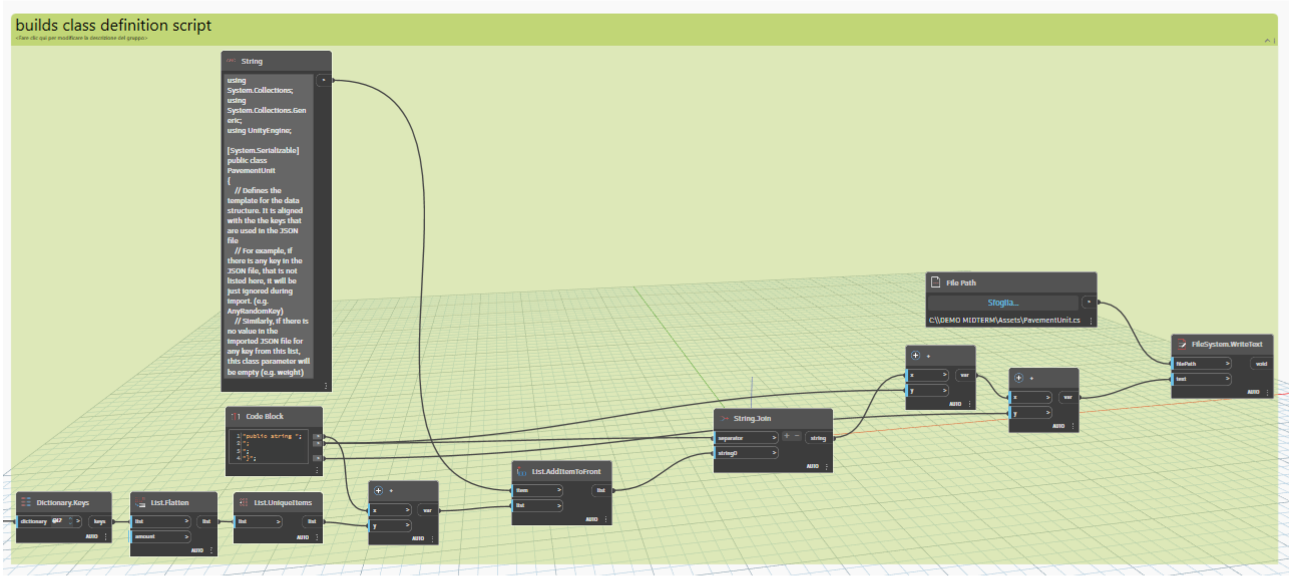

Figure 15 - Dynamo Script Snippet 2 – Pre-set class definition

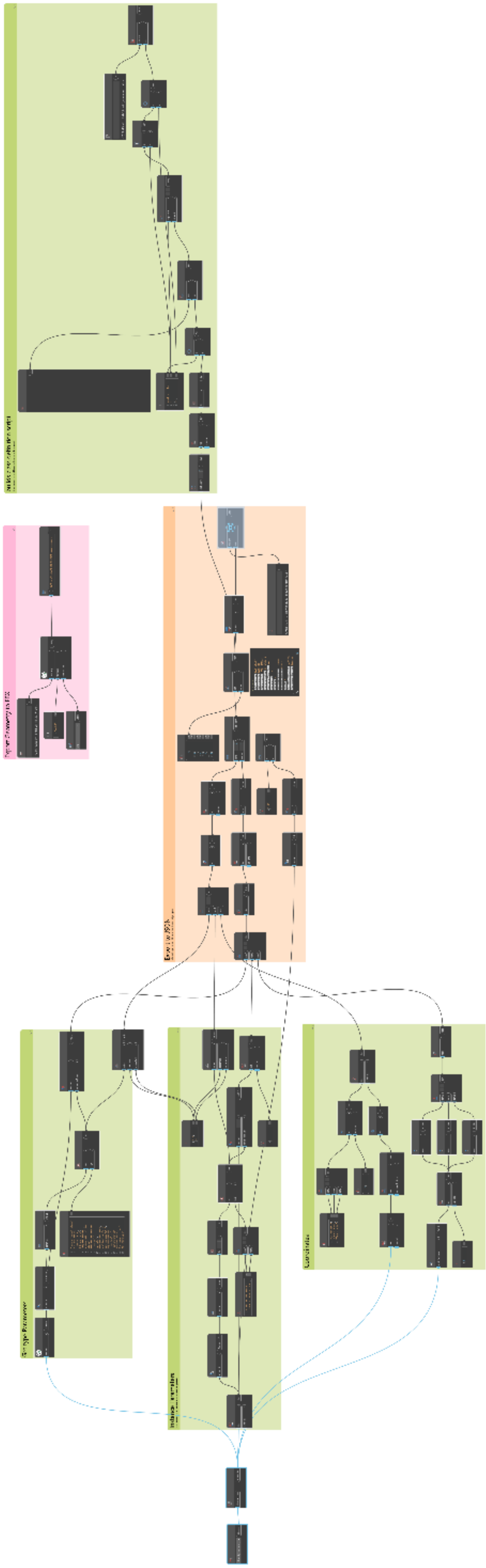

Figure 16 - Full Dynamo Script

4.4.5 Unity3D Integration

Once all the files are exported into the specific Unity3D project folder, the file will automatically show up in the asset library of the project in Unity3D. A few modifications and adjustments need to be here conducted then. First f all, the geometry needs to be places in the virtual environment (Figure 17). Since the dynamo exported FBX file does not retain materials, the geometry will be displayed as a grey object and will require addition processing within Unity3D to re-assign the material information exported as JSON. In order to do so, a script file needs to be assigned to the object an additional component. The script will create properties in the inspector bar (right tab in Figure 17). Finally, after the component embeds the script, the screen needs to be "played" and a button will appear in the left top corner. Users need to interact with this button to load the JSON data values into the object properties. Figure 18 Shows the final result. Further development in script can allow the other data types as materials to also be re-constructed in Unity3D and loaded by the user interface button. This will reflect every change applied to the JSON file, upon exportation in Autodesk Revit and reload in Unity3D.

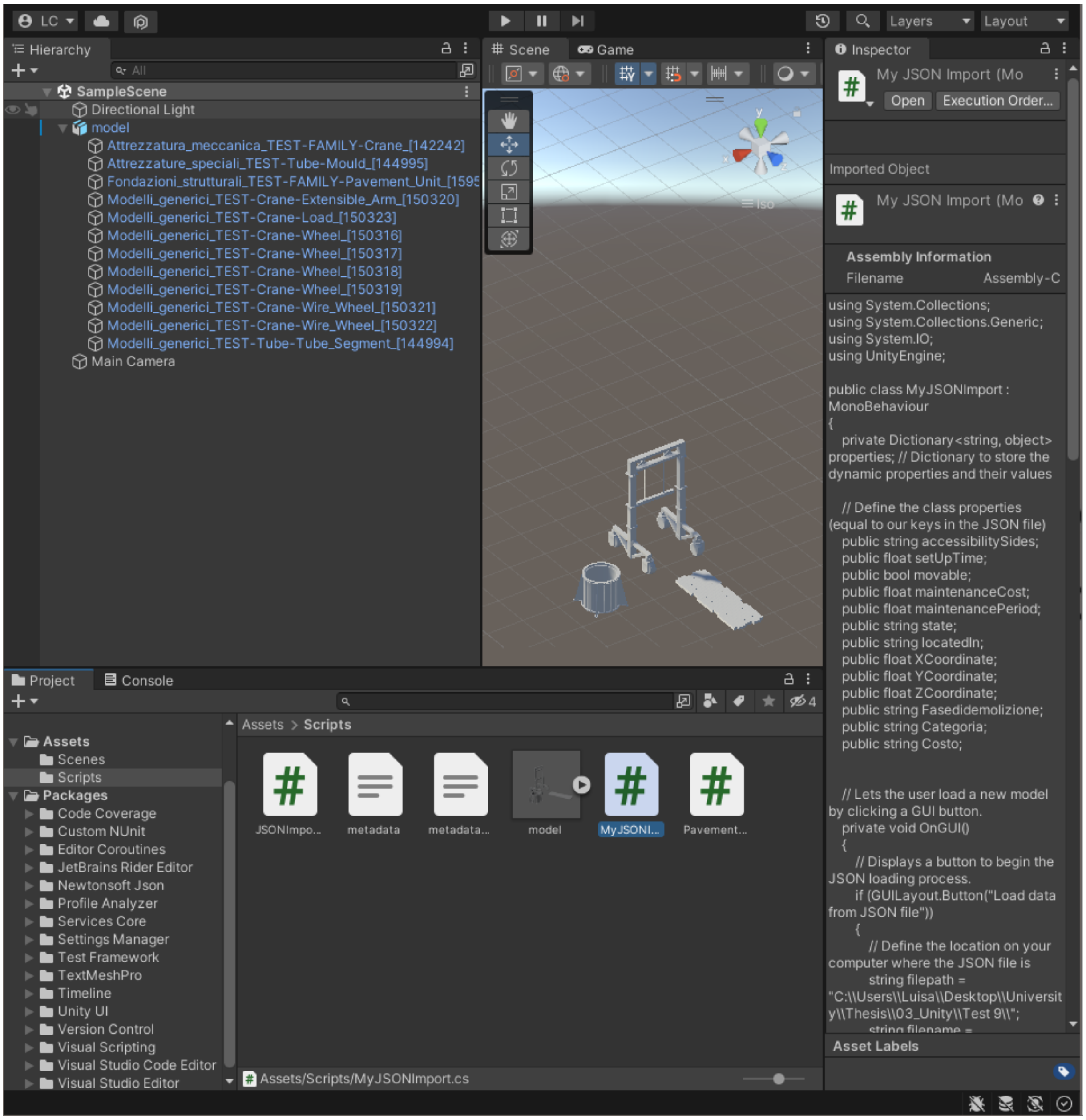

Figure 17 - Unity3D 3D system view - Geometry positioning in the scene

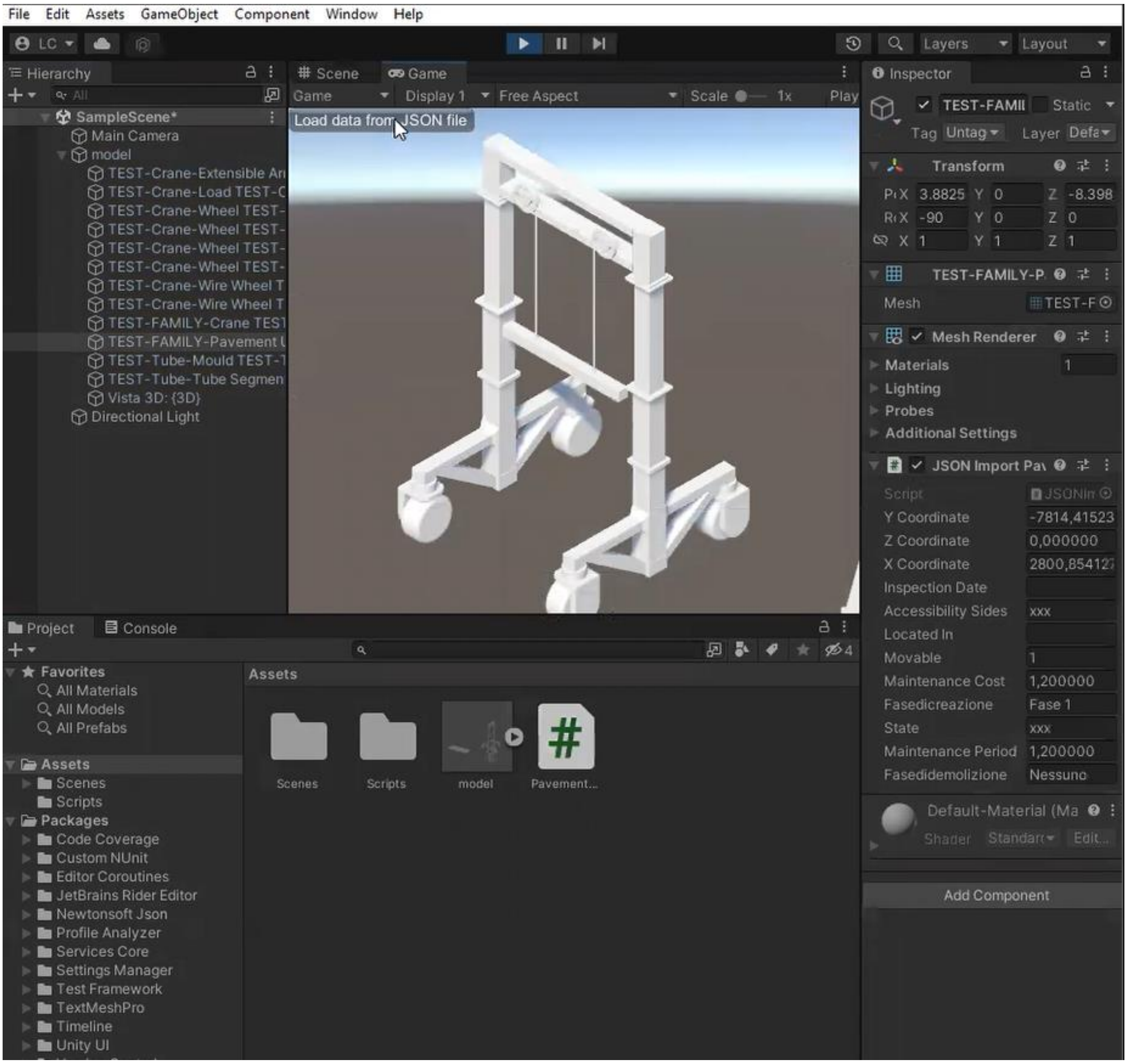

Figure 18 - Final resutl of prototypical data exchaneg method

4.4.6 Limitations

Despite the significant advancements achieved through the development of the Autodesk Revit Dynamo script, certain limitations were encountered during the implementation process. One notable limitation is the inability to retain materials when exporting the geometry model in the FBX format. Although FBX supports material data, efforts to incorporate this functionality proved unsuccessful within the limitations of the script. The ideal solution would have involved leveraging the Forge Software Developer Kit (SDK), which offers comprehensive material handling capabilities. However, due to restricted access and the absence of a free developer kit, integrating the Forge SDK was not feasible for this project.

Another limitation arises from the process of storing data in a JSON file. To write the gathered information into the JSON file, all data had to be converted into strings. While Dynamo typically allows for the reloading of JSON files after external modifications, the conversion of all data into strings raises uncertainties regarding the ability of the updated JSON file to successfully re-parse the data back into the BIM model. Unfortunately, due to time constraints, further research was not possible to determine the compatibility and feasibility of re-parsing the modified JSON file.

These limitations, while significant, should be considered when considering the usability and functionality of the developed script. The absence of material retention and potential challenges associated with reloading modified JSON files underscore the need for future enhancements and exploration of alternative approaches to overcome these constraints. Nonetheless, the developed Autodesk Revit Dynamo script, despite its limitations, remains a valuable contribution towards facilitating the integration of BIM data into Unity3D, enabling enhanced visualization and interaction capabilities for DT applications.

5. Discussion

5.1 General findings

In the construction business, attaining the status of a DT necessitates the selection of data exchange techniques. The conclusions of this study show a number of critical factors to consider while making this choice. Clearly, methods of bidirectional and real-time data sharing have the most potential for properly implementing DTs. To preserve the integrity and efficacy of the DT system, additional procedures and file processing by other applications should be avoided.

In addition, it was discovered that the reassignment of the model's geometrical element structure within the Unity3D environment necessitates a substantial amount of computational effort when using data exportation methods including the Collada file format. In contrast, the Industry Foundation Classes (IFC) file format retained the most BIM data out of all the file formats examined. This emphasizes the importance of choosing file formats that preserve the necessary information for DT implementation.

Considering the management of huge files, polygon reduction emerged as a crucial step for ensuring seamless and effective data interchange. The use of polygon reduction techniques into the data exchange method pipeline for synchronous real-time data sharing helps ease potential processing issues.

In addition, it was discovered that sending geometrical information through databases necessitates a significant amount of computational effort in order to recreate the geometry within Unity3D. This stresses the importance of thorough consideration and optimization of data exchange protocols to provide efficient and accurate representation of geometrical data in the DT environment.

Inclusion of schedule data and 4D simulations may need additional processes unless programmed components are incorporated into the chosen data transmission technique. These concerns are critical for guaranteeing the synchronization and accurate depiction of temporal features within the DT.

Intriguingly, the analysis also revealed a relative dearth of emphasis on zone and area data, object behaviour, and connected data in the existing literature. This could be related to the limited research focus on retrieving and integrating these specific data types into DT implementations. Further analysis and investigation of these data sources may yield useful insights and expand the capabilities of DT systems in the construction industry.

Moreover, the study indicated that custom-built software and commercial solutions frequently impose fewer restrictions on data flow. It should be noted, however, that this result may be affected by the fact that the analysed custom-built software research did not focus on specific use cases with relevant requirements, but rather on the general features and functioning of the software or application.

In general, the debate emphasizes the importance of selecting bidirectional and real-time data exchange mechanisms for an efficient DT implementation. In addition, the findings highlight the significance of addressing file formats, polygon reduction, geometry reconstruction, temporal data management, and the underexplored fields of zone and area data, object behaviour, and linked data. These findings can educate future study and drive the development of effective data interchange techniques to facilitate the successful application of DTs in the construction industry.

5.2 Comparative Analysis

Various conclusions regarding data exchange methods for DT applications in different domains within the construction industry were examined.

In the realm of DT implementation for construction progress monitoring, it was concluded that bi-directional and real-time data exchange methods are essential to achieve the status of a DT. Additional steps and external software file processing should be avoided to maintain the integrity and real-time nature of the DT. It was also noted that data exportation methods using the Collada file format may require extra computing effort to re-assign the model's geometrical element structure in the Unity3D environment. On the other hand, the IFC file format was highlighted as the one that retains the most BIM data among all the file formats. Moreover, polygon reduction was recognized as an important step, especially for handling large files, and it should be seamlessly incorporated into the data exchange method pipeline for synchronous real-time data exchange.

In the context of DT implementation for construction process management, the conclusions emphasized the need for comprehensive data exchange methods that encompass all BIM data types. The IFC file format was recommended for its ability to include a wider extent of information in a single file. Backlog synchronization, both for geometrical and informational data, was highlighted as crucial for capturing historical data and enabling seamless and bi-directional data exchange. Custom-built software solutions were suggested for this use case, while commercial solutions that do not utilize IFC or Avro file formats were not deemed ideal due to potential limitations in supporting all the required features.

For DT applications in facility management, the conclusions focused on the importance of zones and areas data, which is often overlooked in the literature. The IFC file format was suggested for effective data exchange, and emphasis was placed on the significance of backlog management, particularly for capturing historical information such as inspection dates. Custom-built solutions were favoured for enforcing backlog management and storing historical data. While informational data was considered important, caution was advised regarding custom pipelines due to potential limitations and data loss. Commercial solutions supporting bi-directional and real-time data exchange were recommended for their robust features.

In the context of DT implementation for energy performance assessment and management, the conclusions emphasized the significance of zones and areas data, materials data, and automatic exportation methods. The IFC or Collada file formats were recommended for data exchange, considering the importance of materials information. Automating the export process was highlighted as crucial for real-time monitoring and analysis of energy performance metrics. Moreover, the integration of sensor data was proposed as a valuable source of information for energy performance assessment, enabling accurate monitoring and management within the DT environment.

Finally, in the domain of DT implementation for building operations, the conclusions highlighted the importance of object behaviour data, which is often overlooked in the literature. It was suggested that custom-built software development is advisable to establish a tailored data exchange mechanism for object behaviour data in building operations. Alternatively, the re-creation of object behavioural models in the Unity3D environment was considered as an option, albeit requiring additional computational effort. Object behaviour data was recognized as crucial for simulating and optimizing various aspects of operational performance in the DT.

Overall, these conclusions shed light on the diverse considerations and challenges associated with data exchange methods for DT implementations in different areas of the construction industry. They provide valuable insights for researchers, practitioners, and stakeholders involved in developing and utilizing DT technologies to improve construction processes, facility management, energy performance, and building operations.

5.3 Contributions to the field of BIM and DT construction

The research findings and conclusions pertaining to data exchange methods for DT development in the context of BIM and GE make substantial contributions to the field. Specifically, these contributions can be observed in the following areas.

Firstly, in terms of BIM implementation, the identified conclusions underscore the significance of effectively incorporating BIM data into DT development. The delineation of specific BIM data types, necessary for various DT use cases, such as geometrical data, informational data, material data, and zone and area data, enhances the understanding of how BIM can be optimally integrated into DT implementations. Consequently, this knowledge has the potential to advance BIM implementation strategies and practices within the construction industry.

Secondly, the discussions surrounding data exchange methods for DT development shed light on the role of GE, particularly Unity3D, in creating immersive and interactive virtual environments. By delineating the challenges and considerations associated with data transfer from BIM to GE, such as the need for polygon reduction and the reassignment of geometrical element structures, the research provides valuable insights for optimizing the integration of GE into the DT development process. Consequently, this knowledge facilitates the creation of realistic and dynamic virtual representations of physical assets within the DT framework.

Thirdly, the conclusions address the crucial requirement for seamless data exchange between BIM and GE within DT development. Through recommendations regarding file formats that retain BIM data, and the emphasis on real-time and bi-directional data exchange, the research contributes to bridging the gap between BIM and GE. This integration enables the transfer of comprehensive information from BIM models to GE, thereby enhancing the visual representation, behavioural simulation, and interactive capabilities of the DT.

Lastly, the research findings significantly enhance the scope and efficacy of DT applications. By identifying specific use cases, such as construction progress monitoring, construction process management, facility management, energy performance assessment and management, and building operations, the research offers insights into the requisite data types, requirements, and exchange methods for each scenario. Consequently, this knowledge supports the development of robust and tailored DT applications, empowering stakeholders to leverage DTs for enhanced construction project management, operational efficiency, energy optimization, and maintenance practices.

5.6 Prototype development

The growth of the integrated Autodesk Revit Dynamo script was hindered by a number of constraints, notwithstanding its achievements. The inability to keep materials when exporting the geometry model to the FBX format was a serious limitation. Despite FBX's support for materials, it was not possible to integrate it with the Forge SDK due to restricted access. In addition, the process of saving data in a JSON file required the conversion of all information into strings, creating doubts about the successful re-parsing of the changed JSON file into the BIM model. These constraints highlight the need for future developments and alternate approaches to material retention and data compatibility challenges. Nonetheless, the script's contribution to integrating BIM data into Unity3D remains valuable, as it enables greater visualization and interactivity for DT applications.

In conclusion, the contributions of this research to the field of BIM and GE implementation in DT development include advancing BIM integration, optimizing game engine utilization, bridging the gap between BIM and GE, and enhancing the capabilities of DT applications across various construction industry domains. This research encourages the use and application of DTs as potent instruments for simulation, analysis, and informed decision-making throughout the whole lifetime of building projects and facility management procedures.

6. Conclusions

6.1 Summary

The discussions on integrating Game Engines like Unity3D with BIM data showcase potential for immersive and interactive DT environments. Proposed data exchange improvements contribute to seamless integration, accurate representation, and behavioural simulation of physical assets within the DT. These contributions drive innovation, enhance project management practices, and enable informed decision-making throughout construction projects and facility management processes.

The research questions guiding this study were crucial in exploring the data exchange methods and requirements for various DT use cases in the construction industry. The research questions can be found in Chapter 1.3.

The first sub-research question, SRQ1, was effectively addressed through the requirements analysis. The findings from this analysis demonstrated that not all Digital Twin use cases have the same requirements when it comes to BIM data. The varying nature of DT applications in construction necessitates tailored data exchange methods to ensure consistent and useful BIM data retrieval for each use case.

On the other hand, SRQ2 was answered through the performance evaluation conducted during this research. The performance evaluation provided insights into the capabilities and limitations of each data exchange method in terms of BIM data visualization and manipulation within Unity3D. Understanding these aspects is crucial for optimizing data exchange methods and enhancing the visualization and manipulation of BIM data within the digital twin environment.

Lastly, the primary research question, RQ, was comprehensively addressed through the comparative analysis of the various data exchange methods. Drawing on the individual requirements, practical advantages, and disadvantages identified through the research, the comparative analysis resulted in a comprehensive spectrum of effective data exchange methods for each Digital Twin use case. This analysis forms the basis for guiding the selection of appropriate data exchange methods that facilitate consistent and useful BIM data retrieval for specific DT applications in construction.

Overall, the combination of the requirements analysis, performance evaluation, and comparative analysis provided a thorough understanding of the data exchange methods and their suitability for different Digital Twin use cases. This research has shed light on the complex landscape of data exchange in the construction industry, offering valuable insights and guidelines for implementing Digital Twin technology effectively and efficiently across various construction applications.

6.2 Recommendations

This research findings iindicate a number of ramifications and potential study directions in the field of BIM and DT implementation. These consist of:

First, additional research should be undertaken on translating the behaviour of BIM objects from Autodesk Revit to Unity3D. Object behaviour data, which includes the dynamic attributes and interactions of BIM objects, plays a crucial part in the development of realistic and interactive DT environments. It is recognized, however, that this element has received scant consideration in the extant literature. Therefore, additional research is required to develop efficient and trustworthy ways for transmitting object behaviour data from Autodesk Revit to Unity3D, enabling more accurate simulations of object behaviour within the DT framework.

Second, greater research should be conducted on BIM data interchange for Zones and Areas. The discovered conclusions underline the relative underemphasis on this data category in the academic literature. Due to the significance of zones and regions in numerous DT use cases, such as facility management and energy performance assessment, it is necessary to investigate effective data exchange mechanisms and pipelines that are specifically customized to this data type. Investigating the seamless integration and synchronization of zone and area data between BIM and GE would enhance the depiction and analysis of physical spaces inside DTs.

In addition, conventional BIM modelling procedures for DT implementations remain undefined. The lack of clear principles and methods for embedding BIM models into DT frameworks creates a research opportUnity3D. This includes creating standard data extraction, format compatibility, data categorization, and connection with GE operations. The creation of standardized standards would increase uniformity, interoperability, and efficiency in the construction industry's DT implementations, hence enabling widespread adoption and facilitating seamless data sharing.

In conclusion, the implications derived from this research imply the necessity for additional research in other areas. These include developing techniques for transferring BIM object behaviour to improve behavioural simulations, examining data interchange methods and pipelines for zones and area data, and defining standard procedures for BIM modelling in the context of DT deployments. Advancing the knowledge and implementation of BIM and DT technologies through these research directions would contribute to improved construction processes, enhanced facility management, and informed decision-making throughout the lifecycle of constructed assets.

Reflection

Reflecting on my thesis journey, I can't help but acknowledge the challenges I faced along the way. It hasn't been an easy road, but I am proud to say that I made it through. From the very beginning, the topic of digitalization in the construction industry had always fascinated me. The idea of leveraging technology to transform and optimize the construction processes was a driving force that kept me motivated throughout the research.

Undoubtedly, the most enjoyable part of my thesis was the prototype development. Creating a practical and functional solution for data exchange between Autodesk Revit and Unity3D for Digital Twin implementation was a rewarding experience. Witnessing the prototype take shape and seeing its potential in enhancing construction projects was truly gratifying.

However, during the prototype development phase, I encountered a significant barrier - my limited technical programming knowledge. I realized that having a more in-depth understanding of programming languages and tools could have allowed me to explore the full potential of digital implementation for the prototype. This obstacle made me realize the importance of continuously learning and updating my technical skills, especially in a rapidly evolving field like digital construction.

Despite the challenges and limitations, I am proud of the work I have accomplished in my thesis. It has provided valuable insights into the possibilities of digitalization in the construction industry and has opened doors for further research and advancements. Throughout this journey, my passion for leveraging technology to drive innovation in construction has only grown stronger.

One insight that I gained from this experience, to certainly improve in the future, is to avoid always overthinking the simple things. Planning and getting ahead of time was also very challenging and a great deal to me, as writing a master thesis is indeed a full-time job.

As I conclude this chapter of my academic life, I am excited about the future possibilities that await me in the world of construction and digital technology. I am determined to continue honing my technical skills to unlock the full potential of digital implementation in the construction sector. The experience gained and knowledge acquired during this thesis will undoubtedly serve as a solid foundation for my future endeavors in this dynamic and promising field.

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