

Article

Exploring Data for Construction Digital Twins: Building Health and Safety and Progress Monitoring Twins Using the Unreal Gaming Engine

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Abstract: Although digital twins have been established in manufacturing for a long time, they are only more recently making their way into the urban environment and present a relatively new concept for the construction industry. The concept of a digital twin—a model of the physical environment that has a real-time two-way link between the physical and the digital, with the virtual model changing over time to reflect changes in the real world—lends itself well to the continually changing environment of a construction project. Predictive capabilities built into a twin also have great potential for construction planning—including in supply chain management and waste disposal as well as in the construction process itself. Underpinning this opportunity is location data, which model where something is happening and when and can be used to solve a wide range of problems. In particular, location (the power of where) can integrate diverse data sources and types into a single system, overcoming interoperability challenges that are known to be a barrier to twin implementation. This paper demonstrates the power of location-enabled digital twins in the context of a highway construction project, documenting and addressing data engineering tasks and functionality development to explore the potential of digital twins in the context of two case studies—health and safety and construction monitoring. We develop two demonstrators using data from an existing construction project (building on data and requirements from industry partner Skanska) to build twins that make use of the powers of 4D data presentation offered by the Unreal Gaming Engine and CesiumJS mapping, while software development expertise is sometimes available to construction firms, we specifically explore to what extent the no-code approach available within Unreal can be deployed in this context. Our findings provide evidence to construction companies as to the benefits of digital twins, as well as an understanding of the data engineering and technical skills required to achieve these benefits. The overall results demonstrate the potential for digital twins to unlock and democratise construction data, taking them beyond the niche use of experts and into the boardroom.

Keywords: digital twins; construction; gaming engine; Unreal Engine; data integration

Citation: Ellul, C.; Hamilton, N.; Pieri, A.; Floros, G. Exploring Data for Construction Digital Twins: Building Health and Safety and Progress Monitoring Twins Using the Unreal Gaming Engine. *Buildings* **2024**, *14*, 2216. <https://doi.org/10.3390/buildings14072216>

Academic Editor: Hala Nassereddine

Received: 21 April 2024

Revised: 9 June 2024

Accepted: 13 June 2024

Published: 18 July 2024



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1. Introduction

The construction industry is vitally important globally, being one of the largest sectors in the world economy, contributing around 9% on average to the economies of countries [1]. However, a key challenge within the construction industry is poor productivity, with the sector's growth averaging 1% per year over the past 20 years, compared to 2.8% for the total world economy in the same period [1], in addition to suffering from structural fragmentation and low predictability [2]). In parallel with this, the industry is considered one of the least digitised—being slow to innovation and the adoption of new digital technologies [2].

1.1. Transforming Construction

The United Kingdom's construction industry is undergoing a significant digital transformation, driven largely by technologies such as building information modelling (BIM, mandatory for large public sector projects since 2016 [3]). Emerging concepts also relate to the “golden thread” of information for the built environment, which aims to “have the right information in order to understand the steps needed to keep both the building and the people living in it safe” [4]. Overall, this digital transformation is expected to yield significant cost savings and operational efficiencies [3].

Coupled with this digitalisation process is the generation of vast quantities of data—4D models and schedules throughout a project's life cycle (from BIM) and context information (from Geographical Information Systems, GISs). Additionally, data are increasingly being collected on construction sites by sensors and drones [5,6].

1.2. Digital Twins

A digital twin (DT) is a “realistic digital representation of existing assets, processes or systems in the built or natural environment” [7]. It has a “bidirectional connection to the real asset, process or system and contains a way of computationally analysing incoming information to generate valuable insights, for the purpose of one or more specific use-cases” [7]. Digital twins originated in the manufacturing industry to monitor products throughout their life cycle [8]. They are now extensively in use in digitally advanced sectors such as the manufacturing, automotive and aerospace industries [5]. They can facilitate an immersive understanding of infrastructure functionality and its relationship with the surrounding environment, empowering both government and industry to make better-informed decisions for future developments [9]. Although DTs can require a large upfront investment, they can provide long-term high investment return [10]. Improved quality, product operational cost [11] and revenue growth [12] are all benefits of DT approaches. Overall, DTs excel at saving time, cost and energy by offering more efficient performance.

1.3. This Paper—Exploiting and Democratising Data for Construction DT

This paper takes a multifaceted, data-centric data engineering approach to the challenge of digitalisation and DT in construction, where data engineering is “the development and maintenance of systems and processes that take in raw data and produce high quality consistent information that supports downstream use cases” [13]. We recognise that:

- Digital twins must have a purpose—i.e., provide value creation and provision of insight into the built environment [14], with multiple DTs being created for different aspects of construction (see Section 2.2).
- In order to minimise short-term and long-term data capture and curation costs, data must be removed from silos (siloes data are data that are from different sources, stored in different locations and not easily combined [15]), shared and reused where possible [9]. This is particularly important in infrastructure, where the lifespan of assets can run to over 100 years.
- To enable decision making, data need to be democratised—i.e., access to the company's data resources should be given to all employees where possible, and that that data should not only be available to technical experts but also to non-technical staff from the company [16].
- Location—knowing where something is and when—is a powerful integrator of otherwise disconnected data and is the only way to link sources of construction data that might include 4D models of the site, moving plant and equipment, the location of construction workers, weather and much more.

This paper demonstrates how the data generated by new approaches to digitalisation in the construction sector can underpin DT in two areas of construction—health and safety (H&S) and progress monitoring. We answer the following question:

“How can digital data be reused to underpin multiple construction digital twins?”

1.4. Context—Highway Construction

This research was conducted in collaboration with industry partner Skanska, and we address this question in the context of a live construction project. Skanska is one of the world's largest development and construction companies with 30,000 employees worldwide and 2021 revenue totalling around GBP 12.5 billion. To demonstrate data reuse, as well as exploring the interoperability of construction data with UE, we implement two construction digital twins—one related to construction progress monitoring and the other to health and safety.

1.4.1. Health and Safety

Under UK law, an employer must identify the hazards, risks and mitigation methods for their workplace [17]. These terms are defined as follows [18]:

- Hazard: *“Something that has the potential to cause injury or illness in your business”*.
- Risk: *“How likely it is that someone could be harmed and how seriously”*.
- Mitigation: *“The action to eliminate the hazard or control the risk”*.

For Skanska, ensuring the highest standard of health and safety is a top priority. Workforce well-being is prioritised through an injury-free environment (IFE) program which states that *“safety must never be compromised for cost or schedule”* [19]. The program's core principles are as follows:

- All incidents and injuries are preventable.
- Injury-free operations are possible in construction.
- Safety awareness is personalised every day.
- Workers are empowered and accountable to stop any unsafe acts or conditions on the jobsite.

1.4.2. Construction Progress Monitoring

Construction progress monitoring and management were highlighted by [20] as comprising a key cluster for digital twin usage in construction. However, historically, this has been a manual, labour-intensive process. A common method involves the production of regular reports based on on-site manual data collection, which would then be compared against the planned schedule [21]. Such reports have many limitations—they do not encompass a holistic view of progress, they lack visual intuitiveness and they could even misrepresent reality due to human error or conflicting interests [21]. An additional challenge relates to hesitation among stakeholders towards the adoption of new technologies in this area and operational challenges relating to lack of indoor positioning availability as well as the time required to use approaches such as barcoding of assets as they are installed [22], with [23] noting that at the moment, there is a wealth of imagery from construction sites that is underexploited. Improving this process could increase predictability and enable stakeholders to make timely decisions to ensure successful project delivery [21].

1.4.3. Our Approach

Given the use of BIM, infrastructure digital twins are inherently location-based and 3D/4D, and we exploit this fact along with the need to provide a user-friendly environment for non-technical decision makers by developing twins within a gaming engine environment (Unreal Engine, UE [24]). To further maximise the potential for data democratisation, even in a situation where software development skills are not widely available, we explore the potential of creating and the limitations of DTs using a “low-code” environment. Broadly defined, low-code environments allow “non-techies [...] to rapidly build robust business applications for their colleagues, partners and customers” [25]. In UE, this is provided by Blueprints (Section 3.2).

2. Background and Literature Review

This section presents the current state of the art regarding digitalisation and digital twins in construction. We first explore definitions of DTs to identify links with the more well-established building information modelling (BIM) approaches. This is followed by a review of applications of DTs in the construction sector before delving into detail regarding digital technologies and DTs for health and safety and construction progress monitoring. Finally, previous research integrating DTs and gaming engines is presented.

2.1. Digital Twins in Construction—Exploring Definitions

The Center for Digital Built Britain defines a DT as “a realistic digital representation of assets, processes, or systems in the built or natural environment. What distinguishes a digital twin from any other digital model or replica is its connection to its physical twin” [14]. Build Up, the European portal for energy efficiency and renewable energy in buildings, defines a DT as “the real-time digital representation of the physical building or infrastructure. Usually, data is gathered by on-site sensors that continuously monitor changes in the building and in the environment and update the BIM model” [26]. A classification of DTs was developed by [27] based on their level of connectedness to the physical model, suggesting the terms digital model to refer to a model with no connection to the physical twin, digital shadow to refer to a model with an automated unidirectional data flow from the physical to the digital model and digital twin to refer to a model with automated bidirectional data flow, with the DT able to control the physical asset.

Recognising links between BIM and DTs, [28] proposed a five-level ladder ranging from level 1, which involves BIM alone, used for conceptual design and scheduling, scaling up to the integration of IoT devices for real-time tracking and visualisation at level 3 to artificial intelligence (AI) for data-driven prediction and more at level 5.

2.2. Applications of DT in Construction

Viewing accurate and timely construction data together in a 3D environment can reveal insights and facilitate key management decisions [28]. Real-time digital twins as a single source of truth containing current and historical data of a construction site could be a vital component of this process [8,29]. DTs can improve stakeholder collaboration by facilitating information flow and data transparency between stakeholders by providing accurate and up-to-date documentation, as well as providing a “single source of truth” for construction [8]. DTs implemented with a considerable amount of data can reduce construction cost, improve quality and enhance effective stakeholder management by providing a wealth of information about the project [2]. A DT—coupled with information sourced from a construction site—can support various management activities including resource and material management, scheduling, quality management and sequence management [2]. DTs could allow real-time monitoring and real-time tracking as they integrate real-time data into a single location, allowing more informed decisions to be made by utilising all the available data [15]. An additional study explored DT for construction logistics—a DT for bulk silos (providing construction material) can be used as a decision support system for silo dispatch and replenishment activities [30]. The authors found that the visual presentation of data was a key component of its successful implementation [30].

Despite these benefits, in the construction sector, the concept of digital twins is still in its infancy [2]. There is a lack of understanding of the concept in the industry, where the distinction between a digital model and a DT is not clear [31]. This lack of understanding of the concept may slow the adoption of the technology in the industry, as decision makers may not recognise its potential benefits [8].

2.3. Digital (and Twin) Approaches to Construction Health and Safety

Construction sites are dangerous working environments, and [32] noted that the process of how to apply safety management following systematic workflows with clear indicators is still lacking due to the way data are collected. Digital approaches to health and

safety in construction cover two major facets of the challenge—site and equipment safety, which focusses on prevention and early detection of issues, and human-centric measures, which focus directly on ensuring that workers are safe.

2.3.1. Site and Equipment Safety

Sensor technology was developed by [33] to automatically monitor the construction environment, particularly focusing on scaffolding. By attaching strain sensors to the scaffolding itself, the system was able to estimate the status of the scaffolding. A digital model was subsequently created, utilising machine learning and finite element analysis (FEA) to distinguish between different safety conditions and enabling monitoring of real-time alterations in the scaffolding. A comparable method was employed by [34] to compare 2D images by camera and detect unsafe conditions on-site without requiring a manual inspection. [35] captured multiple camera images to estimate the 3D pose and location of heavy machinery, transforming a physical twin into a DT. By analysing the data within a DT, the requirement for manual processing was reduced, thus improving the time and efficiency of the HS monitoring [35].

Virtual construction simulations (VCSs) are very similar to DTs where 3D interactive information can be collected and simulated into a digital replica [36]. VCSs can detect safety risks before and during the construction process, allowing preventive measures to be put in place [37]. HS officers can also be provided with information regarding metro construction safety issues via a VCS system based on its field-monitoring data and 4D BIM-based safety planning [38]. VCSs are able to automatically deliver safety solutions, but this requires the implementation of advanced machine learning technology. The system would need to know the different hazard types and the precursors of the hazards as well as their solutions [39]. Machine learning was used in a study by [40] where they classified scaffolding failure cases based on load weights and reliably predicted safety conditions that could be implemented to mitigate the hazard. Its implementation into the construction site helped improve worker safety; however, it is noted that not every failure case was able to be identified, so more algorithms would need to be developed to identify all possible failures.

2.3.2. Human-Centric DT

Being able to track workers on-site and collect their data is an integral part of improving H&S, and human-focused DTs for HS are noted to be a promising topic for researchers and practitioners [41]. GNSS was used to locate an object being lifted by a crane and individuals located nearby [42], where the system was designed to warn the individual if they entered a dangerous area. With a similar focus on safety, [42] used GNSS tracking to warn workers upon entering a dangerous zone under a crane, with [43] noting potential issues relating to GNSS errors.

It is also possible to visualise situations like this via vision-based positioning methods, which rely on cameras to obtain images [38]. On-site positions can be visualised within DTs by mapping the equipment within the images to the actual location within the model [44]. Exclusion zones can then be displayed on the model so people are aware of what areas to avoid. By combining the individual positioning and object mapping, collisions can be reduced significantly. Installing cameras around machinery can also allow the operator to know the location of surrounding workers. This proved to be successful in studies conducted by [45,46].

In general, the average construction worker's understanding of occupational safety risks is low, and without proper training, workers lack the knowledge of construction risk factors and personal protective measures [47]. Consequently, the creation of an easily accessible DT, especially for HS training and education, is recommended—this builds directly on the concept of the virtual construction system identified above [36].

2.4. Digital Approaches to Construction Progress Monitoring

Construction progress monitoring is essential for ensuring the productivity and quality of a construction project, that the work that has been completed is consistent with the design plans and that it is on track with schedules [48]. The quality of construction progress monitoring methods has a direct impact on critical decision making during a project and to meeting timelines. In recent years, with new technologies being adopted in construction such as LiDaR (light detection and ranging, a form of laser scanning), photogrammetry (creating 3D models from images) and BIM, there have been many studies exploring the possibility of automating progress monitoring [48–51]. Companies such as GeoSLAM offer software that allows users to scan sites and automatically generate progress reports against BIM models or previous scans [52]. A scan-vs.-BIM system, which involves comparing site scan data from a construction site with BIM models to detect change and estimate progress, was proposed by [49]. The use of deep learning algorithms to automate this process was explored by [48], who attempted to use point cloud segmentation to detect objects from the BIM model, thereby estimating project completion. There have been a number of attempts to use multiple point clouds collected over a period of time for change detection in many remote sensing applications [53]. Change detection for construction progress using voxels was demonstrated [51]. This involves dividing the 3D space of a point cloud into a grid of cubes (voxel grid), each with a tag of empty or occupied. Changes are detected by comparing the locations of empty and occupied voxels between scans. In their experiment, [51] correctly classified most voxels, with 21.1% classed as unknown when compared to previous scans. However, it can be noted that difficulties arise with automating progress monitoring using 3D object recognition and point cloud change detection. Real-world data are often not clear, with problems such as noisy data, occlusion due to clutter and low resolution leading to high levels of misclassification [48].

2.5. Digital Twins and Gaming Engines

Gaming engines show great potential for DT development, as they allow rapid development of interactive and immersive virtual applications, real-time connectivity across multiple platforms and support development in 3D, virtual reality (VR) and augmented reality (AR) [54]. Gaming engines such as Unreal Engine 5 (UE5) and Unity have increasingly attracted interest in the literature due to their rapid real-time rendering capabilities, realistic graphics and physics engines [54,55] as well as cross-platform interoperability and cooperative working functionality. The literature exploring the use of gaming engines for DTs has seen a rise in recent years [54–57]. Simultaneously, gaming engine developers have recognised this potential market and have begun tailoring their products to DT development, such as Epic Games’s Twinmotion [24].

2.5.1. DT and Gaming Engine Implementations

Table 1 gives a sample list of DTs developed in gaming engines in the literature. As can be seen, the DTs cover a wide range of topics including health and safety, real-time visualisation and simulation. Both Unity and UE5 are represented. Additionally, two examples using Cesium (Section 2.5.2) are identified. Additional DT development projects in UE5 have been demonstrated in industry, such as 51World’s “Smart Campus” for a company headquarters using a 3D model and real-time IoT data and Tencent Penrose’s DT of a hospital network in Shanghai with real-time hospital bed occupancy information [58]. Two-way interaction was demonstrated by [59], who turned on a light in a meeting room remotely via the DT in UE5 and viewed a video feed of the room inside the twin.

Table 1. DTs developed using gaming engines.

Paper	Software	Application Domain	Data Flow	Brief Description
[60]	Unity3D	Construction: H&S and training	Real-time 2-way	Replicate construction site for H&S alerts and training—hazard detection.
[56]	Unity3D	Manufacturing: monitoring	Prototype	Demonstrating a generic framework for DT implementation.
[29]	Unity3D	Manufacturing: change detection	Real-time 2-way	Manufacturing DT: AI, change detection.
[61]	Unity3D	Manual material handling: H&S	Real-time 2-way	Real-time analysis of worker fatigue and feedback.
[62]	Unity3D	Lab twin: monitoring	Real-time 2-way	Replicating a real lab, prototype—lighting an LED from the DT.
[57]	Unity3D	Asset management—remote infrastructure: monitoring	Real-time 2-way	Synchronise data and communication protocols from different data sources.
[63]	Unity3D	Product development	Simulation	Physics-based DT, VR, simulating prototypes.
[55]	UE5	Asset management: planning and simulation	Simulation	DT for photovoltaics, DTP, predictive.
[64]	UE5	Aerospace and defence: training	Simulation and real time	VR DT—for training and continuous system design.
[54]	UE5	Asset management: monitoring and simulation	Prototype, 2-way	Wind farm simulation and monitoring—data sent to DT via MQTT connection.
[65]	Unity3D	Manufacturing: monitoring	Real time	Prototype 3D engine as a platform for DT monitoring control with VR/AR.
[66]	UE5 and Cesium	Tourism: visualisation	Realtime, 1-way	Tourism—3D visualisation of rural village. Live weather and river flow data.
[67]	Cesium	Shipping: location tracking	Realtime 1-way	Shipping—real-time visualisation.

2.5.2. Gaming Engines, Location Data and DTs

Traditionally, gaming engines have not been developed with real-world location (map, geospatial, coordinate reference system) concepts and use cases in mind—instead, they make use of local reference systems [68].

CesiumJS is an open-source JavaScript library for creating 3D globes, providing access to a high-precision WGS84 globe as well as an online data management service (Cesium Ion) [69]. The 2021 emergence of the Cesium for Unreal plug-in opened the possibility of combining the strengths of gaming engines for real-time interaction with 3D location data. Examples of Cesium for Unreal use include creation of a multifunctional intelligent platform that integrates virtual space tourism, cultural transmission, online rural product shopping, rural management and local culture promotion DTs of Xitang, an ancient town in China, including options for virtual roaming and real-time flow monitoring [66]. A study by [70] used Cesium for Unreal to develop a virtual city space to support disaster situation monitoring in Japan, demonstrating the utility of this approach in identifying disaster victims within dense urban areas. However, to date, none of the Cesium-driven applications have focussed on construction in an infrastructure context.

3. Materials and Methods

3.1. Materials—Data

Table 2 lists the datasets used in the two demonstrators. The data types are split broadly into four categories: sensor data, point clouds, design data and environmental data. Additionally, access to a sample risk assessment was provided for the health and safety DT.

Table 2. Data sources.

Data Type	Source	Format	Description
Sensor data	Skanska	JSON	Access to an API with daily sensor data
Sensor data	Created	UE data table	A data table in UE native format
Sensor data	Created	CSV	A CSV data table
Point cloud	Skanska	.LAS	Single point cloud of a highway section
Design 3D model	Skanska	IFC	15 IFC files, each a separate component of a single highway model exported from Revit
Design 3D model	Created	.datasmith	Revit house model exported using Datasmith plug-in for Revit
Environmental	3rd-party API openweath- ermap.org	JSON	API with weather information for any given coordinates

Point clouds: A point cloud (PC) was provided by project partner Skanska, encompassing the highway construction site. A PC is a set of data points in space, where each point represents a specific set of Cartesian coordinates (X, Y, Z) [71]. The PC depicts the ongoing construction activities along the highway, including vehicles and various construction assets such as traffic cones and barriers. Some surrounding vegetation is also visible.

Three-dimensional highway model: The models consisted of 15 IFC files, constituting a total of 30.8 GB of data with 6851 individual feature elements in the IFC. IFC (Industry Foundation Classes), is an open international standard for exchange of building information modelling data).

Risk assessment data: An illustrative risk assessment (RA) was provided, organised into sections corresponding to distinct machinery and/or equipment, sourced from HSE and Skanska H&S documentation [72,73]. The data from the RA were used to define specific hazards and associated risks within the model and include the following:

- Risks due to hazards, including crushing, falls, hot surfaces, falling from height electrical or visibility issues.
- Risks due to plant/heavy machinery: tripping, crushing, electrical issues, traffic, reversing accidents.
- Risks due to specific types of plant: for an excavator, there is a risk of hitting an underground gas, water or electric main; for a forklift there is a tipping risk.

For each type of risk, there is a corresponding level (low/moderate/high), probability (low/moderate/high) and required mitigation—e.g., wearing personal protective equipment; using signage and barriers; regular inspections of equipment; training requirements; use of mirrors or cameras to improve visibility; and use of radios, hand signals and spotters.

Models of construction equipment: Three-dimensional meshes of construction equipment are sourced from free content within the Unreal Engine Marketplace, as well as from Quixel Bridge, which is an UE5 plug-in that gives access to their free asset Megascans library [74] (see Section 3.2).

Revit model of a building: The provided IFC 3D highway model represents a single-point-in-time export of the construction site. A sample Revit model was also created by the research team to explore options relating to direct connection to the project BIM, which

would ensure that the DT had access to the latest version of the data. This also allowed multiple construction phases to be modelled.

3.2. Materials—Software—The Unreal Gaming Engine

The **Unreal Gaming Engine 5** (UE5) is an open-source game development engine created by Epic Games. It can be used for a variety of creation tools such as game development, architectural visualisation and live simulation [75]. As part of the UE framework, the Unreal Marketplace is a library which provides high-quality content to UE developers for commercial and educational purposes [76]. UE5 is widely recognised as providing the most realistic graphics in the market [54,55].

UE5's **Blueprints** visual scripting language (VSL) enables developers to create functionality without writing code [24]. This is a widget-based interface that the user can use to design and script user interfaces (UIs) and heads-up display (HUD) elements. This acts as the basis for all UIs, with DT developers creating a new widget for each functionality element, for example, menu screens or text boxes. Blueprints are also used for game mechanics—i.e., to create the rules that govern how a player moves around the game; how the other elements of that game interact with the player and each other; and how external data are incorporated into the game (via plug-ins).

Plug-ins are prepackaged code, developed by third parties, that are available to other developers in the form of a tool, greatly reducing development time. The UE Datasmith plug-in is worthy of particular mention, as it is designed to provide links to 3D models in formats that include Revit and Industry Foundation Classes (IFC, for BIM data interoperability). It allows the import of scenes from software such as Autodesk Revit into UE [77]. The imported scenes must always be 3D, and the selected elements from Revit are translated into UE static mesh assets. Materials can also be transferred over to maintain the look that was originally created. In addition, survey and base points can be imported into the project level and represented as plain actors; their metadata is also recorded.

Cesium for Unreal

Cesium is an open platform for creating powerful three-dimensional (3D) geospatial applications. The plug-in combines the 3D geospatial capability of Cesium with the high-fidelity rendering power of Unreal Engine 5 [78]. Additionally, the Cesium for Unreal integrates with Cesium Ion, a platform for providing global high-resolution geospatial content, which grants access to a range of geospatial data such as digital terrain models (DTMs), computer-aided design (CAD) models and aerial/light detection and ranging (LiDAR) imagery. Cesium for Unreal achieves realistic visualisation within a geospatial context by enabling the alignment of digital objects within precise real-world locations. This ensures that the DT accurately represents the physical environment, making it ideal for construction and HS management. UE's real-time capabilities allows for interactive simulations to be created [79].

3.3. Method 1—Data Integration and Interoperability Tests

A systematic review was carried out to determine optimal no-code approaches to incorporating a variety of sources of data into the DT, with particular attention paid to location-enabled data and options for including the real-time/sensor data that distinguishes a twin from a model.

The list of tested data formats is given in Table 2.

3.4. Method 2—DT for Health and Safety

A two-part approach was used for identifying functionality requirements for a health and safety DT. Firstly, Health and Safety Executive [72] and Skanska [73] health and safety documentation was reviewed. Secondly, functional requirements were confirmed via an interview with a Skanska health and safety expert. The interview used a semistructured format, which combines the use of both closed and open questions [80], which was chosen

as it ensures that the participant does not veer from the chosen topics but at the same time allows for the interviewee to share their knowledge. It covered topics including the role and responsibilities of the interviewee, an overview of health and safety activity at Skanska, their feedback on proposed DT functionality and the future of DTs in health and safety.

3.5. Method 3—DT for Construction Progress Monitoring

The specific components for construction progress monitoring were identified from the relevant literature, which as a minimum require the comparison of design, scheduling data and point clouds [21,49]. Further input was obtained via conversations with members of the Skanska team collaborating on the project.

4. Results

4.1. Results 1—Data Integration and Interoperability Tests

4.1.1. Importing the IFC Files

A number of different methods were trialled to import the provided files, summarised in Table 3. The results obtained highlight the difficulties with incorporating large IFC datasets into both Cesium and Unreal.

Table 3. Alternative approaches to IFC import.

Method	Steps	Outcome
Method 1	1. Export Revit model as IFC. 2. Import IFC into UE5 with Datasmith.	Failed due to IFC filesize.
Method 2	1. Export Revit model directly as .udatasmith format using Datasmith for Revit plug-in. 2. Import model into UE5 with Datasmith.	Failed due to IFC filesize.
Method 3	1. In Revit, select Datasmith -> Direct Link; copy link. 2. In UE5, select Import Data -> Datasmith Link and paste link. 3. Model is uploaded with a connection to Revit.	Partially successful (when tested with a small dataset); however, a key disadvantage identified was that location data were not preserved, so the model had to be placed manually.
Method 4	1. Open IFC in Revit, export as .OBJ file. 2. Upload .OBJ file to Cesium Ion. 3. Use the Cesium Ion platform to georeference the model. 4. Import to UE5 through Cesium for Unreal.	Partially successful—however, attribute/semantic information was lost and manual georeferencing was required.

4.1.2. Importing and Georeferencing the Point Cloud

Figure 1 illustrates the successful georeferencing and alignment of the highway PC on the Cesium World Terrain in UE. Two approaches were trialled to import the point cloud into the DT, as follows:

- Uploading point cloud directly to UE5—the file was automatically broken up into smaller sections and location information was lost, meaning that this method was not successful.
- Uploading the point cloud via Cesium Ion and then adding to the scene through Cesium for Unreal. In this case, the data are tiled and stored in the Cesium ecosystem. Once again, location data are not retained, but in this case, the data can be manually georeferenced. Georeferencing is the process of assigning locations to geographical objects within a geographic frame of reference [81], which enables integration of real-world location data [70] based on datasets related to a common location.



Figure 1. Point cloud georeferenced within the Cesium World Terrain (source: authors).

4.1.3. Incorporating Other Data Types

Table 4 summarises the outcome of tests carried out on the other data types.

Figure 2 shows the results of static meshes (asset representations from the Unreal Marketplace) placement in the same location as the corresponding features located within the PC. This manual georeferencing of construction assets is not completely accurate, usually with positional errors of up to 1 metre occurring. Within Unreal's Edit Mode, users can view the absolute location XYZ coordinates through the asset's Details panel.



Figure 2. Example of how the point cloud was used as a guide for placing 3D static meshes (source: authors).

Table 4. Methods to upload data into UE5/Cesium.

Type	Format	Description	Upload Methods	Result	Comment
Sensor data (table)	CSV	Simulated data to test CSV format. Include timestamp, location and value.	Upload of local CSV file via content browser. Timestamp used to determine visible data. Location data used to place in level and reading shown.	+ Displayed in scene effectively. + Allows external data entry to CSV.	- Needs to be manually refreshed in Unreal Editor. - Location data are supplied in Unreal Coordinates—further tests required.
Sensor data (API)	JSON	API from server with daily sensor data. No location data.	VaRest plug-in used to retrieve JSON from API. Appended date information depending on time sliders.	+ Successful call of JSON data to the engine.	- Utilisation of JSON not demonstrated due to poor plug-in documentation.
Point cloud	.las	A point cloud file of a highway section.	Uploaded to Cesium Ion and added to UE5 via Cesium for Unreal.	+ Displayed in scene overlaying the base map at the correct location. + Demonstrated layer control during runtime.	- Loss of location and colour data when uploaded. Manually georeferenced in Cesium Ion. - Manipulation via blueprints complex—different to UE5 assets.
Three-dimensional design	Datasmith (Revit)	Simple house model created in Revit.	Direct link between Revit and UE5 via Datasmith plug-in. Export as .udatasmith from Revit, upload to UE5.	+ Direct link preserves asset data in a usable format for UE5 development and allows changes to the Revit model to be reflected in UE5.	- Location data lost—placed manually in the scene.
Open-source weather	JSON	An API connection to openweathermap.org is also used to provide further contextual real-time data for the site.	VaRest plug-in used to make API request. Coordinates automatically sourced from Cesium scene location or entered manually via the UI.	+ Successful call of data to engine. Key: value pairs used to extract data. + Values visualised—displayed on UI and used to spawn rain particles.	- Issues with limited documentation, 3rd-party API plug-in.

4.2. Results 2—DT for Health and Safety

The literature review, with validation from an interview with a Skanska H&S expert, identified the following functional requirements for this DT:

- Site inspection and monitoring—walk through and fly through: this permits the user to explore the site in virtual mode and keep track of changes.
- Managing asset inspections—prevent accidents by regularly scheduling physical site inspections and managing these through the DT. Couple these with virtual inspections of the site's current and future states to preemptively identify issues.
- Hazard/risk analysis—make use of the DT as a training tool and to raise awareness of risks.
- Real-time site alerts—monitor workers' movements in real time and issue alerts if a hazardous situation arises.

4.2.1. Building the DT

A total of 25 event graphs were created, encompassing 41 linked Blueprint node functions to facilitate the various functionalities within the DT. Core functionality included two camera controls—third-person, for a realistic “on-site” experience, and first-person, for a higher, wider field of view. A camera zoom function (Blueprint shown in Figure 3) was added to the third-person character Blueprint code, enabling the user to adjust the camera's zoom level by using the mouse wheel.

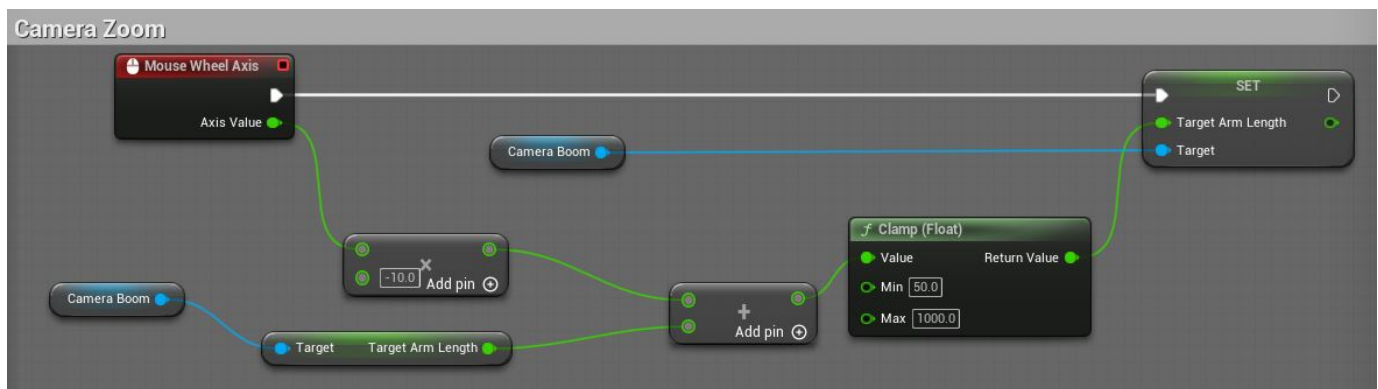


Figure 3. Camera zoom function (source: authors).

4.2.2. Site Inspection and Monitoring

The Basic Site Walk-Through/Fly-Through level allows the user to explore the construction site from a third-person (walk-through) or first-person (fly-through) perspective. Multiple levels were created to allow the user to explore the site from different perspectives.

4.2.3. Managing Asset Inspection

The Asset Inspection level uses the first-person camera and allows the user to click on an asset and view its asset information. This includes the Asset Name, ID Number, Last Inspection Date, Next Inspection Date, Last Maintenance Date and Previous Defects. Each clickable asset is highlighted with either a blue or orange arrow above it.

The results are displayed in Figure 4. When an inspection is scheduled within the upcoming month, an orange arrow is visible. This serves as a clear indicator to inspectors, prompting them to prioritise those specific assets.



Figure 4. Asset information text box (source: authors).

4.2.4. Hazard/Risk Analysis

The Hazard/Risk Analysis level works similarly to Asset Inspection as it uses the same camera controls and one-click functionality. Hazards identified in a risk assessment are marked with an orange outline which the user can click on. Orange was selected for visibility purposes, as it appears very bold onscreen. To ensure that all the assets received the outline, the material was applied to a postprocessed volume within the level, the “Infinite Extent (Unbound)” setting was enabled and the “Render Custom Depth” option was also enabled within the asset’s “Details” panel.

When the user clicks on a highlighted asset, it brings up a text-box that includes the Asset Name, RA Reference Number, Potential Hazards, Risk Level and Risk Probability. The box is also colour-coded depending on the risk level. High risk is red, moderate is amber and low is green.

Figure 5 displays an example of a low-risk forklift. The UI contains only essential hazard information to prevent overwhelming the user with excessive text. Further information is documented within the RA, which the user can read if required.

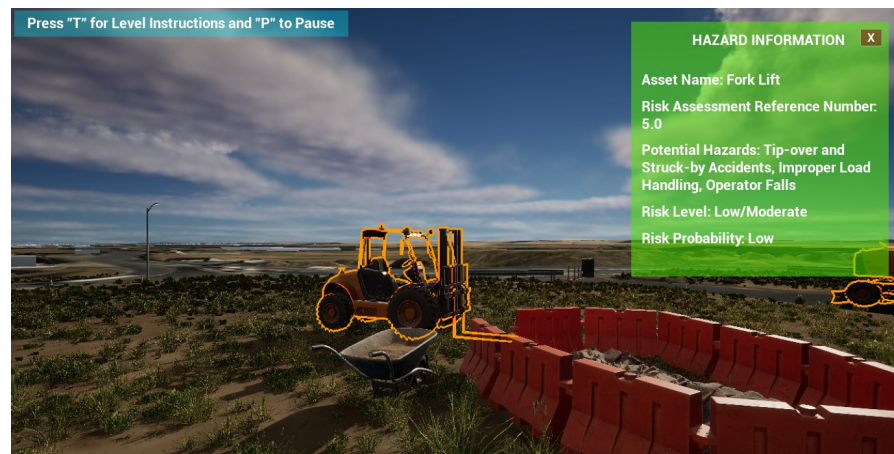


Figure 5. Hazard/risk information text box (source: authors).

4.2.5. Real-Time Site Alerts

An example Blueprint for this functionality is shown in Figure 6. A third-person character view is created to simulate the experience of an on-site worker. This level has the same controls as the Basic Site Walk-Through; however “collision” functionality has been introduced. UE has an in-built collision response where if a collision event occurs, then all objects involved can be set to be affected [82]. This level incorporates overlap events. Overlap events are when

two objects overlap or intersect with each other in the level, which allows interactions between objects to be detected. The machinery in the level has been given 1-metre radius collision zones. This is Skanska’s recommended clear zone when working with dangerous equipment [73]. The overlap event trigger code was then added to the construction assets, whereby a widget message displays when the user enters into the danger zone and is removed once they exit.

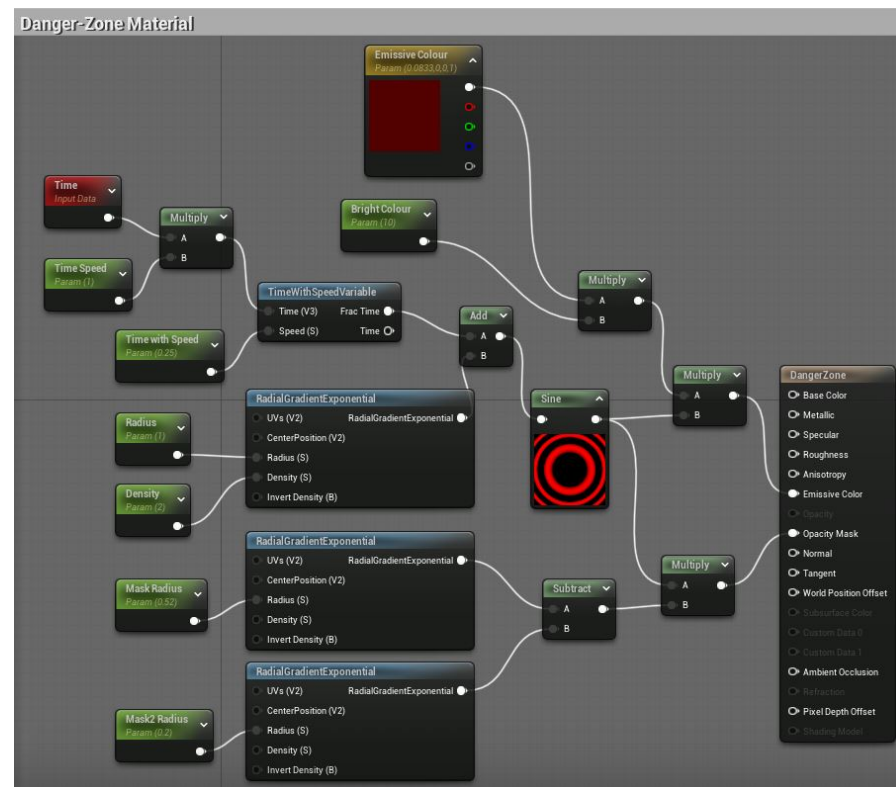


Figure 6. Blueprint steps for danger zone functionality (source: authors).

Figure 7 shows a danger zone around an asphalt paver. The motion of the zone makes it stand out and be highly noticeable when navigating the site. Upon entry into the zone, an instant alert message appears, displaying “DANGER ZONE—EXIT IMMEDIATELY.” This serves as a cautionary notification, urging the user to promptly leave the zone and mitigate potential risks. The danger zones are clearly distinguishable except when multiple zones overlap due to their close proximity. This creates a clustered appearance, which makes it more challenging to differentiate between the various hazardous zones.



Figure 7. Simulated “danger zone” around an asphalt paver (source: authors).

4.3. Results 3—DT for Construction Progress Monitoring—Prototype Development

4.3.1. Identifying Required Functionality

This DT focusses on live data and presenting a realistic environment—including sensor data and weather—to the user. Following the review and with input from Skanska, the required functionality includes the following:

- Interaction and exploration—to allow the user to explore the site and interact with both static and moving assets.
- Visualising sensor and movable asset data—the DT should be updated every time a sensor value changes or a movable asset changes position.
- Progress monitoring—schedule of work—explore plan construction work in a visual manner, phase by phase.
- Progress monitoring—scans of the site—explore the actual progress on-site.

4.3.2. Interaction and Exploration

This functionality included visualisation of a 3D model of the site and interaction with asset data. An asset information widget was developed to show to the user a specified subset of the data related to an asset when clicked.

For the sensors, this involved showing their type and current reading, while for 3D models uploaded with Datasmith, the DT shows the asset type, name and phase created. Through Blueprints, the text information was made to only appear when the player was within a certain distance (determined by preference through iterative testing) and to rotate to face the player. This reduces clutter when there are many sensors in a small area and allows the player to read sensor information from any direction. As an additional visual representation of the sensor value, the colour of the sensor was linked to the reading value, appearing green or red (Figure 8).

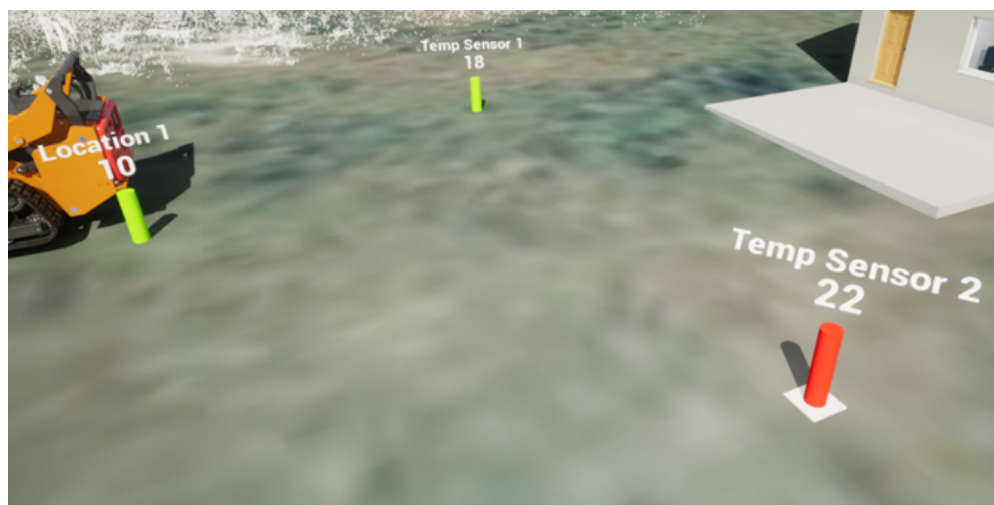


Figure 8. Screenshot of sensors showing information during runtime (source: authors).

The sun position is controlled by the date and time sliders and set automatically to the current time when the application is started. Live weather data are retrieved using a RESTful API connection and—through the creation of a “mechanic” (an interaction rule, implemented for rain in our case)—can influence the environment in response to changes in rainfall, wind speed, visibility and cloud cover.

4.3.3. Visualising Sensor and Movable Asset Data

Live data from Internet of Things sensors can be streamed via known protocols such as MQTT. However, making use of these would require software development and is thus beyond the “no-code;” approach taken in this research. No-code approaches trialled included the following:

- UE5's own data tables were trialled, along with a link to an external CSV file, but both of these were discovered to require coordinates in UE5 space rather than using real-world coordinate reference systems.
- An additional attempt was made to use Blueprints to link each sensor visible at a particular level to a table and retrieve the latest readings, although this did require hard-coding the links and would require further Blueprint development each time additional sensors are added.
- A more promising result was obtained by iterating through the data and spawning (showing) a sensor if its timestamp matched the required range. Additionally, the VaRest plug-in was able to successfully link to Skanska's IoT API and can be set to regularly poll the API for updated data.

4.3.4. Progress Monitoring

For schedule-of-work-based monitoring, two approaches were implemented to view planned changes to the site through time:

- Manually setting view variants where certain components of the model are hidden or visible and linking each variant to a button on the UI, allowing the user to cycle through them. This method assumes no scheduling data are embedded in the model.
- Making use of the "Phase Created" parameter—an inbuilt Revit option for construction scheduling.

Theoretically, using scans of the site for progress monitoring would involve a similar mechanism to the view variants above—i.e., setting buttons in the UI that link to specific views. However, it was found that hiding a PC during runtime did not work. A workaround is proposed, which could involve a convoluted chain of event dispatchers that completely remove the PC from the level and then add it to the level when visibility is reactivated. The mechanic (rules) for toggling visibility could be triggered based on a time variable to show or hide a given point cloud if the date it was created matches certain criteria.

5. Discussion

5.1. Reviewing the Approach

This paper addresses the question "How can digital data be reused to underpin multiple construction digital twins"? To answer the question, we take a data-centric data engineering approach and work closely with industry partner Skanska to ensure that the digital data under test are representative of those from a live construction project. We additionally explore the potential of a no-code approach, making use of Unreal Engine and CesiumJS to test to what extent data integration and interoperability can be implemented without requiring specialist software skills. To further validate on the interoperability outcomes in a real-world context, we identify requirements for and build two prototype digital twins—one for health and safety and a second for construction progress monitoring. Our results demonstrate that a no-code approach can provide the vast majority of required functionality, and that—with a number of workarounds—the required data can be linked to multiple construction DTs.

Overall, the DT framework/architecture proposed by [29] can be fully addressed using the gaming engine approach across all three of the challenges explored.

5.1.1. Integrating Data

We demonstrate that a wide range of data can be sourced and incorporated both from existing project data and third parties. This is not limited to data from the project/organisation itself (e.g., up-to-date BIM data via the Datasmith plug-in) but also extends to third-party APIs for sensor and weather data via the VaRest plug-in and 3D models of assets/heavy plants (via the UE Marketplace).

The integration of Cesium and UE5 means that the power of location can be used as an underpinning framework for all digital data. “Since location is a common attribute among different datasets, it can be used to combine and integrate them” [83]. Without this option, linking these diverse datasets would not be possible.

5.1.2. Improved Health and Safety Management

The implementation of H&S DTs can lead to improved safety performance by reducing on-site accidents and improving site monitoring and hazard identification, thus enabling proactive interventions to recognise potential hazards before they can escalate.

- **Risk assessment:** DTs can help to facilitate more comprehensive RAs by the DT acting as a hub for all HS data, for example, asset data can be saved and their hazards can be logged. Better site monitoring makes it easier for construction companies to adhere to HS regulations. The automated tracking and reporting of HS practices and hazards can not only improve site safety but also reduce the risk of regulatory fines and penalties if HS standards are not met [84]. Similarly, when fewer HS incidents occur, project schedules can be maintained for greater efficiency and cost saving. Additionally, maintaining good HS standards will result in an improved corporate image among investors, clients and communities [85]. The Hazard/Risk Analysis level allows users to access RA details by clicking on highlighted assets. This visualisation facilitates the rapid identification of hazards and their associated risks. The [86] risk colour system is employed, and it serves as an additional visual cue, drawing upon the familiar use of red, amber and green—commonly seen in various contexts.
- **Visualising hazards and training:** The most effective way to learn is through multisensory training protocols [87], in this case visually and physically, as they best approximate natural settings. Utilising the DT to navigate and visually observe the site has the potential to enhance hazard awareness. Due to this, the DT could be used for training and education purposes. On-site workers are required to attend regular training sessions which may not always pertain directly to their specific work site [88]. Introducing training through a DT could provide workers insights into the specific hazards present at their site. Additionally, this approach could help them familiarise themselves with the site’s layout and emergency exit routes via the third-person character control.
- **Danger zone alerts and clash detection:** Functionality to raise an alert when users go into a danger zone. This level was developed to try to simulate real-life scenarios within the DT. It successfully was able to detect whether a user entered into a dangerous zone surrounding heavy machinery. Collision/clash detection is particularly useful for preventing accidents as workers are more aware of the dangerous areas and know to avoid them. By identifying and preventing collisions before construction starts, the DT can reduce the cost of extensive site reworks and shorten the construction timeline [89]. Traditional 2D site safety plans have severe limitations in addressing dynamic on-site collisions [90]. Three-dimensional approaches can reduce “struck-by” hazards and improve site productivity [90].

5.1.3. Construction Progress Monitoring

Similar to the health and safety DT, we were able to demonstrate the potential of a combined UE5/Cesium approach to construction progress monitoring.

- **Exploring the site in real time:** We integrated sensor data, 3D models, a site scan and live weather data in the UE5 gaming engine with the Cesium for Unreal plug-in to construct a real-time DTP for progress and site monitoring. Virtual representations of sensors in the 3D environment were created and both simulated data in CSV format and real-time data from an API were successfully imported to the platform. Site scan data in LAS format were displayed in the 3D environment overlaying the Cesium scene. A connection to a live weather API was established, and a particle system to graphically represent live rain conditions developed.

- **Progress monitoring—schedule of work:** The ability to link to a live 4D model of the construction site (held in Revit) ensures that all DT users are presented with the most up-to-date version of the project. It additionally enables users to project forwards to review planned work. As well as having health and safety benefits (see above), this enables planning with regard to construction logistics (materials to site, waste from site), traffic and noise mitigation (in particular in populated urban areas).
- **Progress monitoring—scans of the site:** A basic method of progress monitoring using existing 3D data was identified as the overlay of a point cloud and 3D model to identify completed sections [49] and compare planned status with actual progress on-site. This was demonstrated (in a limited context due to file complexity) using a simple BIM model. Extending this to real-time progress monitoring—perhaps via regular 3D scans of the site—has multiple benefits: problems on-site can be identified early and resolved before major issues develop; delays in the schedule can be detected and schedules updated accordingly; reasons for the delays can also be explored; and contractual payments (related to completion of work) can be facilitated.

5.2. Democratising Data

Data quality and access to data in one location is critical for an organisation to gain insights into the progress and performance of the construction project, make informed decisions and ultimately adhere to schedules [15]. Our proposed data engineering approach to DT can achieve this goal, improving data quality and reducing data silos.

5.2.1. Sharing Data

As can be seen from the results, much of the data provided by Skanska are shared across both DTs, although with a different perspective. In particular, the current state of the site—what has been constructed, what is under construction, where mobile assets (e.g., heavy machinery) are located—underpins both applications. Having construction sequence details enables both progress monitoring and risk reduction (e.g., if a particular process will generate excessive noise, the H&S team can ensure that workers are not located in close proximity at that time).

Similarly, realistic representation of weather data (e.g., rain) can provide a more intuitive understanding of site conditions. The progress monitoring DT demonstrated the graphical representation of sun position, true to location and time of year, and live rain conditions—generating rainfall at a rate proportional to live rainfall data. This can be used to predict delays on-site due to weather conditions. However, it can also be used by the H&S teams to identify when dangerous working conditions could arise due to the weather.

More broadly, a data engineering, data-centric approach to DT development maximises reuse of the data, which in turn leads to higher data quality (as issues within the data are identified by users and corrections made) and lower data cost (knowing where and when data provide benefit allows decisions to be made around long-term curation).

5.2.2. Sharing Functionality

We demonstrated that the UI, the functionality and the data available can be tailored to the specific needs of different user communities. This is particularly important due to the abundance of data [56]. However, both DTs benefit from the abundance of visualisation tools in UE5, and much of the required functionality is or could be shared, reducing the required effort for development. This includes the following: a user interface (UI) for user navigation and interaction, time sliders, BIM model viewing and construction phase toggles, controls for toggling data layers, buttons for saving and snapping to locations, buttons for viewing a fly-through sequence and a pop-up widget when an asset is clicked to allow users to view details/semantics related to the asset. Collision detection is the process of identifying and preventing potential collisions between two or more objects [91]. It was deployed here to ensure that workers are not in danger zones. However, the approach

is identical to that required to ensure—in advance—that plant/equipment is not going to collide.

5.2.3. Reviewing the No-Code Approach

Our no-code, Blueprints-based approach demonstrates the extent to which functionality can be rapidly developed and tested by non-programmers. This can be highly beneficial, providing a low barrier to entry for potential contributors, saving costs and allowing rapid prototyping [92]. This approach takes advantage of the Unreal Marketplace, which offers a plethora of open-source tools and assets for developers. Additional out-of-the-box functionality provides options that include cinematic sequences, level variants and custom UI widgets, along with animations (identified as important by [54]).

Using this approach, coupled with high-quality data engineering to ensure that the required data are easily available, Skanska can therefore spin up a bespoke DT very quickly, for example, to develop a DT that allows users to explore one specific aspect of the project (e.g., the location of supplies on-site), delve into the detail of a specific location in a multidisciplinary way or even provide a precreated 3D walk-through from a single button.

Although an initial learning process is required to work with Blueprints, a no-code approach also greatly reduces the cost of DT deployment and—perhaps more importantly—long-term maintenance. Additionally, the focus of the learning is not on how to write code but rather how to chain activities and existing functionality together to meet a user need. This provides a lower barrier to entry for DT development and reduces the need for the perhaps more expensive software developer skills (although they may still be required for bespoke functionality). Furthermore, the visual nature of Blueprints means that they can be clearly linked to flow diagrams reflecting current practice and processes, thus taking advantage of Skanska's in-depth construction expertise.

5.2.4. Demolishing Data and Software Silos

A gaming engine approach to DT enables the combination of shared functionality and data to benefit users. Perhaps the most important consequence of this approach is the overall democratisation of construction data, i.e., make it “accessible beyond the BIM and GIS expert group” [93]. This is achieved in multiple ways: firstly, the general skills required to interact with UE5 games—the ability to zoom, pan, click on objects and navigate around a 3D world—are related to those used by any users of commonplace mapping apps found on mobile phones. Secondly, the DT interface can be customised—using Blueprints—to only provide the functionality required by a specific user group, reducing cognitive load. Thirdly, UE5 can be deployed on mobile devices, desktops, tablets and laptops, as well as in an augmented reality (AR) or virtual reality (VR) [64] context, giving users a wide choice of how they interact.

5.3. Limitations of This Study

The study described in this paper focussed on developing a proof of concept to inform Skanska of the potential of Cesium and Unreal for DTs. This was performed within the context of two specific case studies. As such, the samples of data explored in the study may not be fully representative of all data that might need to be incorporated in a construction DT. Only a small subset of live/sensor data was explored, and we did not consider issues relating to how the big data generated from sensors should be managed. Functional requirements were also only identified via key Skanska staff and again may not comprise a full set.

This research was also very geospatial/visualisation-focussed (and demonstrated the ability of disparate datasets to be viewed in a single platform). However, although some feedback was obtained, no formal usability tests were carried out to validate the assumption that a 4D globe/gaming engine interface is appropriate/usable for decision makers. Additionally, we did not incorporate any of the analytics tasks that are typically

associated with DTs (including AI options). These may require new/additional data or data formats and if carried out in real time may also impact the performance of the DT.

The following sections explore challenges relating to the Unreal Engine and to data and interoperability. Section 6.1 further highlights considerations that need to be made and issues that need to be addressed to move this research into practice.

5.4. Assessing the Suitability of Unreal Engine

Overall, UE5 and the Blueprint approach has proved very successful. Additionally, the Unreal Marketplace contains many realistic assets that can be directly employed in the DT to represent the heavy plant used in construction. The addition of Cesium brings both geolocation and links to the Ion environment, enabling the integrating of data that could otherwise not be easily linked. However, a number of challenges were encountered during the development process:

- **Lack of documentation:** The plug-ins used in this project had poor or limited documentation, which meant it was difficult to gain an understanding of how to use the features provided. For the Cesium for Unreal plug-in, there were comprehensive guides available for basic functionality, but beyond that, information was difficult to find. It proved difficult to find any guidance on any issues encountered. The VaRest plug-in used for the API connection had poor-quality documentation, with very limited information, making it considerably more difficult to develop functionality. This was in large part why the API sensor data were not utilised past retrieving the JSON data in this project.
- **Modelling change over time/4D:** For progress monitoring, it is necessary to view multiple point clouds across time to visually observe change on-site. To enable this, the point cloud layer should be connected to the time slider. However, this functionality was not successfully implemented due to difficulties when manipulating Cesium layers during runtime and no retention of metadata, meaning the point cloud had no timestamp.
- **Gaming engine versus digital twin software:** Much of the required DT/geospatial functionality is not prebuilt in UE5, which ultimately is a platform to enable gaming. As such, many basic functions had to be built from scratch, such as layer toggles and data loading systems. Though this gives a degree of freedom to the developer, it also means that there is a high initial cost to creating the DT platform and a low degree of standardisation.

5.5. Data and Interoperability Challenges

Though the volume of data collected on construction sites has grown exponentially, they are often inaccurate, incomplete, inaccessible, inconsistent or untimely [15]. Difficulties in construction data management including difficulties in visualisation; information integration issues and siloed data also exist [94]. These issues are reflected in the data-related challenges encountered by this project:

- **Challenges when handling real-time data:** Using MQTT to send information directly from IoT devices to UE5 has been demonstrated in the literature [54], but [56] point out that it is unsuitable for historical data viewing as it only stores the latest message. An additional challenge in terms of the coordinates is that they need to be expressed in UE5 level coordinates XYZ—further steps would be required to convert real CRS values to level coordinates.
- **Point cloud quality:** The overall PC quality was quite low, and some features were not scanned correctly, e.g., vehicles were only scanned from one side so they appeared to be cut in half. This made it harder to discern important elements within the scan, meaning some key features could have been missed.
- **IFC and Revit interoperability:** In theory, IFC models can be uploaded directly to UE5 or through Cesium Ion. However, it is ideal to link directly to Revit files as these provide up-to-date information. Revit files for the project were not available (due to confidentiality issues), and a major challenge was encountered when attempting

to reimport the provided IFC files back into Revit, despite originally being exported from that software. IFC interoperability issues such as this are well-known in the literature [95].

- **Georeferencing assets using the point cloud:** During the development of the DT, Skanska placed significant emphasis on ensuring accurate georeferencing of the site. This was successful, as the construction site was precisely positioned on the globe. By ensuring the site's accurate location, the DT can simulate and model real-world scenarios and interactions. The PC ensured that the site location was correct; however the location of site assets are not completely accurate, as their location data were not provided. Consequently, assets were placed in accordance to an approximate position in the PC or randomly for simulation purposes. Importing coordinates for automatic asset placement could be achieved by uploading a comma-separated value (CSV) document into the engine. The imported data must use the following format: ID, X, Y, Z [96]. By using this method, the time spent placing assets would be reduced significantly, and the data could be updated regularly to match the changes on-site.
- **Loss of information in the point cloud:** When explored in the UE environment, the point cloud did not retain any semantic information. Including date/time data is something that would need to be explored further to enable progress monitoring both in real time and historically.
- **Cesium interoperability issues:** Loss of location and colour data on upload to Cesium Ion, both for the point cloud and IFC files, required the models to be georeferenced manually.

6. Future Work and Conclusions

6.1. Future Work

The development work carried out in this research is prototypical and does not take full advantage of the wider range of UE5 functionality or potential sources of data. Two parallel options should be considered here—firstly, using an AGILE approach to development, the minimal functionality developed should be deployed in trial mode to obtain feedback from users. Secondly, further research and development should be carried out to overcome the challenges identified above and extend the provided functionality.

- **Validating Datasmith scalability:** Given the challenges with IFC/Revit interoperability, the Datasmith/Revit plug-in approach was only tested on a small Revit file. This does not represent the multifile complexity of a large construction project, and it is unknown whether the approach will scale. Future trials will include large Revit files and also using the Datasmith plug-in with other CAD platforms.
- **Creating new asset models:** The UE marketplace provides precreated models for a number of plant and equipment types. However, it is also possible to use bespoke models. These could be created by making use of reality capture approaches to create 3D meshes of assets and equipment. The level of generalisation (how much detail can be included before performance issues arise) should also be explored.
- **Data storage, data sharing and data security:** Relational databases are commonly used for storing, managing and retrieving large amounts of geospatial data and provide extensive geospatial functionality. Therefore, being able to directly connect to a database and import the data into UE is highly advantageous. However, it can also be noted that such databases are not suitable for all construction data. For example, BIM data are managed within a common data environment (CDE, file-based), and NoSQL approaches are perhaps more relevant for sensor data. Data security challenges should be considered for all data sources due to intellectual property within 3D models, privacy of personal data and security challenges for infrastructure. Multilevel security is required, allowing users to only access specific datasets depending on their role.
- **Improving data quality:** To maximise the potential of a DT, data quality is extremely important. Data from the construction site will need to be frequently collected and kept up to date if real-time results are desired. Manual data collection is expensive,

inaccurate and inefficient [97]; investment will be needed in new automated data collection technologies.

- **Automating construction progress monitoring:** The proposed method for construction progress monitoring compares the planned work (from Revit) with the current status of the site (via a point cloud). This method is limited as it is based on visual comparison and does not quantify progress. Exploring the visualisation of voxels in UE5 (to highlight change) would additionally enable quantifiable progress monitoring.
- **Automatic asset and plant location:** The approach taken in the prototype involved manually placing the assets and plant models. However, given real-time tracking, this could be automated. Appropriate representation will also be required for each asset, depending on the detail available and the level to which a user is zoomed in or out of a scene.
- **Adding analytics and prediction:** While—as demonstrated by this research—it is possible to create a DT without coding, it should be noted that for more advanced DTs, a level of analytical functionality is usually required. Two options exist for implementation. As UE5 also provides a development environment, it is possible to write bespoke code (perhaps using existing libraries) within the UE5 environment. This requires software development skills. An alternative to explore would be to use a Blueprint approach to send data out to a third party service for processing, adding the results into the DT once available.
- **Using wearables for live location tracking of workers:** If a worker on-site is detected to be in a danger zone, the plant could automatically be shut down. Future work would involve wearable devices to track location, preempt danger and identify near misses, thus improving site safety [98]. However, care will need to be taken into account for GNSS errors.
- **Exploring the human/social side of DTs:** There is currently a debate of whether tracking employees is an ethical business practice, as some might believe it is an invasion of privacy [99]. Therefore, it is important to consider these issues when investigating whether to implement live location tracking in future DTs. More broadly, the human/social side of construction DTs should also be explored.
- **Exploiting sensors for off-site asset status information:** Construction assets and plants should be inspected in line with a risk assessment. The purpose of an inspection is to identify whether work equipment can be operated safely by identifying any deterioration or issues before it becomes an HS risk [100]. The circumstances where inspection is required are as follows: an asset should be inspected after installation and before use, at suitable time intervals and whenever there are exceptional circumstances, such as suspected serious damage [101]. Regular inspections should also be made before use, weekly and monthly depending on the asset.
- **Emergency scenario simulation:** DTs have the capability to simulate and visualise scenarios via machine learning algorithms [33]. This could be used both for H&S and construction planning. Examples include preplanning of emergency routes so that emergency services know the most efficient way to get onto the site and from there to a specific location; “rolling the site forwards” to explore how construction will progress under different scenarios (e.g., supply chain issues); and simulating rescue drills virtually within the DT to identify any safety concerns or areas of improvement [102].

6.2. Conclusions

The list of future work provided here is extensive and is intended to serve as a first approach to a technical research agenda to facilitate the deployment of construction DTs, in particular in settings where extensive, bespoke software development or proprietary software is not available. More broadly, the purpose of this research was to explore the potential of no-code approaches to construction DT, developing an understanding of the challenges towards data integration and the extent to which functionality could be developed that meets the needs of a real-world construction project. Broadly speaking, digital

twins involve communication between the digital and physical environment. For full twins, this communication is often two-way and real-time; for digital shadows, one-way communication from the physical to the digital is enabled. A middle ground between the two—human-in-the-loop DT (two-way with manual decision making) have been demonstrated in this research [103].

It can be anticipated that the multiple DTs required within a construction project will span all three of these cases. Our data-centric, gaming engine-based, no-code approach to DT development enables multiple DTs to be easily spun up or additional functionality added as required to underpin these DTs.

Our work also highlights the importance of location—knowing where something is and when—as an integrator and enabler of both the data and the functionality required for such twins—in fact, it is potentially the only way that such data can be effectively utilised in combination. The integration of Cesium with UE enables this location-driven approach.

The overall results demonstrate the potential for digital twins to unlock and democratise construction data, taking them beyond the niche use of experts and into the hands of decision makers in the boardroom.

Moving forward, it is hoped that our work contributes to furthering the understanding of the potential of DTs in construction, with an end goal of having bespoke DTs deployed as needed throughout the construction process and also across the construction/operation handover boundary, ensuring that the rich wealth of expensive construction data are of benefit to operators of infrastructure assets now and into the future of their long lifespan.

Author Contributions: Conceptualisation, C.E., N.H., A.P. and G.F.; methodology, C.E., N.H. and A.P.; software, N.H. and A.P.; validation, G.F.; investigation, N.H. and A.P.; resources, G.F.; writing—original draft preparation, C.E.; writing—review and editing, C.E., N.H., A.P. and G.F.; supervision, C.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of University College London, UK (Application Number: 25595/001, approved 21 June 2023).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. UCL Ethics Application Number: 25595/001.

Data Availability Statement: Data for this study are unavailable due to commercial confidentiality.

Acknowledgments: We would like to thank the team at Skanska for providing the data and extensive input into the requirements for the case studies described in this paper.

Conflicts of Interest: Author George Floros was employed by the company Skanska. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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