

Exploring the Process and Applications of Digital Twins: What are the Key Steps in Creating Digital Twins and How Can They Transform Urban Design?

School of Architecture, Built and Natural Environment
BSc Architecture

Drew Dennehy

2100980

ACAA6003

9,711 words

19.04.2024

Author's Declaration

I declare that the work in this dissertation was carried out in accordance with the regulations of the University of Wales, Trinity Saint David. The work is original except where indicated by special references in the text and no part of the dissertation has been submitted for any other degree.

Any views expressed in the dissertation are those of the author and in no way represent those of the University of Wales, Trinity Saint David

The dissertation has not been presented to any other University for examination either in the United Kingdom or overseas.

I hereby give permission for my work, if accepted, to be available for photocopying and inter-library loan, and for the title and summary to be made available to outside organisations.

Signed:



Date: 19.04.2024

Copyright Statement

The copyright of this dissertation rests with the University of Wales, Trinity Saint David. No information derived from this dissertation shall be published without the prior written consent of the University.

Signed:

A handwritten signature in black ink, appearing to read 'D Dewi'.

Date: 19.04.2024

Abstract

Exploring the Process and Applications of Digital Twins: What are the Key Steps in Creating Digital Twins and How Can They Transform Urban Design?

By Drew Dennehy

University of Wales Trinity St David

This dissertation outlines the processes of producing digital twins and underscores their applications within urban settings. They are acknowledged for their diverse utility during, and after, the design phase to aid in the construction of more resilient and efficient cities. The rising trend of this technology is acknowledged, introduced with a brief history of digital twins and the concept behind them. The dissertation compares three case studies that operate at different scales—local, city-wide, and global. For each, the organisation and its initiatives are discussed, followed by their individual processes and challenges associated with them. Each case study concludes by discussing the potential uses of digital twins and their broader implications.

Chapter 1 refers to a gondola project by Augment City, who collaborated with the architecture practice Snøhetta to transport people to the summit of Rundehornet, Norway. Here, the application of scenario planning and public engagement was featured.

Chapter 2 involves a live project to construct a twin for Swansea City, spotlighting the use of drone survey imagery to produce a model. Uses such as thermography, flood mitigation and traffic simulation are studied to assess what twins can do to future-proof urban environments.

Chapter 3 covers how digital twins can assist in making environmentally conscious decisions on a global scale. This twin exemplifies using verified, pre-existing data sets to generate a model that produces accurate, real-time information. This is an EU initiative and will be the largest of its kind.

This research concludes by evaluating our progress toward net-zero goals and discussing how digital twins could play a crucial role in achieving these targets, enhancing transparency for both private and public entities.

Acknowledgements

In alphabetical order, I would like to thank:

Ian – For introducing me to the subject of digital twins and inviting me to participate in the associated project.

Liz – For her help throughout the summer and all through the year in making my dissertation what it is today. I'm grateful for the instantaneous response time and her advice on any queries that arose.

Matt – For his time during our interview and his patience with the endless questions I posed. Thank you for arranging the thermographic drone survey out of hours, despite your busy workload.

Paul – For his advice and guidance on Harvard referencing.

Ryan – For being an excellent tutor and always keeping it engaging. Thank you for your responsive feedback and for always showing a keen interest in my research.

Table of Contents

PAGE TITLE	PAGE NO
Author's Declaration	2
Copyright Statement	3
Abstract	4
Acknowledgements	5
List of Illustrations	7
Introduction	9
Methodology	10
Chapter 1: Sula Gondola	13
Chapter 2: Swansea City	21
Chapter 3: Earth	40
Conclusion	44
Reference list	46
Bibliography	51
Appendix A: Stakeholder meeting notes in preparation for COP28	53
Appendix B: Questionnaire for Joern Hoffmann, Application Partnership Lead for Destination Earth	55
Appendix C: Questionnaire for Richard Adewale, Global Business Development Manager for Augment City	56
Appendix D: Questionnaire for Matthew Drummond, Technical Demonstrator for ACE	57

List of Illustrations

PAGE TITLE	PAGE NO
Figure 1: Visualisation of the digital twin concept (Photo credit: Altexsoft)	9
Figure 2: Visualisation of the NZUP concept (Photo credit: KPMG)	13
Figure 3: Defining file format terms (Photo credit: D. Dennehy)	14
Figure 4: Digital twin of Tokyo City (Photo credit: 51World)	16
Figure 5: Digital model of Tokyo City (Photo credit: Google Earth)	16
Figure 6: Visualisation of Snøhettas' proposal (Photo credit: Sula Gondola)	17
Figure 7: Proposed route for the gondola (Photo credit: Flakk Group)	18
Figure 8: Diagram illustrating the distances between the gondola cables and the rooftops below (Photo Credit: Flakk Group)	19
Figure 9: Scenario planning: running the simulation with clear glazing (Photo credit: Augment City)	19
Figure 10: Scenario planning: running the simulation with frosted glazing (Photo credit: Augment City)	19
Figure 11: Effects of rolling shutter on golf club travelling at speed (Photo credit: Canon)	22
Figure 12: Effects of mechanical shutter on golf club travelling at speed (Photo credit: Canon)	22
Figure 13: DJI Phantom 4 Pro V2.0 drone (Photo credit: DJI)	23
Figure 14: DJI Matrice 350 RTK drone (Photo credit: DJI)	23
Figure 15: Diagram illustrating RTK signal transfers (Photo credit: D.Dennehy)	23
Figure 16: Cover of the CWIC drone operations manual (Photo credit: CWIC)	24
Figure 17: Double grid flight path for the initial survey (Photo credit: M. Drummond)	27
Figure 18: Flight path for the second survey (Photo credit: M. Drummond)	27
Figure 19: Flight path for the final survey (Photo credit: M. Drummond)	28
Figure 20: Measuring wind speed using an anemometer (Photo credit: D. Dennehy)	29
Figure 21: DJI Phantom drone on landing pad (Photo credit: D. Dennehy)	29

PAGE TITLE	PAGE NO
Figure 22: Swansea digital twin displaying road traffic data (Photo credit: Augment City)	30
Figure 23: Swansea digital twin displaying flood simulation data (Photo credit: Augment City)	31
Figure 24: Swansea digital twin displaying the Blue Eden project (Photo credit: Augment City)	32
Figure 25: Thermal image of the UWTSD library façade (Photo credit: M. Drummond)	33
Figure 26: Thermal image of the UWTSD library side elevation (Photo credit: M. Drummond)	33
Figure 27: A copy of an invoice to UWTSD for the purchase of a DJI Matrice 350 RTK drone (Photo credit: Drones Direct)	35
Figure 28: Extract from the UWTSD data protection impact assessment referring to potential risks and likelihoods (Photo credit: UWTSD)	37
Figure 29: Zurich digital twin showing number plates are indistinguishable (Photo credit: Wingtra)	37
Figure 30: Graphic depicting a 60% overlap between images (Photo credit: D. Dennehy)	38
Figure 31: Graphic depicting an 85% overlap between images (Photo credit: D. Dennehy)	38
Figure 32: The relationship between heat and green spaces (Photo credit: National Geographic)	41
Figure 33: Sample image from C3S software (Photo credit: C3S)	42
Figure 34: Sample image from UrbCLIM software (Photo credit: UrbCLIM)	42
Figure 35: Levels of energy generated by each fuel source (Photo credit: BBC)	44

Introduction

In 1991, American computer scientist David Gelernter published the idea of a symbiotic relationship between the physical and the virtual. However, this idea was not realised until 2003, when Professor Michael Grieves applied the technology to manufacturing. Grieves, a computer engineer specialising in digital twins, has played a key role in developing them. He has consulted for renowned organisations such as NASA (National Aeronautics and Space Administration), Boeing, and General Motors but currently operates as an executive director for the American Institute of Aeronautics and Astronautics (AIAA, 2022). Digital twins gained recognition after Grieves demonstrated their ability to enhance product quality along production lines. Since then, the technology has expanded into disciplines such as aerospace, engineering, and healthcare (Attaran and Celik, 2023). The term “digital twin” was later coined in 2010 by John Vickers, a Principal Technologist at NASA working alongside Grieves at the time. The original concept featured 3 elements: a physical product, a virtual representation, and bi-directional data links between the two (Jones *et al.*, 2020). In the context of urban planning, a town or city serves as the physical model depicted on the left in Figure 1. This model is equipped with sensors and other data collection devices that feed into its digital counterpart. These two components share information in real-time to draw analytics, run simulations, and aid sustainable urban design. Such information is collected using IoT (Internet of Things) sensors, which detect pressure, temperature, proximity, and motion data (ArchDaily, 2022).

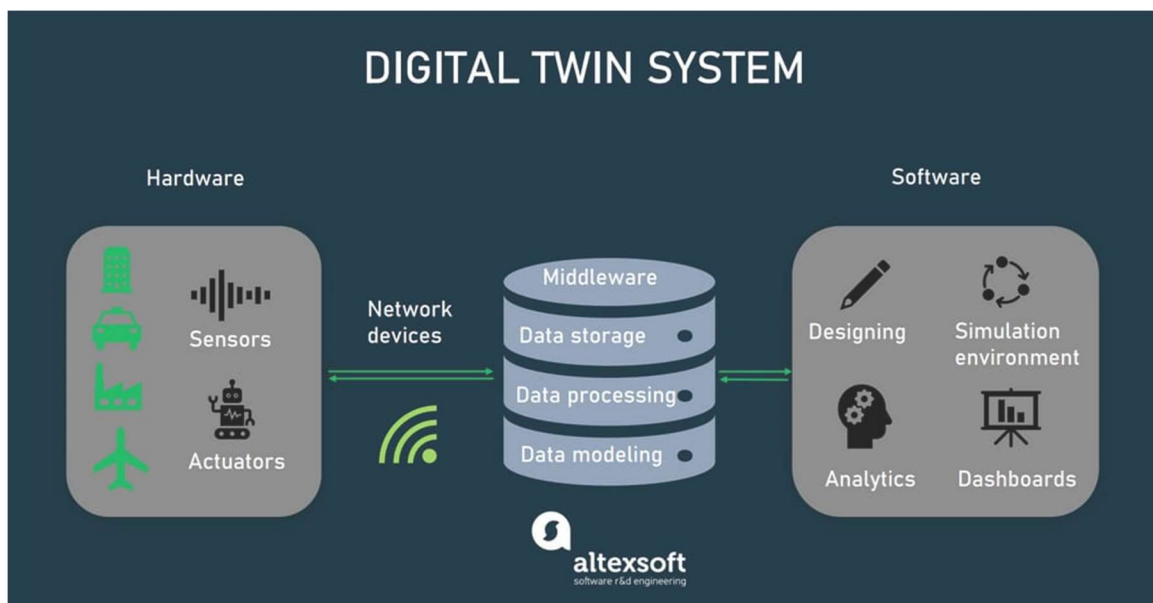


Figure 1: Visualisation of the digital twin concept (Photo credit: Altexsoft)

There is no clear distinction as to when digital twins were first introduced to the field of architecture, though they now range from domestic to global-scale models and are utilised throughout various project phases. In conceptualisation, they can facilitate simulations to test project specifications. Further into the project lifecycle, digital twins can assist in creating maintenance schedules and optimising the performance of the building. Finally, they develop suitable action plans for the end-of-life phase of a project.

In exploring digital twin technology within urban planning, this research identifies a significant gap in understanding the development processes of digital twins and their potential as pivotal tools in becoming a net-zero planet. While previous studies have documented the technological principles and applications of digital twins in other disciplines, there is a notable lack of information on analysis focusing on their capabilities in urban development. Specifically, there is an absence of research into how digital twins can support urban planning processes, facilitate stakeholder engagement, and contribute to the construction of adaptive, resilient environments. To bridge this gap, the study will provide a thorough assessment of digital twins as transformative tools for future-proofing cities, as well as highlighting best practices, challenges, and opportunities for their implementation in urban planning and design.

Methodology

This research employs a variety of methodologies to address the central question. A significant part of the approach involved participating in a live project creating a digital twin for Swansea, Wales, which was later showcased in Dubai during COP28 (Conference of the Parties). This involvement provided firsthand experience and continuous dialogue with professionals throughout the process. To further understand the subject, interviews were conducted with experts involved in the production of twins on both local and global scales. These discussions explored the production processes, capabilities, and challenges associated with constructing each digital twin. Following this, case studies of cities that have successfully implemented digital twin technology were assessed. These case studies were selected based on criteria to ensure a diverse representation of geographic locations, scales of implementation, and urban challenges are addressed. Through the combination of these methods, this research seeks to provide a detailed understanding of how digital twins are produced and how they can be employed as a tool to inform urban policies.

Ethical standards were exercised throughout this study to ensure its integrity. Full consent was obtained from all participants who contributed to this research; they were fully informed of the nature of the study and any wishes to be presented as anonymous were upheld. The

interviews that took place throughout this research were transparent and the information received from such discussions was, where possible, cross-referenced to validate its authenticity. In addition, provisions were made to ensure that any written sources included within this study were accessed through academic journals, peer-reviewed studies, and reputable outlets to avoid the inclusion of exaggerated or false information in this study.

Aims and Objectives

The primary aims of this research were to observe the process of creating a digital twin from conception to completion and identify its applications. To support these aims this research set out a list of objectives, beginning with understanding the purpose of virtual twins and their role in urban design. This included reviewing the history of twins to understand how the technology has evolved and its significance in current times. Another objective was to outline the challenges associated with the construction of a twin and discuss how these could be mitigated. This research could offer guidance to those who may consider creating a model of their own, informing them of strategies that will improve its overall quality and significantly reduce the time taken to build it. Finally, this research seeks to study the broader implications of employing digital twin technology. A key benefit of twins is to provide transparency of data, likely incurring indirect consequences which are explored in this analysis. These aims and objectives should provide a thorough understanding of the term 'digital twin', how they are used in an urban context, and the changes this may cause regarding urban environments.

Literature Review

This section underscores several key sources from this dissertation as outlined below.

- The article 'Digital twin: Benefits, use cases, challenges, and opportunities', curated by Attaran and Celik, provides a history of digital twins, their applications across multiple professions, and the challenges associated with them. This research defines the term 'digital twin' and details their involvement in each profession, with the exception of architecture and planning. Section 4.5 discusses digital twins in construction and real estate but remains general, focusing on their capabilities through the construction phase but much less before and beyond that. Overall, this article presented a clear understanding of twins and their respective challenges, whilst reinforcing the knowledge gap surrounding their use in urban design.

- VITO's use case on heat island effects complemented an interview conducted with a member from Destination Earth. These organisations are currently collaborating on a project to monitor current and future heat distribution in built-up areas. Here they draw comparisons on the technology currently in place against their latest model to showcase the advanced potential and ability in aiding sustainable design. Whilst emphasising the benefits of this new initiative, it fails to explore any adverse effects that would've made for a more balanced view.
- The case study written by Lanengheim *et al* on monitoring surface water management utilising twin technology outlines the need for more effective planning to mitigate flooding. The three types of flooding are explained, focusing on a flood-prone area in Melbourne to produce a prototype twin used within the planning stages to run scenarios. This prototype was then developed into a tool that can be used in the construction industry to inform flood resilience strategies.

Chapter 1: Sula Gondola

Launched in 2022 during COP27, the Net Zero Urban Programme (NZUP) aims to support cities in achieving net-zero carbon emissions. By leveraging the latest technologies, NZUP can identify investment opportunities and anticipate future risks, enabling a proactive approach to solving urban environmental challenges. For this initiative, 5 key themes were focused on: the built environment, transport, energy infrastructure, water, and waste (KPMG, 2024). It was developed by the accounting organisation KPMG (Klynveld Peat Marwick Goerdeler) and includes a collaboration of both private and public sectors, including the Norway-based organisation Augment City. This organisation is a daughter company of the Offshore Simulation Centre (OSC) which began producing digital twin prototypes to reduce risks for ships involved in fishing and oil platform supply (Adewale, 2024). In 2019 Augment City was founded, where their process of a virtual model, informed by real data to visually communicate information, was then applied to cities. Studies show that people understand data better when presented in a visual format, which offers the opportunity for the public to engage with the data sets, understand the current state of their region, and become more inclined to support the net-zero goals (Augment City, 2019).



Figure 2: Visualisation of the NZUP concept (Photo credit: KPMG)

At Augment City, the structure for making their digital twins is bespoke to each project. Firstly, the stakeholders and the needs of the project are identified to establish the conditions the twin will need to address. Once this has been fulfilled, the next phase is to understand which types of data are required to fulfil the brief and how to access them, such as population density and transport statistics. The task of collecting such data can become challenging to obtain: some datasets are open-sourced and easily accessible, whereas others are proprietary and require access permission that isn't always available. In such a situation where information cannot be accessed, the digital twin model will be unable to wholly satisfy the scope set out in the initial stages, though synthetic data could be used at the risk of inaccuracies within the model. The issue of data availability varies by location. In Europe, Augment City's projects often involve collecting a wide range of data, which is typically open-sourced. However, in Africa and India, the organisation has faced challenges from privatised information or the absence of systematic data collection altogether. If obtained, disparate sets of data are integrated into the model for comparison to refine the accuracy of the twin.

Terminology	Definitions
LiDAR	Light Detection and Ranging is a technology that measures distances by applying a laser to a target and analysing the light reflected from it. It creates precise, accurate three-dimensional information (Choi, Ramirez, and Kwon, 2023).
GeoTIFF	GeoTIFF is a file format that allows geographical information to be embedded within a TIFF file (Tagged Image File Format) (NASA, 2021).
GML	Geography Markup Language (GML) refers to a modelling language that is used to represent geographic information, including spatial properties (Huang <i>et al.</i> , 2009).
LAS/LAZ	LAS is the standard file used for storing airborne LiDAR data such as X, Y, Z coordinates. LAZ is simply a compressed version of LAS to make the data more manageable while retaining the quality (ASPRS, 2011).

Figure 3: Defining file format terms (Photo credit: D. Dennehy)

Generally, Augment City relies on orthophotos in the form of ariel or satellite imagery, to produce the building data in the virtual model. Orthophotos are ariel photographs taken from a plane or drone that have been corrected to eliminate distortion caused by the camera angle and the ground topography (Booyesen *et al.*, 2021). This process results in a photograph that represents the Earth's surface with uniform scale and true geometry that can be used to draw measurements of distances, angles, and areas. This is typically used in urban planning, forestry, environmental monitoring, and mapping. Elevation models produced from LiDAR technology or GeoTIFF data formats are also suitable forms of building mass information that can be used to produce a model. This form of data can be obtained from GML or CityJSONs, an open-sourced database that stores 3D building and landscape models.

At this stage, the analytical data has been collected and the building mass data has been converted into a virtual model. The next phase of the project is to add land and water surfaces. Digital surface formats come in the form of LAS/LAZ files and bathymetry is used to mimic seabed levels. The integration of the building and surface models creates the digital replica, which is solely a visual representation of the city. The specified datasets are then added to provide utility and interaction making it a digital twin product.

In addition to data accessibility, another significant challenge lies in technological familiarity. This refers to the need for clients to have access to individuals who are proficient in understanding and operating the associated software required to use the twin effectively. Geographic Information Systems (GIS) play a vital role in many urban planning and design projects, used to capture, analyse, manage, and present spatial or geographic data. This tool enables users to assess environmental, demographic, and topographic information, among others, to make informed decisions about the layout, planning, and management of urban spaces. However, the effective use of GIS requires a comprehensive understanding of both the software itself and the principles of geographic data analysis.

It is important to acknowledge that until the real-time data is integrated into the virtual model the outcome is simply a visual representation of the city and not an analytical tool that can be used to benefit the environment it represents. Jörn Hoffmann (2023), the applications partnership lead for the global-scale digital twin producers at DestinE, noted, "It's worth appreciating that 'digital twins' are a bit of a buzzword. The term is not always understood in the same way." This is in response to the incorrect use of the term to describe a model that is absent of analytical data, as opposed to a model that is informed by such (examples of each are depicted in Figures 4 and 5).

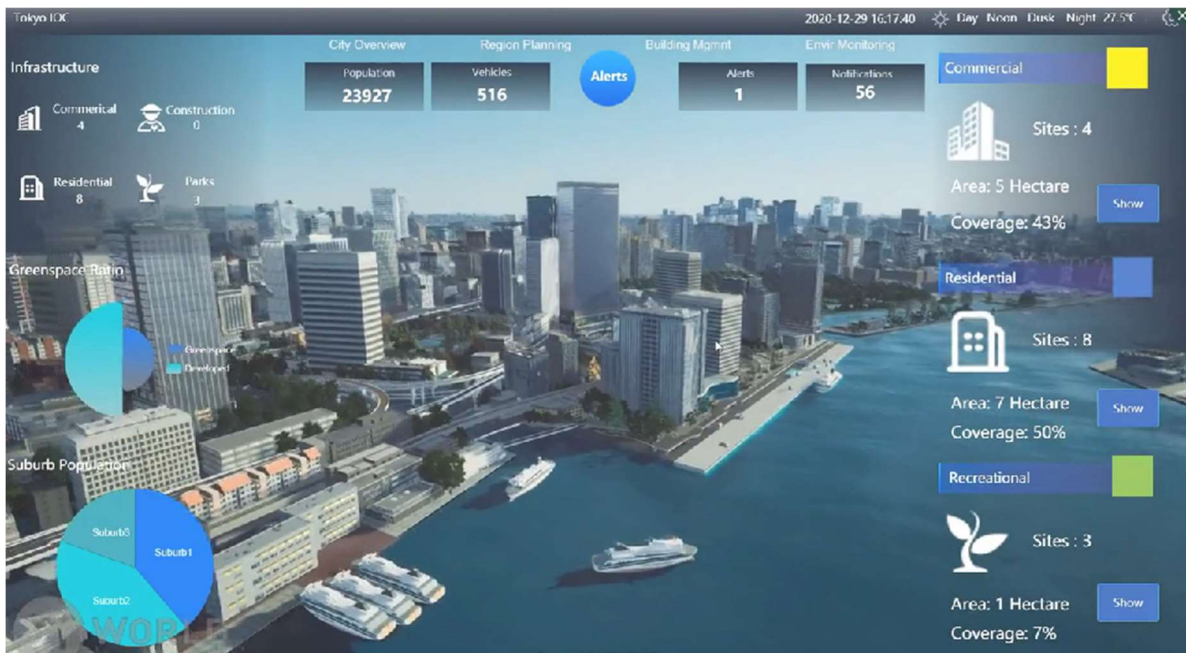


Figure 4: Digital twin of Tokyo City (Photo credit: 51World)

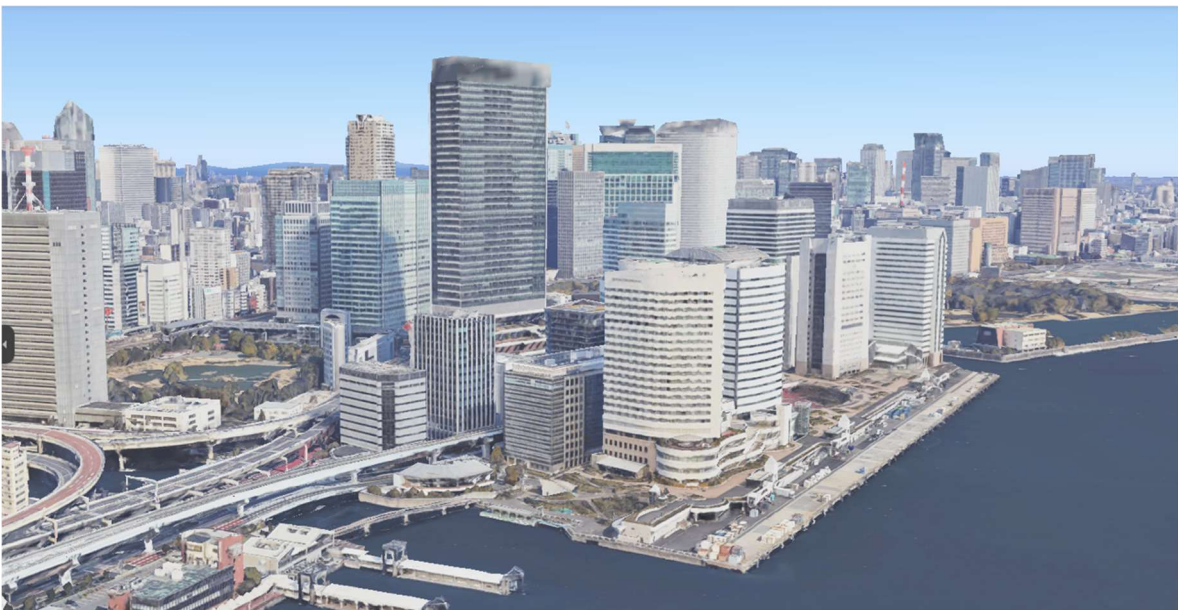


Figure 5: Digital model of Tokyo City (Photo credit: Google Earth)

A prime illustration of digital twins in urban design emerges through the methodologies of scenario planning and public engagement. Scenario planning stands as a leading application for digital twins across various professions, characterised by the ability to conduct iterative tests swiftly to identify the most beneficial outcome (Debnath, Pettit, and Leao, 2023). This approach was exemplified by Augment City in the process of determining the location of a new school. In this instance, the Building Information Modelling (BIM) framework was utilised,

situating the model in three distinct locations to facilitate comparative analysis. This enabled stakeholders to review the project within its context, evaluate the effects of shadow, analyse impacts on local traffic flows, and compare projected energy costs.

The applications of public engagement and scenario planning were featured in the recent collaboration between Augment City and award-winning architectural practice, Snøhetta. This partnership aimed to design a gondola system in Norway intended to transport individuals from Devoldfabrikken to the summit of Rundehornet (Flakk Group, 2020). For this project, the practice chose to work exclusively with digital twin technology, rather than physical models. The project aimed to make the summit accessible for all ages and boost the visitation statistics of the town through year-round activity facilities, and a market focused on cruise tourists and business travellers.



Figure 6: Visualisation of Snøhettas' proposal (Photo credit: Sula Gondola)

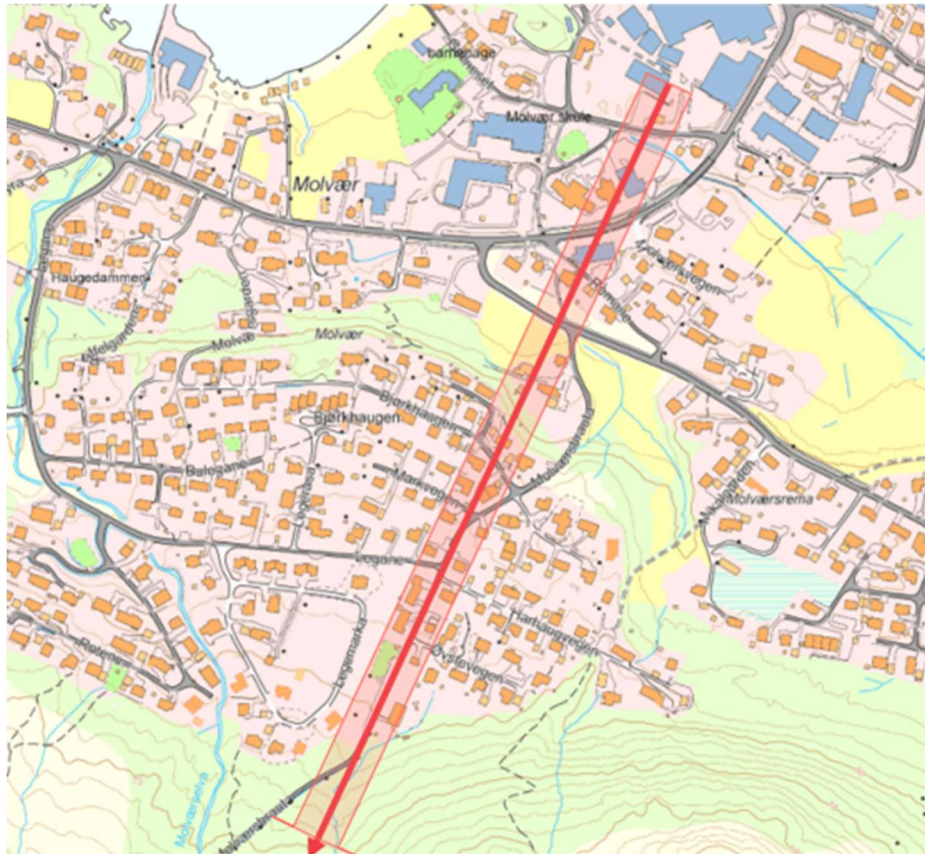


Figure 7: Proposed route for the gondola (Photo credit: Flakk Group)

The gondola was set to travel 2,570m over the town, which received resistance from the local citizens with justifiable concerns regarding privacy. The initial design positioned the cable cars less than 7 metres above multiple homes (as seen in Figure 8), which resulted in direct views into the gardens and properties below. Augment City invited the residents to their immersive room, where they were able to experience the journey from inside the lift at a 1:1 scale (Flakk Group, 2021). Interestingly, this experience not only verified the public's concerns to be true but also highlighted the additional issue of shadow. At peak time it was estimated there would be a lift passing over every 20-30 seconds, casting large shadows across many of the properties (Adewale, 2024). Due to twin technology, Snøhetta was able to engage with the homeowners and make suitable design adjustments to satisfy them. The original specification for clear glass was revised and modified to incorporate frosted glass to the lower section of each lift, (shown in Figures 9 and 10) and scenario planning was used to discover the most appropriate height and route path to mitigate shadow casting. The versatility of the digital twin was further demonstrated in its application across the roles within the project. Doppelmayr, the company responsible for supplying the lifts, effectively utilised the digital twin to calculate the placement of support posts and the arrangement of the connecting cables. The use of a digital twin throughout these instances underscores its significant role in the project's overall execution and success.

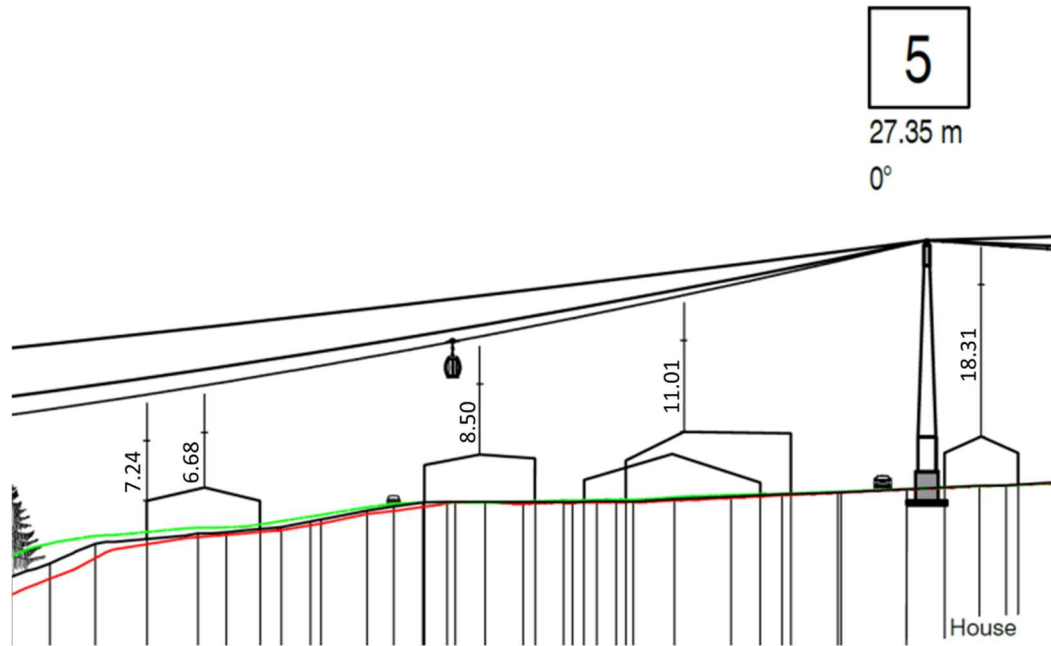


Figure 8: Diagram illustrating the distances between the gondola cables and the rooftops below (Photo Credit: Flakk Group)



Figure 9: Scenario planning: running the simulation with clear glazing (Photo credit: Augment City)



Figure 10: Scenario planning: running the simulation with frosted glazing (Photo credit: Augment City)

One of the key themes explored in this project was co-design, enabling members of the public and the construction team to voice their ideas, likely resulting in a more widely supported proposal. Considering ideas from both professionals and the community ensures that decisions are not just technically sound but also environmentally and socially responsive. These 3 components are essential in producing sustainable design. This strategy generates transparency by revealing the intentions of the project, reassuring the public and reinforcing

the connection they have to the concept (Nguyen, Collins and Collins, 2024). Considering all ideas is a proactive approach to mitigating issues that could arise during the construction phase where any alterations could impact the overall time and cost.

Another proactive approach is the use of scenario planning. These iterative simulations can produce instantaneous calculations such as displaying the cost differences in material specification and estimating utility expenses based on the orientation of a building. The ability to review information such as this offers foresight to optimise the design, enhancing economic viability and contributing to long-term operational needs (Mannucci *et al.*, 2023). Through saving time, cost and resources, scenario planning will arguably be one of the most beneficial applications that digital twins have to offer urban design.

Chapter 2: Swansea City

In 2023, a project was launched to create a digital twin for Swansea City to showcase the capabilities of the Net Zero Urban Programme (NZUP) at COP28. This initiative was given a 5-week timeline to establish project objectives, conduct drone surveys, and produce a model that could visualise real-time city data. The Swansea digital twin was featured at the 'Empowering Cities with Digital Twins' session on December 6th, alongside those of Stavanger, Norway, and Kochi, India. This session evaluated the significant impact of digital twin technology in urban environments, drawing on the various case studies (Augment City, 2023). The project's initial goals included plans to expand the Swansea model post-conference, aiming to explore long-term community benefits such as enhanced data collection and education.

Drone Technology, Safety, and Data Processing

Upon request, Augment City have produced digital twin models working from drone-collected imagery, as opposed to their conventional process of collating existing geographical datasets. This direct form of data captures the required information in its true state, whereas drawing from existing data can lead to inaccuracies. These inaccuracies can stem from outdated information, or in circumstances where alterations have been made to a property without planning consent and are not recognised by official bodies who manage the regional building mass data. The Swansea City digital twin exemplifies the use of drone surveying technology to produce a compatible model.

During the initial phase of the surveying process, a DJI Phantom 4 Pro V2.0 drone equipped with a 20MP camera was used to capture data for the twin. Determined through personal flight testing, this drone has an average battery life of 30 minutes and operates using a mechanical shutter. This shutter type controls the level of exposure that enters the camera to deliver quality images, particularly at speed (Canon, 2024). As opposed to a rolling shutter, which captures images through a line-by-line process, often causing distortion and blur when in motion (as seen in Figures 11 and 12) (Zhou *et al.*, 2020). Because of this, a mechanical shutter is better suited for efficient mapping, allowing for the capture of clear images quickly and effectively along a survey path.

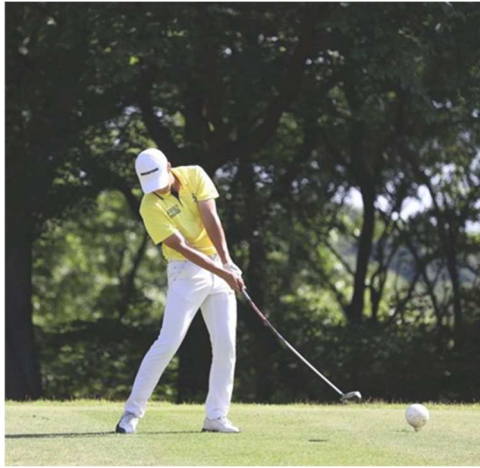


Figure 11: Effects of rolling shutter on golf club travelling at speed (Photo credit: Canon)

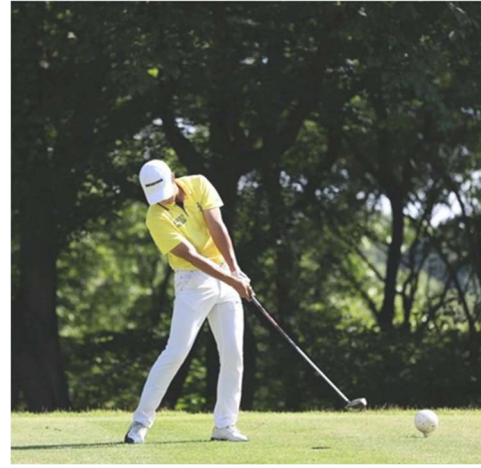


Figure 12: Effects of mechanical shutter on golf club travelling at speed (Photo credit: Canon)

After completing the first of the three surveys, funding was made available to CWIC (Construction Wales Innovation Centre) to purchase a more advanced drone, the DJI Matrice 350 RTK. This model possesses a 45MP camera - offering more than double the resolution of the Phantom - and is also fitted with a mechanical shutter (DJI, 2024). Its significant size and enhanced capabilities enable the Matrice to survey at greater altitudes while producing higher-quality images resulting in reduced survey times. The maximum battery running time is greatly increased to 55 minutes, yet the Matrice's primary advantage is its Real-Time Kinematic (RTK) capabilities which vastly improves the accuracy of the drone's geolocation. Tie points were created by setting an overlap between each picture to distinguish a common feature, such as a roof ridge, across multiple photos. These serve as a reference point for aligning and relating individual images and converting them into a unified model (Drummond, 2024). It is these tie points on which the Phantom drone heavily relies to coordinate the survey data, whereas the Matrices RTK system is paired to a base station that communicates with the drone in-flight to consistently calibrate itself, a more precise and efficient surveying technique (illustrated in Figure 15) (DJI, 2023). The drone's ability to orientate itself also significantly reduces the time required to edit the model, post-flight. Once flights were conducted, the imagery was uploaded to Pix4D Capture, a photogrammetry software used for pre-planning and product management.



Figure 13: DJI Phantom 4 Pro V2.0 drone
(Photo credit: DJI)



Figure 14: DJI Matrice 350 RTK drone
(Photo credit: DJI)

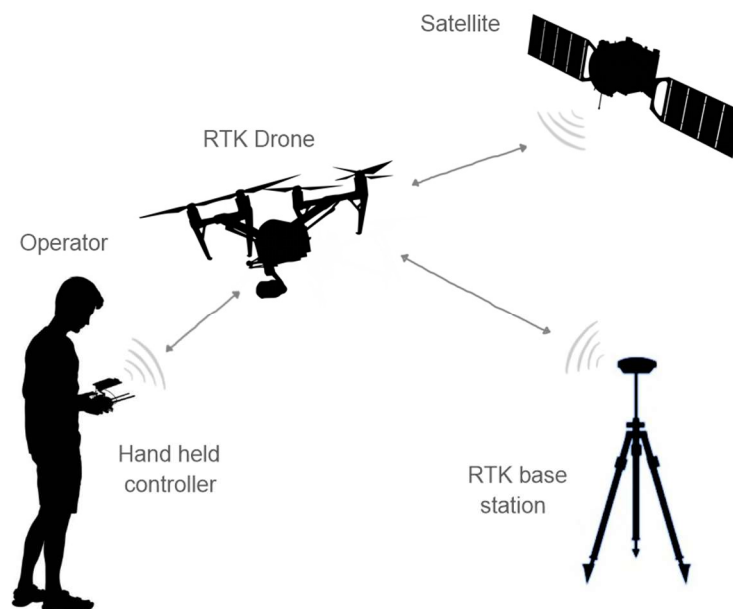


Figure 15: Diagram illustrating RTK signal transfers (Photo credit: Drew Dennehy)

The deployment of both drones presented an opportunity to assess their respective performances and distinguish the influence of drone quality on the final digital twin model. In summary, the surveys carried out using the DJI Matrice were of superior quality, completed in less time, and easier to manage post-flight, exemplifying the proficiency of RTK technology.

All three scans included within the Swansea twin were piloted by ACE's (Architecture, Construction, and Environment) technical demonstrator, Matthew Drummond, assisted by the head of the Swansea School of Architecture (SSA), Ian Standen, Part 1 architecture student, Brandon Roberts, and SSA undergraduate student, Drew Dennehy. Individuals must undergo specific training and obtain the appropriate licenses to legally operate drones in the United Kingdom (UK). This process includes acquiring a Certificate of Competency (CoC) plus a General Visual Line of Sight Certificate (GVC), demonstrating the operator's proficiency, and understanding of drone operation (Gov.UK, 2017).

In addition, pilots must also secure operational authorisation from the Civil Aviation Authority (CAA). This is attained by producing an operator's manual detailing pilot credentials, drone specifications, responsible parties, intended use, emergency procedures, and insurance information. Guidance and templates are available online to assist in assembling such a document. Once received, the CAA performs a thorough review of the document and issues an operational authorisation certificate validating compliance, requiring annual renewal (CAA, 2024a).

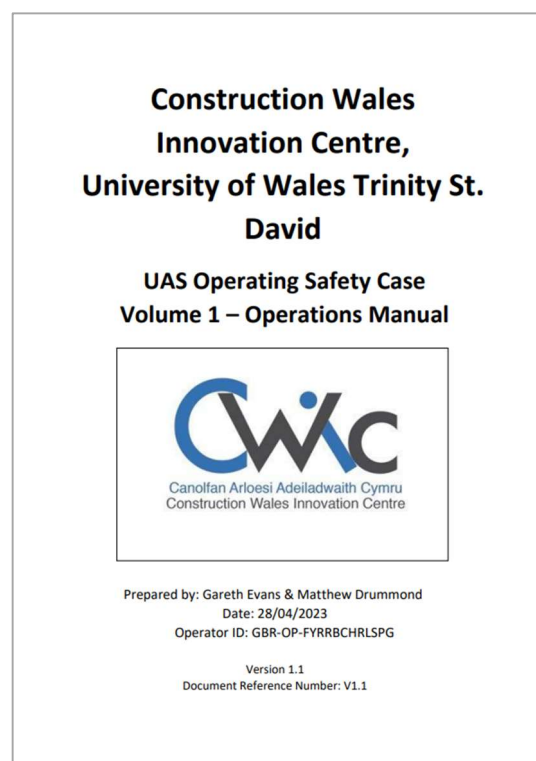


Figure 16: Cover of the CWIC drone operations manual (Photo credit: CWIC)

Operators flying commercially in the UK must obtain public liability insurance that complies with EC785/2004, outlining the insurance requirements for air carriers and aircraft operators, though the level of insurance coverage varies by country. Those operating for personal use are not legally required to hold insurance, though it is recommended. The insurance held during this use case provided coverage of up to £50 million in respect to product liability and was limitless for public liability (Drummond, 2024).

A comprehensive list of permissions and checks were completed before entering local air space:

Prior to flight:

- Flight planning (mandatory): In this instance, the programme 'Foresight' was employed to organise each scan. This is a subscription-based online drone operations management platform developed by AirDataSystems and was used to define the flight area and complete preliminary risk assessments. This software is also used to identify the flight path within the specified area and monitor the airworthiness of each drone.
- Identifying flight zones (mandatory): Verify that the proposed flight path does not enter flight-restricted zones. Swansea prison was the only area of unauthorised air space that would impact the planned routes and so the perimeter of the flight path was adjusted accordingly to avoid entering it.
- NOTAMs (mandatory): Notice To Airmen information websites house details for pilots on potential hazards that are within their intended flight path. This information needs to be reviewed to ensure the safety of the flight.
- Informing stakeholders (advised): Notify the relevant stakeholders to update them on the progress of the project.

Day of flight:

- Notify the local authorities (advised): The police were contacted via email informing them of the intended flight times, survey area, and planned flight height. Once this was reviewed, the pilot was given confirmation and a reference number. This is typically only advised unless the flight concerns public safety or is operating over sensitive areas.
- Alert other airspace users (mandatory): The app 'Drone Assist' was used to upload the flight path, schedule, drone information, and pilot contact details to mitigate the risk of collision with other unmanned aircraft systems (UAS). The pilot, Matt Drummond, also posted on associated social media pages as an additional measure. Whether this is a

mandatory requirement or not is dictated by the class the flight is operating in, set out by the CAA.

- Update risk assessment (mandatory): When onsite, the preliminary risk assessment was reviewed in the event that additional hazards needed to be added that weren't previously apparent.
- Timings (advised): A note of the time at initial take-off and final landing was recorded as well as the time at battery interchanges.
- Concluding report (mandatory): Post-flight, a closure report was drafted to list any issues or unplanned incidents that arose throughout the survey.

Some of the checks mentioned are legally required to operate in the UK, as with insurance, this changes with each country. Guidance on flying in other countries is detailed on the CAA website.

Constructing the Model

Each flight path is represented in Figures 17 to 19 and required appropriate measures to protect the public from entering the operational area. The first survey was conducted on Tuesday 31st October 2023 and captured the SA1 area covering the UWTSD campus, as well as a section of the primary thoroughfare into Swansea, Fabian Way. Matthew was joined by Drew Dennehy who acted as a visual observer (VO) throughout the course of the flight. The presence of a visual observer is an advisory requirement that becomes mandatory in instances where flights exceed the general line of sight or for flights conducted under operational authorisation; given in instances where flights are required to fly outside the general standards (CAA, 2024b). The general line of sight is defined as having a constant visual on the drone within 500 metres unaided, anything above this distance is considered an Extended Visual Line of Sight (EVLOS) operation and requires further authorisation. The role of a visual observer is to provide a second line of sight to the drone and identify any potential airborne or ground-level hazards, particularly when the pilot is focused on a manoeuvring. For the initial scan, the appointed operational area was within a fenced-off zone adjacent to the University library and illustrated as a white circle in Figure 17. This also shows the double-grid flight path, capturing a total of 2,447 images, each one represented as a red point.



Figure 17: Double grid flight path for the initial survey (Photo credit: M. Drummond)



Figure 18: Flight path for the second survey (Photo credit: M. Drummond)



Figure 19: Flight path for the final survey (Photo credit: M. Drummond)

Before take-off the drone was calibrated and a home point was established for the drone to autonomously return to in the event connection to the controller is lost, or the battery is low (N.C. *et al.*, 2022). During calibration, the wind speed was recorded using an anemometer to ensure the drone was capable of flying in the current conditions. The DJI Phantom was used for this flight, withstanding speeds of up to 10m/s which comfortably surpassed the present conditions of 3.3m/s (DJI, 2018). Once calibrated, a landing pad was laid on the ground serving 2 functions: to mark where the drone will be landing and to protect the camera. The camera is fitted to a gimble that points the camera facing down upon landing. In the final stages of this manoeuvre the drone makes contact with the floor with the propellers still engaged, this creates a downward thrust that can disturb small stones on the ground that could damage the camera. Weighted pads are recommended as they do not shift when such down thrust occurs, though these are more costly. Due to heavy rainfall, the survey was split into 2 stages, taking a total of 120 minutes to complete the 0.35km² area.



Figure 20: Measuring wind speed using an anemometer (Photo credit: D. Dennehy)



Figure 21: DJI Phantom drone on landing pad (Photo credit: D. Dennehy)

The final two surveys took place on 3rd November 2023 and 15th November 2023, conducted using the more advanced DJI Matrice drone. The flight path in Figures 18 and 19 incorporate a grid path, notably different from the double grid path set out in the initial scan. This is a benefit achieved from the use of smart oblique capture (SOC). The Phantom uses a standard oblique camera function which operates at a set angle and flies through 2 perpendicular grids to capture the necessary imagery. The Matrice is fitted with a gimbal that allows the camera to quickly alter its position and capture multiple angles, removing the need for a perpendicular grid and significantly reducing flight time (Drummond, 2024). Figure 18 also features an orbit path around the Meridian Tower, typically used for collecting images around a tall building or a singular point.

Applications

The Swansea model was completed in late November 2023, though at this time it was simply a digital representation of the city. No data had yet been integrated into the project and therefore the product could not be identified as a digital twin (Hoffmann, 2023). The next phase was to send the model to Augment City where they implemented data collected from online open sources and Swansea Council. Outlined below are the initial applications of the twin that were showcased during COP28.

Traffic simulation, as shown in Figure 22, demonstrates a sample of how a road network system can be represented to outline traffic intensity levels. In this image, busier roads are represented in green, while those with less activity are shown in red. As expected, Fabian Way, the primary thoroughfare into Swansea, is highlighted as one of the busiest; conversely, the less trafficked areas typically include access roads and cul-de-sacs. The ability to monitor the flow of traffic in a city could have a substantial impact on reducing congestion and improving road safety. This data will allow developers and city planners to assess the impact a new project could have on current traffic conditions, enabling them to investigate issues before they are realised saving both time and costs (Kušić, Schumann and Ivanjko, 2023). This technology would also highlight areas in need of investment and recognise how traffic patterns fluctuate according to different times of the day. In a wider context, this dataset could be paired with others such as carbon emission and acoustic levels to determine a correlation between them. This is a primary motivation for digital twins in their ability to bring together various forms of data to compare them in a way that is easily readable to both public and private entities.

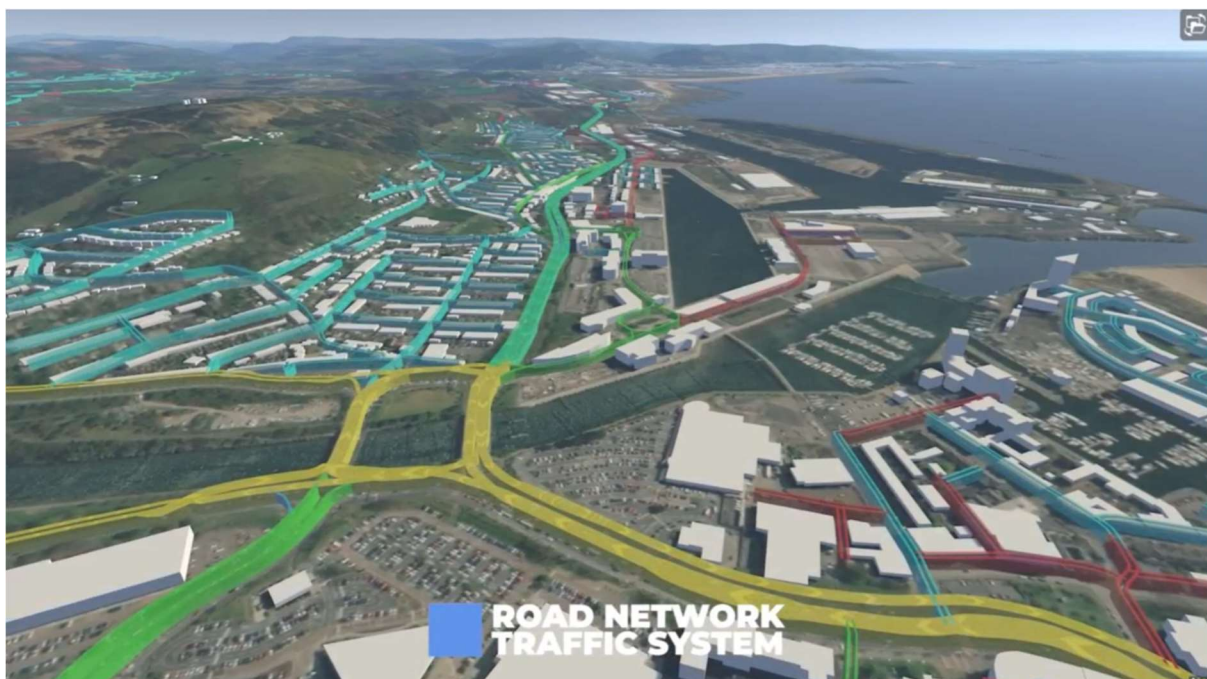


Figure 22: Swansea digital twin displaying road traffic data (Photo credit: Augment City)

Flooding simulation projects the risks of future sea level rise showing which areas will be impacted and to what extent (as shown in Figure 23). This device offers city planners the chance to prepare and employ flood mitigation strategies to protect regions at risk (Langenheim *et al.*, 2022). Despite aiding in flood resilience, the transparency of this dataset

will also highlight properties that are expected to flood and potentially deter the public from buying or renting them. As a result, these dwellings are likely to decrease in value and incur high insurance premiums, potentially condemning the neighbourhood and leading to local economic decline. At a larger scale, as the levels rise and consume the coastline, it is plausible for urban settings to begin drifting inland toward low-risk environments, reshaping the geographical distribution and infrastructure of the country.

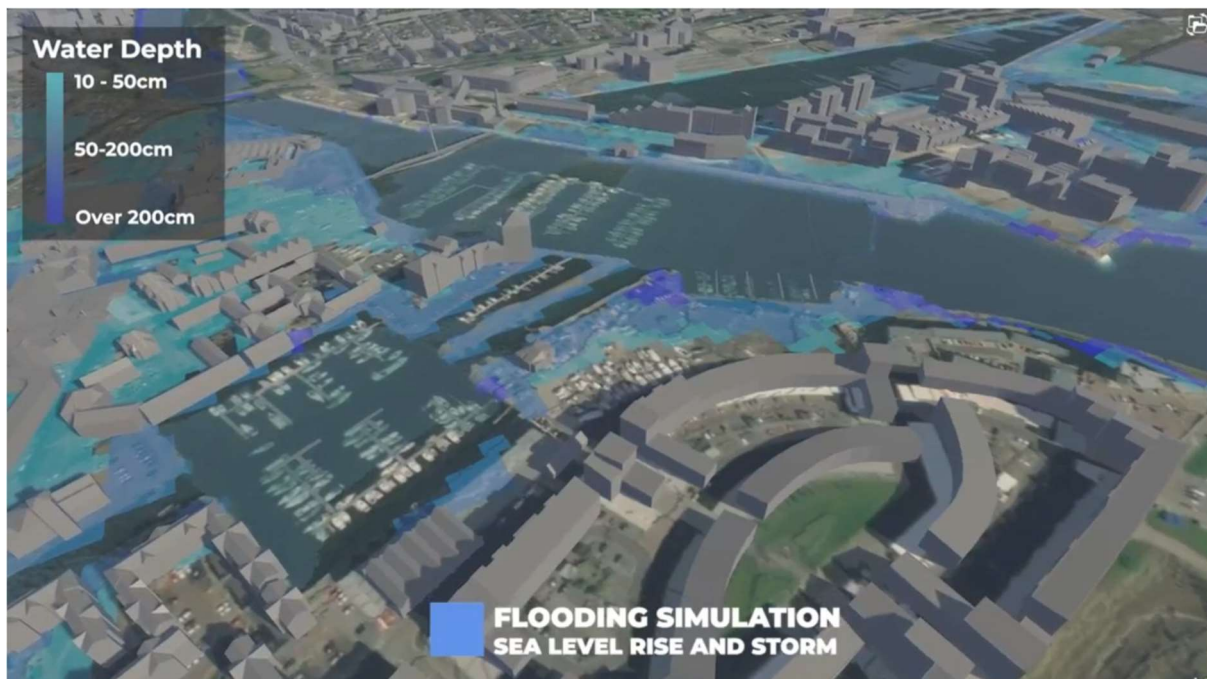


Figure 23: Swansea digital twin displaying flood simulation data (Photo credit: Augment City)

Swansea Council leader, Rob Stuart, has claimed that Swansea is currently underway into its biggest transformation since World War II (Grundy, 2022). This includes the addition of a new 3,500-seat arena, a 1.1-acre coastal park, and the £1.7 billion Blue Eden project, all of which have been positioned within the digital twin. Amongst other things, the Blue Eden project is proposed to comprise the world's largest battery facility for storing renewable energy, a 72,000m² solar farm, and approximately 150 floating eco homes (Swansea Council, 2021). Due to the size and significance of the project its inclusion within the twin offers various benefits, most namely public engagement and statistical analysis. Providing an open-source tool that visualises upcoming projects could allow residents to feel more connected to the development of the city, particularly if the twin encourages them to express their opinions and ideas. Data collected from the tidal power station could be communicated to show the

distribution of renewably generated power and its consumption throughout the day. Consequently, this could be cross-referenced against environmental impact metrics to report project contributions toward reducing carbon emissions and meeting sustainability goals. It would also mark the region's capable of operating solely on renewable energy and begin neutralising the use of fossil fuels. Overall, the addition of upcoming projects in a digital twin will assist in assessing the sustainability of the future and the resilience of urban areas.



Figure 24: Swansea digital twin displaying the Blue Eden project (Photo credit: Augment City)

Thermographic capabilities were exercised using the UWTS library as a sample building to test the effectiveness of the technology. As depicted in Figures 25 and 26, the survey exposed multiple areas of significant heat loss throughout the building, primarily stemming from the junction between the roof and walls. The areas of red and yellow indicate higher temperatures while the blue and green represent the lower ones. The thermal mass of the brick is expressed in the side elevation against the cooler surfaces of the aluminium panels adjacent. In an urban context, this form of imagery will allow planners to prioritise areas in need of retrofitting and assist them in pinpointing areas where each building is lacking in efficiency. It could also be used to assess a roof's exposure to light and determine its suitability for solar panels, ensuring an effective use of resources and optimal energy generation. In addition to planning, this could assist other professions such as policing which uncovered a cannabis-growing operation after discovering excessive temperature signatures from an apartment in Birmingham (BBC, 2013).

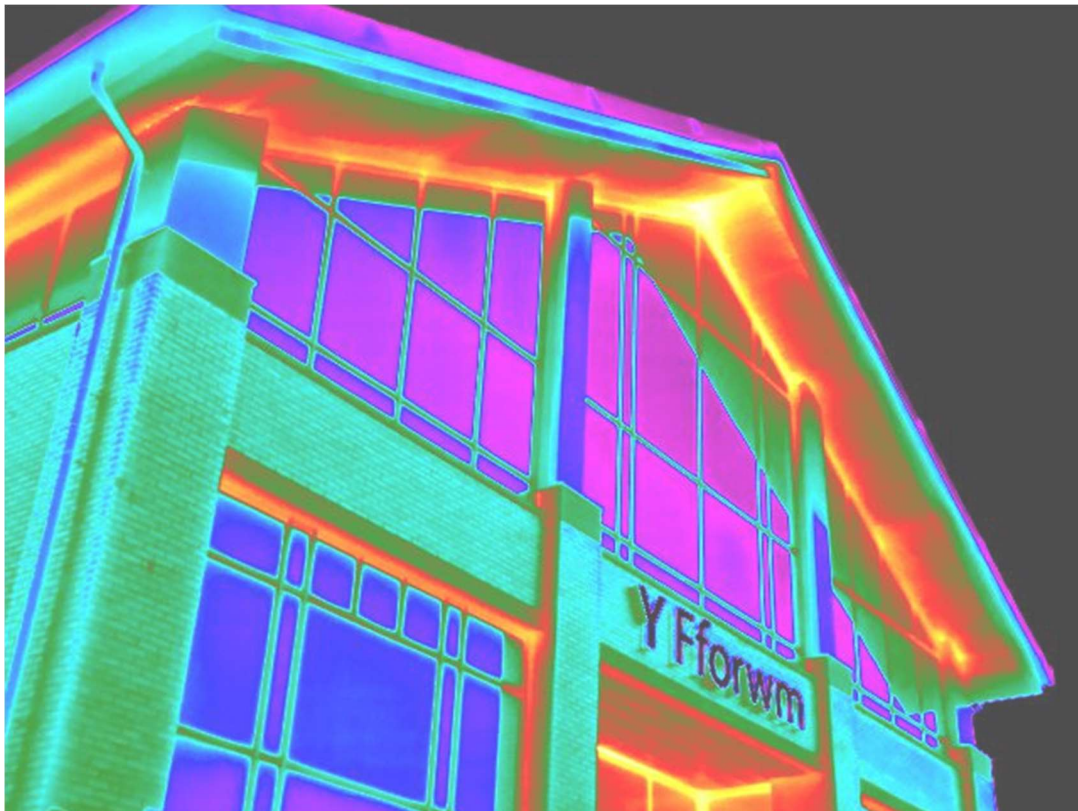


Figure 25: Thermal image of the UWTSD library façade (Photo credit: M. Drummond)

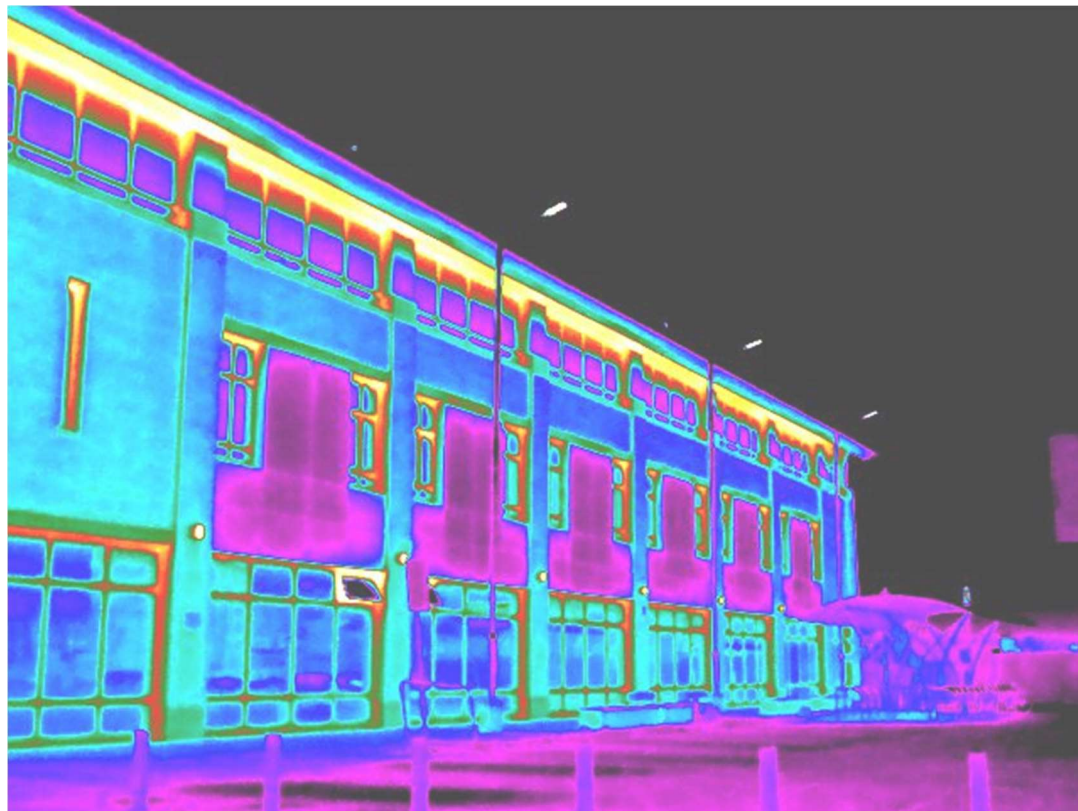


Figure 26: Thermal image of the UWTSD library side elevation (Photo credit: M. Drummond)

Evaluating Current Challenges

Despite first being applied in 2002, this technology is still in its infancy and comes with its limitations. Many of these were experienced throughout the development of the Swansea City digital twin, affecting the overall quality of the model and the time taken to produce it. The most substantial limitation is weather conditions. Swansea experiences an average of 201 days of rain each year where the drone is unable to perform the necessary surveys required for constructing a model. In addition to rain, the level of cloud cover can be a contributing issue; too little and the imagery is covered in strong shadows cast from buildings and other objects, too much and the quality is reduced as a result of insufficient light. The average drone can fly in wind speeds of up to 10m/s, increased to 12m/s for weather-resistant drones, however, if this is exceeded then this is yet another condition that would inhibit a scheduled flight (Gao *et al.*, 2023). Wind speeds are more of a concern in areas with high-rise buildings due to a phenomenon referred to as the 'wind tunnel effect'. The proximity of tall buildings creates a channel where turbulence and wind speeds are intensified making it a dangerous airspace to operate in.

When considering suitable flying conditions, the environment for thermal imaging to take place is even more delicate. The ideal humidity level should be below 70%, which is unachievable in areas such as Swansea where the levels range from 73%-89%. The water vapour present from high levels of humidity absorbs the infrared radiation sent out from the thermal camera. This absorption reduces the intensity of the radiation that is required to return to the device, diminishing the clarity and contrast of the image (Usamentiaga *et al.*, 2014). To increase the quality, the survey should be done on a day with lower temperatures to enhance the thermal contrast between surfaces, preferably during the early hours of the day or late in the afternoon to avoid excess solar gains. Thermographic imagery should also not be taken in the presence of precipitation or surface water as this has a direct and indirect cooling effect on surfaces, leading to inaccurate results.

The sensitivity of the environment required for flying, paired with the unpredictability of the local weather led to the cancellation of multiple flights during the production of the Swansea model. Weather conditions are a global factor that will influence drone surveys across the world, with little to control this issue. Initiatives and projects with a shorter timeline should employ strategies to reduce their flight times where possible to maximise productivity when opportunities are available.

The solution to more efficient flying typically comes at the value of cost. For the Swansea twin, the purchase of a more advanced drone proved greatly beneficial for the twin, reducing the

average survey time as much 61%. However, this investment exceeded a total of £18,000, over 3x the cost of the original drone (DJI Phantom) (outlined in Figure 27). To collect the necessary imagery within one scan, a collection of batteries is required. Without the ability to replace them during a flight, this means splitting a scan into phases which can potentially lead to inconsistencies within the model. In the instance of the Swansea twin, the Matrice used 6 fully charged batteries in a single survey to cover 0.53km², valued at £693 each. The other scans required a similar amount, though the number of batteries required is largely dependent on wind speeds, flight altitude, and weight of the drone (Jung and Kim, 2022).



PRO FORMA INVOICE

BILLING ADDRESS

Matthew Drummond
University of Wales Trinity St. David
College St
Lampeter
SA48 7ED

Date: 25/10/2023

Invoice Number: 46607042

Account Number: B3024711

Your Reference:

Sales: 0871 750 2970

Customer Service 03300 412 271

Manufacturer	Stock code	Description	Unit	Qty	Net	Inc Vat
DJI	BUN/CP.EN.00000222.0 1/87515	Matrice M350 RTK + DJI Zenmuse P1 Payload + Battery Bundle	£0.00	1	£0.00	£0.00
DJI	CP.EN.00000468.01	DJI Matrice 350 RTK Drone Only	£6,595.00	1	£6,595.00	£7,914.00
DJI	CP.ZM.00000136.01	DJI Zenmuse P1 Payload for the Matrice 300 RTK	£4,300.00	1	£4,300.00	£5,160.00
DJI	CP.EN.00000457.01	DJI TB65 Intelligent Flight Battery	£577.50	6	£3,465.00	£4,158.00
DJI	CP.EN.00000464.01	DJI BS65 Intelligent Battery Station	£890.00	1	£890.00	£1,068.00
Delivery	CAR/LD/D1/FREE	Free Next Day Delivery	£0.00	1	£0.00	£0.00
DJI	CP.BX.000229	DJI CrystalSky & Cendence Intelligent Flight Battery WB37 - 4920mAh	£44.00	2	£88.00	£105.60
					Sub-Total	£15,338.00
					VAT:	£3,067.60
					Total:	£18,405.60

Please make cheques payable to Buy it Direct

BACS payments to A/C Name: Buy it Direct BANK: HSBC plc, SORT CODE: 40-13-15, A/C No: 24473779, IBAN Number: GB25HBUK40131524473779, BIC/Swift Code: HBUKGB4B

Figure 27: A copy of an invoice to UWTSd for the purchase of a DJI Matrice 350 RTK drone (Photo credit: Drones Direct)

Signal interference is another possible issue when collecting data and was encountered when setting up the drone for the initial survey. The take-off position was located across from the local marina station where their communication systems interfered with the connection between the drone and the controller. Interference occurs when a radio wave from an external source resonates with the same wave used by the drone, in this case, 2.4GHz. Without an established connection, the drone will remain grounded, negating the risk of losing control during take-off. If the connection is lost while airborne, the drone will abandon the survey and return to the set home point. Where the interference is too strong to initiate a connection between the drone and the controller, the pilot can simply adjust the channel to reduce it. Some drones can operate across multiple band frequencies and cycling through these will further minimise the issue (Ellis, Zhang and Marojevic, 2016).

There is significant concern regarding drone surveys and the General Data Protection Regulation (GDPR) to ensure the privacy of individuals. Due to the nature of these surveys, people and their possessions are often included within the imagery and care must be exercised to protect their identity and information. Faces, property, and number plates are all elements of sensitive data that can be captured during a scan. The pilot liaised with the university data officer to complete a data protection assessment form (depicted in Figure 28) and the CAA's information commissioner to underline risks associated with GDPR when conducting the proposed flights. Depending on the specification of the camera, faces and car registrations are generally unidentifiable, however, the modelling software can analyse the photos and identify moving components such as people, cars, or cyclists. These are then automatically removed from the model. The Information Commissioner's Office (ICO) is an official body appointed by the crown that stands to uphold the information rights of the public and recommends using obfuscation devices as an additional measure to protect people's identity (ICO, 2023). This idea is used in applications such as Google Maps where private information is blurred to make it unrecognisable. As well as piloting the drones, Matt Drummond also processed and developed the data to form the model. Whilst working on this project, the data was saved on a single local hard drive, handled by one individual, and the imagery was deleted once the project was complete (Drummond, 2024). Minimising access to sensitive information should be exercised wherever possible to mitigate data breaches.

Ref.	Risk (descriptor)	Pre-control			Control measures	Post-control		
		Likelihood (d)	Impact (e)	Risk level (d)x(e)		Likelihood (f)	Impact (g)	Risk level (f)x(g)
	<i>For example, 'A' leads to 'B' resulting in 'C' (this should include a description of the impact on individuals, <u>compliance</u> or the reputation of the institution.</i>	1 - 5	1 - 5			1 - 5	1 - 5	
1	The raw photographic images could possibly enable the identification of people and/or vehicles located outside within the subject area.	2	3	6	Raw images will be carefully handled and securely stored. Once project is complete, all images will be permanently deleted.	1	3	3
2								
3								
4								
5								

Impact

	Individuals	Compliance	Reputation
1	None	None	None
2	A data breach resulting in the sharing/loss/use of data that does not identify an individual.	Requires notification to Head of Data Protection for assessment of remedial steps.	Negligible, no impact on student recruitment, government perception or public opinion.
3	A data breach resulting in the sharing/loss/use of data that identifies an individual, which is already <u>publicly</u> available elsewhere.	Sharing of data without permission requires notification to Head of Data Protection for assessment of notification individuals concerned, to ICO and UWTSD internal investigation.	Will / may have short-term (weeks) impact on student recruitment, government perception or public opinion.

Figure 28: Extract from the UWTSD data protection impact assessment referring to potential risks and likelihoods (Photo credit: UWTSD)



Figure 29: Zurich digital twin emphasising indistinguishable number plates (Photo credit: Wingtra)

Key Takeaways and Insights

The Swansea City digital twin was well received at COP28 and featured in articles such as Business News Wales and the South Wales Evening Post (Technology News Wales, 2023). Though the finished product was of a high standard, the pilot discussed lessons learned throughout the development of the twin that will be adopted next time to produce a model of superior quality. The pilot's inexperience with technology as advanced as the Matrice drone had an impact on the overall speed and quality of the finished product. It was later discovered that when conducting the second and third surveys, the exposure had not been set to automatic. Without this the imagery will gradually become darker throughout the course of a survey as the sun begins to set; enabling the automatic feature allows the camera to adjust itself to create a common level of exposure across the imagery.

Setting an overlap defines the level of overhang between each image in order to generate tie points and commonalities between them. This was factory set at 60% and left unadjusted throughout the development of the Swansea twin. By increasing the overlap to 85%-90% the imagery collates into a model more easily and at a higher quality, at the expense of time. With a larger overlap, the survey times are extended, more batteries may need to be used, and additional storage is required.



Figure 30: Graphic depicting a 60% overlap between images (Photo credit: D. Dennehy)



Figure 31: Graphic depicting an 85% overlap between images (Photo credit: D. Dennehy)

The data was stored in a JPEG format, which created limitations when editing the images for the model. RAW files are uncompressed and lossless, allowing for more flexible editing as each element can be adjusted accordingly. As they are not compressed, they are typically much larger but can be edited or converted in a non-destructive manner to deliver high-resolution images (Adobe, 2017).

This case study demonstrates the potential of digital twins in a city-wide context, assisting with making environmentally conscious decisions, preserving resources, and fabricating safer neighbourhoods for the people who inhabit them. It elaborates on the initial study which fixates on using the twin as a visual aid and exemplifies its utility in informing statistical data in a much wider context. Though the production and application of both of these differ, the concept remains the same: to unify information from a range of datasets into one visual format that is easily understood.

Case study 3: Earth

Destination Earth, otherwise known as DestinE, is an EU initiative funded by the Digital Europe Programme to build a virtual representation of Earth. Launched in 2022, the initiative was comprised of three entities: the European Centre for Medium-Range Weather Forecasts (ECMWF), the European Space Agency (ESA), and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) (Hoffmann *et al.*, 2023). The global-scale twin aims to support the Green Deal Strategy by aiding climate change adaptation and associated policies, both in development and implementation. This project is still under development with a full replica of the world expected to be ready by 2030, anticipated to be a highly accurate digital twin powered by supercomputers, artificial intelligence (AI), and high-speed connectivity networks. The vision for this proposal has previously existed for some time but was only recently made possible by advances in numerical modelling and computational power which have made such a scheme much more feasible.

Constructing the Twin

DestinEs twin focuses on pairing existing impact actor models to visualise climate data, meaning it collects a range of pre-existing data sets and presents them in a visual language that can be understood much more effectively than conventional statistical data. The accuracy of the model is validated by the source from which the information was taken, namely weather station satellites and research entities that have operated for an extensive period of time, acquiring billions of data points that are measured by a network of stations. Unlike the Swansea twin, no permissions or observations were required to produce this model as the data has already been collected and is simply being reformatted. It was acknowledged by DestinEs application partnership lead, Jörn Hoffmann (2023), that although the accuracy of the information models has been verified with quite some effort, the scientific community is still exploring methods of enhancing it; this technology is very recent and held back by our limited understanding of quantitative uncertainties.

Cost and data storage are the biggest challenges concerning such a large project. As this initiative is part of an EU programme, DestinE was granted free access to supercomputers across Europe as well as €50 million a year to support the development of the twin. The output of these climate models is in the petabyte volume, an extensive amount of data to store. The secondary issue regarding data is how it can be made accessible to clients using their current technologies. Producing a product that requires the user to update its hardware to run a digital twin could likely generate issues. Thus, DestinE is faced with the challenge of condensing the

twin for it to relay the same information at a more manageable size, ensuring compatibility without necessitating hardware upgrades. This approach allows them to maintain the twin's functionality and value while ensuring it remains accessible to clients relying on existing technological infrastructures.

Heat Island Effects

Since the Industrial Revolution, there has been a rise of over 1°C in global land temperature, generally acknowledged within the scientific community to be a result of human influence. Though a rise of 1°C in background temperature may seem insignificant, it is the result of extreme heat events leading to record-breaking temperatures and heat waves that are gradually becoming longer and more intense. These instances are one of the leading causes of weather-related deaths around the world; people living in built-up areas are likely to have twice the amount of exposure due to the effects of urban heat islands (UHI) (Met Office, 2021). This occurs where a densely built-up area intersects with significant human-related activity, such as transportation, body heat, and high energy consumption within buildings. Where cities feature light-coloured building surfaces, such as Santorini, the heat is reflected, and those featuring dark surfaces and minimal vegetation face a higher risk of heat accumulation (National Geographic, (2011). Green spaces facilitate evapotranspiration, producing a cooling effect. Trees form a canopy that cools the ground level, absorbs warm air, and releases moisture into the atmosphere through transpiration. The air quality within heat islands is of a lower quality and as a consequence of the higher temperatures, more air conditioning is used thus using more energy and adding to the issue (Jiang *et al.*, 2024).

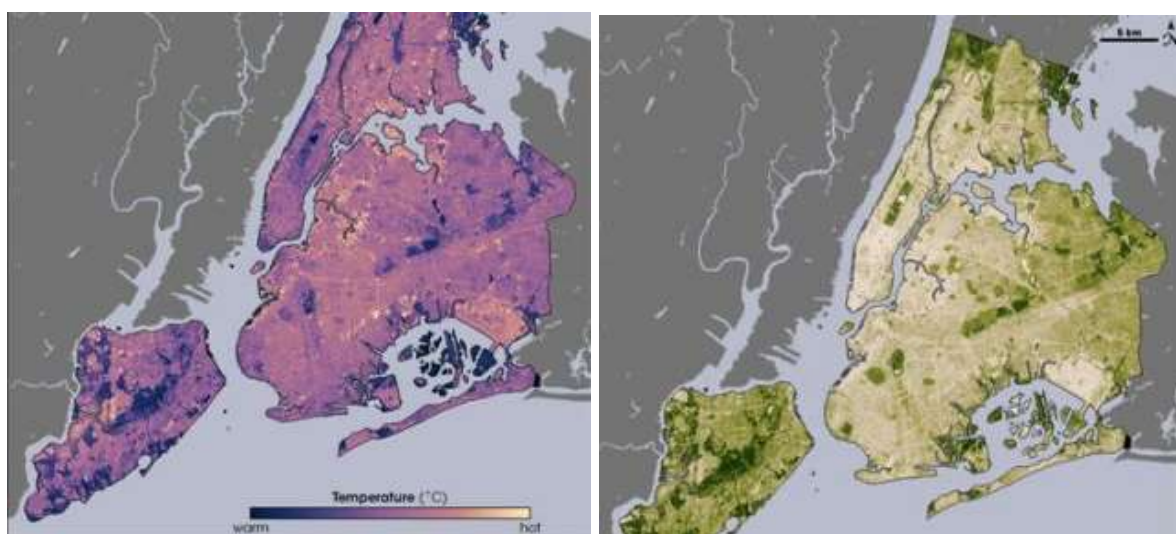


Figure 32: The relationship between heat and green spaces (Photo credit: National Geographic)

DestinE is currently involved in a precursor project alongside VITO (Vlaam Instelling voor Technologisch Onderzoek) and other organisations to demonstrate the capabilities of the global twin. This use case identifies the issue of urban heat islands and aims to find solutions to reduce it. It will offer institutions an insight into how heat is distributed through built-up areas, plus, the impacts of people, infrastructure, services, and economic activity to plan mitigation and cohesion strategies (ECMWF, 2023). This high-resolution, interactive tool will be integrated with VITO's own UrbCLIM model, one that has been used successfully in cities across the world using physics-based urban climate datasets. Currently, the most advanced form of this technology in Europe is CS3's 'Climate variables for cities in Europe from 2008 to 2017' which provides information on wind speed, air temperature, and relative humidity (VITO, 2023). With input from ECMWF, this new twin will operate at a much higher resolution, operating at a scale up to several tens of metres, with the ability to calculate projections decades into the future.

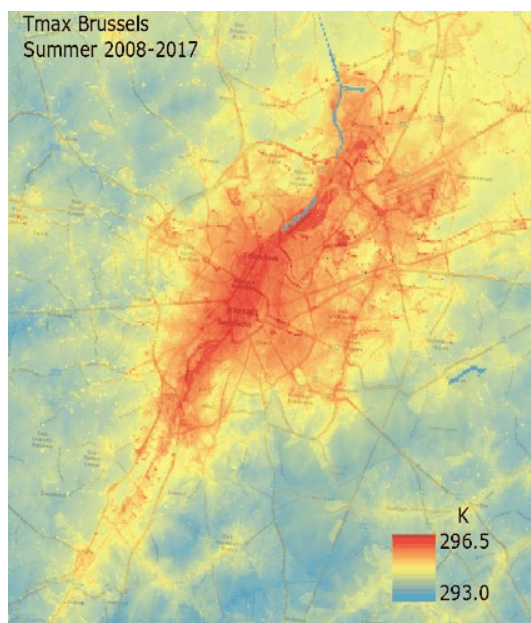


Figure 33: Sample image from C3S software (Photo credit: C3S)

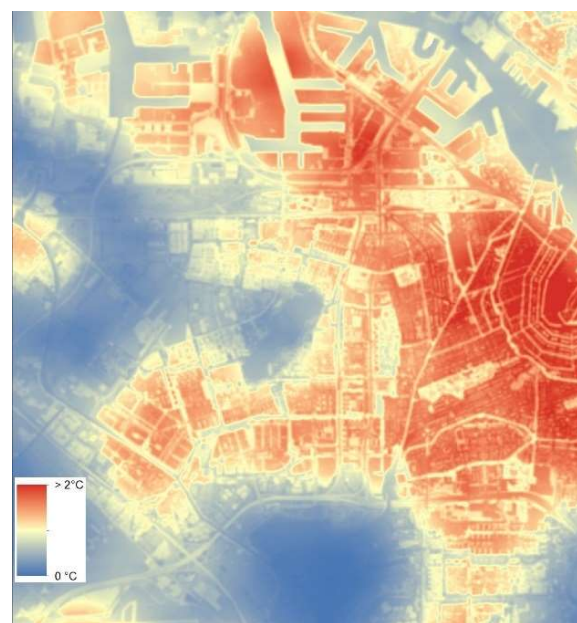


Figure 34: Sample image from UrbCLIM software (Photo credit: UrbCLIM)

In addition to these advancements, the new twin will also assess and monitor thermal comfort levels, vegetation, radiative influence from buildings, and topography to achieve a higher level of accuracy than its predecessors. Levels of thermal comfort typically correlate with those of stress and discomfort; therefore this dataset offers research opportunities to study the relationship between the two.

In 2026, Destination Earth will further complement this model with the launch of a new satellite that will analyse the emission and spread of Carbon Dioxide at the kilometre scale. It will be used to validate emission reports set out by the UNFCCC (United Nations Framework Convention on Climate Change) and will develop our understanding of urban heat islands. Receiving CO₂ measurements at such a detailed scale will indicate the impact energy consumption has on the local environment, separating it from other factors such as body heat and building surface type. For each project, DestinE will utilise a co-design strategy approach where they will work directly with the client to construct a twin that meets their needs. The data from this use case will offer city planners, public health officials, and policymakers real-time insights into the effects of climate change at a regional scale, enabling the development of policies aimed at mitigating heat-related health issues.

Ethically, the authorising body of the programme will need to establish how access to the digital twin is distributed among stakeholders. Offering equitable access will allow smaller entities and communities to benefit from the technology, as well as large organisations and official bodies. However, if the twin is only made available to those who can afford to pay for the services, it could exacerbate existing inequalities and widen the digital divide throughout the world (Francisco and Linnér, 2023). Another ethical argument is whether this project is an effective use of the substantial energy and resources it requires to produce and maintain it. A twin of this size will need data centres, which are energy-intensive due to the constant power supply and large cooling systems necessary to keep the servers in optimal operating conditions. In addition to this, there is the continuous feed of data from IoT sensors to the centralised processing centre, the repair and replacement of hardware, and the task of maintaining a robust cybersecurity system to prevent breaches and misuse of the data.

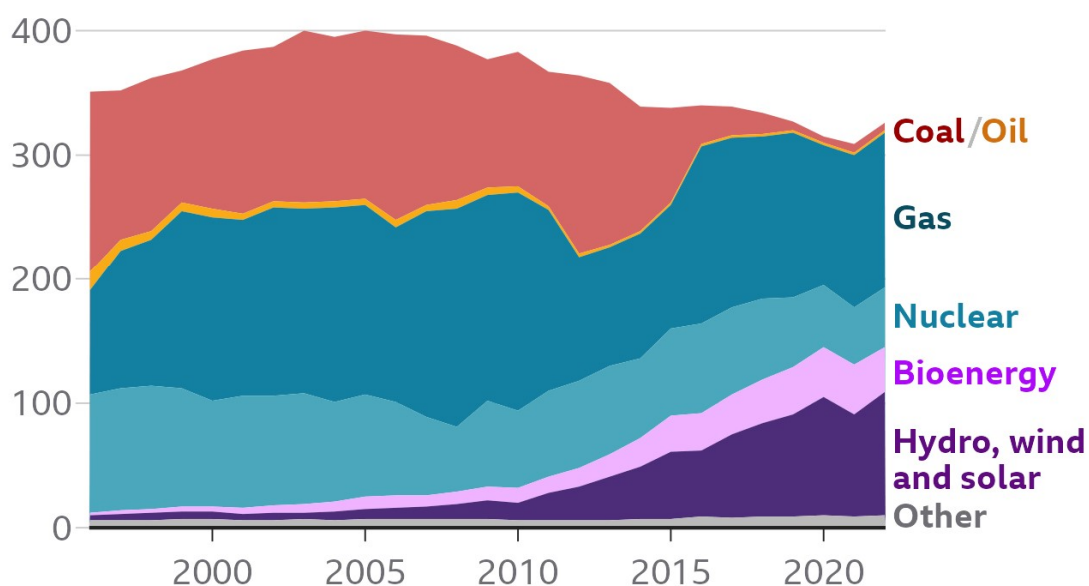
DestinE's digital twin technology, holds the potential to significantly influence building regulations, particularly regarding urban heat island mitigation and infrastructure resilience. An example of a regulation inspired by DestinE's insights might involve the mandatory implementation of green roofs, urban forestry initiatives, and the use of reflective building facades in new developments to bring about cooler temperatures. These measures, informed by detailed simulations, could significantly reduce excessive heat, improve air quality, and create healthier cities. Additionally, the technology's predictive modelling could also lead to the development of infrastructure resilience regulations, requiring all new constructions to be designed to withstand anticipated extreme weather events like intensified storms or heat waves. By leveraging the predictive ability of DestinE's digital twin, policymakers can enforce building codes and urban planning principles that prepare cities for current environmental challenges as well as future hazards (Marcucci *et al.*, 2020).

Conclusion

The production of local, city, and global scale digital twins have been discussed as well as a handful of their corresponding applications to form an understanding as to the potential of the technology. Figure 35 shows a reduction in fossil fuels with an increase in all forms of renewable energy use in the United Kingdom. Despite this, the UK government's independent advisers, the Climate Change Committee (CCC), have voiced their concerns that the nation may not meet its sustainability targets for 2035, or 2050, without improved action. The use and capabilities of digital twins are growing exponentially, with advances in computational power, and could be a crucial component in assisting the UK and other countries back on track to meeting their criteria.

How the UK's electricity mix has changed

Amount of electricity generated by fuel source (terawatt hours)



Source: Department for Energy Security and Net Zero

BBC

Figure 35: Levels of energy generated by each fuel source in the UK (Photo credit: BBC)

As there are various ways to construct a model, either through directly sourced photogrammetry or pre-existing data sets, it is possible for any town, city, or country to develop one. However, the usefulness of the model as a digital twin will be determined by the availability of data in that region, which could present challenges in less developed countries. Throughout interviews, digital twin professionals expressed their thoughts on the future of digital twins as a long-term solution and believe rather than having one core twin that provides all the information in itself, there will be many twins that are specialised in different fields and

locations. Jörn Hoffman (2023) went on to say he envisions the smaller models being informed by competitive global-scale twins where additional standards are regularly introduced to produce highly accurate sources of reliable data.

To extend this topic it could be of interest to conduct an extensive assessment a few years from now to assess whether digital twins delivered on their promised potential or to investigate into how the public adopted the transparency and inclusion they provide. A study could also be launched to review the statistical data of a city before and after the implementation of a twin to compare the differences. The twin could even be utilised as a source of credible information itself, being able to visualise related data and draw calculated comparisons instantaneously. A final area of interest could be to study data ownership, liability, and ethics to establish guidelines and aim to clarify accountability.

Digital twin technology brings added inclusivity into projects, visualising and demonstrating information to every member involved within it, from the client to the suppliers. It can also predict future events, highlight areas in need of redevelopment, and run limitless scenarios to enable urban planners to make informed decisions. There are many ways that twins can be utilised to design safer and more efficient environments, though it does come with the concern of mass uncertainty. As mentioned previously, these virtual models could expose information that could condemn coastal areas and alter the geography of a country. It could be revealed that some urban environments correlate to particular health issues, such as a vast number of respiratory difficulties paired with high levels of air pollution. This presents a large issue in how residents respond to this information; it opens complex legal challenges if they look to prosecute and would be difficult to distinguish who is liable. While digital twin technology promises to reshape urban planning and development, it also underscores the need for vigorous ethical frameworks and participatory governance models. The benefits of digital twins should be equitably distributed, and their applications should not inadvertently harm vulnerable communities. Communication between technology developers, urban planners, policymakers, and the public must remain open, inclusive, and responsive to the diverse needs of the people and the planet.

Reference List

Adewale, R. (2024) *Interview via Microsoft Teams* (09 January 2024).

Adobe (2017) *RAW files*. Available at: <https://www.adobe.com/creativecloud/file-types/image/raw.html> (Accessed: 13 April 2024).

American Institute of Aeronautics and Astronautics [AIAA] (2022) *Michael Grieves*. Available at: <https://www.aiaa.org/detail/person/michael-grieves> (Accessed on: 09 April 2024).

American Society for Photogrammetry & Remote Sensing [ASPRS] (2013). *LAS Specification*. Available at: https://www.asprs.org/wp-content/uploads/2010/12/LAS_1_4_r13.pdf (Accessed: 10 March 2024).

Attaran, M. and Celik, B.G. (2023) 'Digital Twin: Benefits, use cases, challenges, and opportunities', *Decision Analytics Journal*, 6 (March) article 100165. Available at: <https://www.sciencedirect.com/science/article/pii/S27726622300005X> (Accessed: 19 April 2024).

Augment City (2019) *Konferanse 2019*. Available at: https://www.youtube.com/watch?v=S_FsFWMmrBY&t=62s (Accessed: 10 March 2024).

Augment City (2023) 'Preparation for CoP 28'. Augment City. Unpublished.

Booyesen, R., Gloaguen, R., Lorenz, S., Zimmermann, R and Nex, P.A.M (2021) 'Geological remote sensing', *Encyclopedia of Geology*, 6, pp. 301-314. Available at: <https://doi.org/10.1016/B978-0-12-409548-9.12127-X>

British Broadcasting Corporation [BBC] (2013) *Helicopter thermal imaging leads to cannabis factory conviction*. Available at: <https://www.bbc.co.uk/news/uk-england-birmingham-24542698> (Accessed: 13 April 2024).

Canon (2024) *Electronic vs mechanical shutter*. Available at: <https://www.canon-europe.com/pro/infobank/electronic-vs-mechanical-shutter/> (Accessed: 13 March 2024).

Choi, S.-K., Ramirez, R. A. and Kwon, T.-K. (2023) 'Acquisition of high-resolution topographic information in forest environments using integrated UAV-LiDAR system: System development and field demonstration', *Heliyon*, 9(9). Available at: <https://www.sciencedirect.com/science/article/pii/S2405844023074339> (Accessed: 19 April 2024).

Debnath, R., Pettit, C. and Leao, S. Z. (2023) 'Opportunities and limitations of integrating computational and collaborative approaches to scenario planning', *Journal of Urban Management*, 12(4), pp. 314-316. Available at: <https://doi.org/10.1016/j.jum.2023.07.002>

DJI (2023) *DJI Matrice 350 RTK: Everything you need to know*. 7 June. Available at: <https://www.youtube.com/watch?v=eS78BDigxso> (Accessed: 13 March 2024).

DJI (2018) *Specs*. Available at: <https://www.dji.com/uk/phantom-4-pro-v2/specs> (Accessed: 19 April 2024).

DJI (2024) *Specs*. Available at: <https://enterprise.dji.com/matrice-350-rtk/specs> (Accessed: 13 March 2024).

Drummond, M. (2024) *Interview via Microsoft Teams* (16 January 2024).

Ellis, C., Zhang, M. and Marojevic, V. (2023) 'Interference Analysis and Mitigation for UAV Communications in Drone Corridors', *2023 26th International Symposium on Wireless Personal Multimedia Communications (WPMC)*. IEEE, pp. 1–6. Available at: <https://doi.org/10.1109/WPMC59531.2023.10338970>.

European Centre for Medium-Range Weather Forecasts [ECMWF] (2023) *DestinE for human heat stress: ECMWF use case to tackle urban heat islands*. Available at: <https://stories.ecmwf.int/destine-for-human-heat-stress-ecmwf-use-case-to-tackle-urban-heat-islands/index.html> (Accessed: 13 April 2024).

Flakk Group (2020) 'Destinasjon Sulafjellet'. Flakk Group. Unpublished.

Flakk Group (2021) *Sula Gondola*. Available at: <https://www.dropbox.com/scl/fo/zjo861hkgmlh87r5v1vxd/h?dl=0&e=1&rlkey=ggdctau1go13f3f3n2vrwe7ee> (Accessed: 10 March 2024). Unpublished.

Francisco, M. and Linnér, B. -O. (2023) 'AI and the governance of sustainable development. An idea analysis of the European Union, the United Nations, and the World Economic Forum', *Environmental Science & Policy*, 150 (December) article 103590. Available at: <https://www.sciencedirect.com/science/article/pii/S1462901123002393> (Accessed: 19 April 2024).

Gao, M., Hugenholtz, C.H., Fox, T.A., Kucharczyk, M., Barchyn, T.E. & Nesbit, P.R. (2021) 'Weather constraints on global drone flyability', *Scientific Reports (Nature Publisher Group)*, 11(1) Available at: <https://www.proquest.com/docview/2538877273?accountid=130472&parentSessionId=xa4UzvjmSDhNhqWGoMLZuW6%2FeZzuws/destination-earth-urban-heat-maps-lisbon-and-prague> (Accessed: 19 April 2024).

Gov.UK (2017) *Drones: how to fly them safely and legally*. Available at: <https://www.gov.uk/government/news/drones-are-you-flying-yours-safely-and-legally> (Accessed: 11 April 2024).

Grundy, D. (2022) *Swansea: £135m Copr Bay district opens to the public*. Available at: <https://www.bbc.co.uk/news/uk-wales-60604290> (Accessed: 11 April 2024).

Hoffman, J. (2023) *Interview via Microsoft Teams* (04 December 2024).

Hoffmann, J., Bauer, P., Sandu, I., Wedi, N., Geenen, T. and Thiemert, D. (2023) 'Destination Earth – A digital twin in support of climate services', *Climate Services*, 30 (April) article 100394. Available at: <https://www.sciencedirect.com/science/article/pii/S2405880723000559> (Accessed: 19 April 2024).

Huang, C.-H., Chuang, T.-R., Deng, D.-P. and Lee, H.-M. (2009) 'Building GML-native web-based geographic information systems', *Computers & Geosciences*, 35(9), pp. 1802-1816. Available at: <https://www.sciencedirect.com/science/article/pii/S0098300409001113> (Accessed: 19 April 2024).

Information Commissioner's Office [ICO] (2023) *Commercial use of drones*. Available at: <https://ico.org.uk/about-the-ico/research-reports-impact-and-evaluation/research-and-reports/technology-and-innovation/tech-horizons-report/commercial-use-of-drones/> (Accessed: 13 April 2024).

Jiang, Y., Li, C., Li, X., Li, X., Song, T. and Liu, Y. (2024) 'Exploring the adaptive spatial patterns and impact factors for the cooling effect of park green spaces in riverfront area', *Urban Climate*, 55 (May) article 101900. Available at: <https://www.sciencedirect.com/science/article/pii/S2212095524000968> (Accessed: 19 April 2024).

Jones, D., Snider, C., Nassehi, A., Yon, J. and Hicks, B. (2020) 'Characterising the Digital Twin: A systematic literature review', *CIRP Journal of Manufacturing Science and Technology*, 29 (Part A), pp. 36-52. Available at: <https://www.sciencedirect.com/science/article/pii/S1755581720300110> (Accessed: 19 April 2024).

Jung, H. and Kim, J. (2022) 'Drone scheduling model for delivering small parcels to remote islands considering wind direction and speed', *Computers & Industrial Engineering*, 163 (January) article 107784. Available at: <https://www.sciencedirect.com/science/article/pii/S0360835221006884> (Accessed: 19 April 2024).

Klynveld Peat Marwick Goerdeler [KPMG] (2024) Net Zero Urban Program. Available at: <https://kpmg.com/xx/en/home/insights/2022/10/net-zero-urban-program.html> (Accessed: 09 April 2024).

Kušić, K., Schumann, R. and Ivanjko, E. (2023) 'A digital twin in transportation: Real-time synergy of traffic data streams and simulation for virtualizing motorway dynamics', *Advanced Engineering Informatics*, 55 (January) article 101858. Available at: <https://www.sciencedirect.com/science/article/pii/S1474034622003160> (Accessed: 19 April 2024).

Langenheim, N., Sabri, S., Chen, Y., Kesmanis, A., Felson, A., Mueller, A., Rajabifard, A. and Zhang, Y. (2022) Adapting a digital twin to enable real-time water sensitive urban design decision-making. Available at: <https://isprs-archives.copernicus.org/articles/XLVIII-4-W4-2022/95/2022/isprs-archives-XLVIII-4-W4-2022-95-2022.pdf> (Accessed: 11 April 2024).

Leete, R.I. (2022) *What is a Digital Twin?*. Available at: <https://www.archdaily.com/975256/what-is-a-digital-twin> (Accessed: 09 April 2024).

Mannucci, S., Kwakkel, J.H., Morganti, M. and Ferrero, M. (2023) 'Exploring potential futures: Evaluating the influence of deep uncertainties in urban planning through scenario planning: A case study in Rome, Italy', *Futures*, 154 (December) article 103265. Available at: <https://www.sciencedirect.com/science/article/pii/S0016328723001696> (Accessed: 19 April 2024).

Marcucci, E., Gatta, V., Pira, M.L., Hansson, L. And Bråthen, S. (2020) Digital Twins: A Critical Discussion on Their Potential for Supporting Policy-Making and Planning in Urban Logistics. *Sustainability*, 12(24) article 10623. Available at: <https://www.proquest.com/docview/2471984579?accountid=130472&parentSessionId=5eGyM25%2FO8na08R0guRXFjHROIUGFlm9YxEBSJZSH8k%3D&pg-origsite=primo&sourcetype=Scholarly%20Journals> (Accessed: 19 April 2024).

Met Office (2021) *UK and Global extreme events – Heatwaves*. Available at: <https://www.metoffice.gov.uk/research/climate/understanding-climate/uk-and-global-extreme-events-heatwaves> (Accessed: 13 April 2024).

N.C., A.V., Yadav, A.R., Mehta, D., Belani, J. and Chauhan, R.R. (2022) 'A guide to novice for proper selection of the components of drone for specific applications', *Materials Today: Proceedings*, 65(8), pp. 3617-3622. Available at: <https://www.sciencedirect.com/science/article/pii/S2214785322041499> (Accessed: 19 April 2024).

National Aeronautics and Space Administration [NASA] (2021) *GeoTIFF*. Available at: <https://www.earthdata.nasa.gov/esdis/esco/standards-and-practices/geotiff> (Accessed: 10 March 2024).

Nguyen, N.T., Collins, A. and Collins, C.M. (2024) 'Trends and patterns in the application of co-production, co-creation, and co-design methods in studies of green spaces: A systematic review', *Environmental Science & Policy*, 152 (February) article 103642. Available at: <https://www.sciencedirect.com/science/article/pii/S1462901123002915> (Accessed: 19 April 2024).

Seifert, E., Seifert, S., Vogt, H., Drew, D., Jan, V.A., Kunneke, A. and Seifert, T. (2019) Influence of Drone Altitude, Image Overlap, and Optical Sensor Resolution on Multi-View Reconstruction of Forest Images. *Remote Sensing*, 11(10). Available at: <https://www.proquest.com/docview/2303283087?accountid=130472&parentSessionId=OqJBIC58yCLupEk3ebAXr7oZO6lOpzaz94yi3XxPBpl%3D&pg-origsite=primo&sourcetype=Scholarly%20Journals> (Accessed: 13 April 2024).

Swansea Council (2021) *£1.7 billion Blue Eden project announced for Swansea*. Available at: <https://www.swansea.gov.uk/BlueEden> (Accessed: 11 April 2024).

Technology News Wales (2023) *UWTSD Collaborates with World Leading Innovative Digital Technology Companies*. Available at: <https://businessnewswales.com/uwttd-collaborates-with-world-leading-innovative-digital-technology-companies/> (Accessed: 13 April 2024).

UK Civil Aviation Authority [CAA] (2024a) *Getting what you need to fly legally*. Available at: <https://www.caa.co.uk/drones/drone-code/getting-what-you-need-to-fly-legally/> (Accessed: 11 April 2024).

UK Civil Aviation Authority [CAA] (2024b) *First person view flying*. Available at: <https://www.caa.co.uk/drones/rules-and-categories-of-drone-flying/first-person-view-flying/> (Accessed: 11 April 2024).

Usamentiaga, R., Venegas, P., Guerediaga, J., Vega, L., Molleda, J. and Bulnes, F.G. (2014) 'Infrared Thermography for Temperature Measurement and Non-Destructive Testing', *Sensors (Basel)*, 14(7). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4168422/> (Accessed: 19 April 2024).

Vlaam Instelling voor Technologisch Onderzoek [VITO] (2023) *DESTINATION EARTH: URBAN HEAT MAPS FOR LISBON AND PRAGUE*. Available at: <https://vito.be/en/news/destination-earth-urban-heat-maps-lisbon-and-prague> (Accessed: 13 April 2024).

Zhou, Y., Daakir, M., Rupnik, E. and Pierrot-Deseilligny, M. (2020) 'A two-step approach for the correction of rolling shutter distortion in UAV photogrammetry', *ISPRS Journal of Photogrammetry and Remote Sensing*, 160 (February), pp. 51-66. Available at: <https://www.sciencedirect.com/science/article/pii/S0924271619302849?via%3Dihub> (Accessed: 19 April 2024).

Bibliography

- Barricelli, B.R., Casiraghi, E. and Fogli, D. (2019) 'A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications', *IEEE access*, 7, pp. 167653–167671. Available at: <https://doi.org/10.1109/ACCESS.2019.2953499>.
- Caprari, G., Castelli, G., Montuori, M., Camardelli, M. and Malvezzi R. (2022) 'Digital Twin for Urban Planning in the Green Deal Era: A State of the Art and Future Perspectives', *Sustainability*, 14(10) article 6263. <https://doi.org/10.3390/su14106263>
- Chandhana, T., Vellore, A. B., Kumaran, S. R. R & Singh, B. (2023) 'Digital Twins-Enabling Technologies Including AI, Sensors, Cloud, and Edge Computing', *Handbook of Research on Applications of AI, Digital Twin, and Internet of Things for Sustainable Development*, (pp. 306-331). Available at: <https://www-igi-global-com.ezproxy.uwtsd.ac.uk/gateway/chapter/full-text-html/318860> (Accessed: 19 April 2024).
- Charitonidou, M. (2022) 'Urban scale digital twins in data-driven society: Challenging digital universalism in urban planning decision-making', *International Journal of Architectural Computing*, 20(2), pp. 238-253. Available at: <https://journals.sagepub.com/doi/10.1177/14780771211070005> (Accessed: 19 April 2024).
- Dassault Systèmes (2016) *3DEXPERIENCity® - Virtual Singapore: Singapore's Innovative City Project - Dassault Systèmes*. 8 July. Available at: [3DEXPERIENCity® - Virtual Singapore: Singapore's Innovative City Project - Dassault Systèmes \(youtube.com\)](https://www-3dexperience-com.ezproxy.uwtsd.ac.uk/gateway/chapter/full-text-html/318860) (Accessed: 19 April 2024).
- Deng, T., Zhang, K. and Shen, Z. -J. (2021) 'A systematic review of a digital twin city: A new pattern of urban governance toward smart cities', *Journal of Management Science and Engineering*, 6(2), pp. 125-134. Available at: <https://www.sciencedirect.com/science/article/pii/S2096232021000238?via%3Dihub> (Accessed: 19 April 2024).
- Destination Earth (2023) *DestinE Partnership Plan, Use cases and upcoming opportunities by Jörn Hoffmann* (ECMWF). 25 July. Available at: [DestinE Partnership Plan, Use cases and upcoming opportunities by Jörn Hoffmann \(ECMWF\) - YouTube](https://www-destinationearth-com.ezproxy.uwtsd.ac.uk/gateway/chapter/full-text-html/318862) (Accessed: 19 April 2024).
- Dhibar, K., Maji, P., Prasad, S., & Pal, M. (2023) 'Sustainable Development Using Digital Twin Technology With Image Processing', *Handbook of Research on Applications of AI, Digital Twin, and Internet of Things for Sustainable Development* (pp. 344-360). Available at: <https://www-igi-global-com.ezproxy.uwtsd.ac.uk/gateway/chapter/full-text-html/318862> (Accessed: 19 April 2024).
- European Centre for Medium-Range Weather Forecasts [ECMWF] (2022) *ECMWF Destination Earth Digital Twin 2022*. 5 July. Available at: <https://www.youtube.com/watch?v=8BLNxRoP3o0> (Accessed: 19 April 2024).

Schrotter, G. and Hürzeler, C. (2020) 'The Digital Twin of the City of Zurich for Urban Planning', *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, 88, pp. 99–112. Available at: <https://link.springer.com/article/10.1007/s41064-020-00092-2#citeas> (Accessed: 19 April 2024).

Appendix A: Stakeholder meeting notes in preparation for COP28



PREPARATION FOR COP 28

1. Overview of OSC's attendance at COP (activities).
 - o Augment City will be present at COP28 between 3-6 December participating in two KPMG led events:
 - Breaking Financial Barriers in Decarbonizing Cities – December 5th, 2023, 10:00-11:30, REA Pavilion, Blue Zone.
 - Empowering Cities with Digital Twins: Advancing Policies, Investments, and a Just Transition via a Whole Systems Approach – December 6th, 2023, 17:00-18:15, Panel Discussion and Q&A, 18:15-19:00 Networking and Light Refreshments, UNFCCC GIH, Blue Zone.
2. How the Swansea digital twinning model will feature at COP (i.e. conference presentation, exhibition, etc?).
 - o The digital twin model of Swansea will be used during the 'Empowering Cities with Digital Twins: Advancing Policies, Investments, and a Just Transition via a Whole Systems Approach' session on December 6th. During this session, we will explore how digital twins are making substantial impacts in urban environments, showcasing practical case studies in the form of digital twins from cities worldwide. Cities will include: Bodø & Stavanger, Norway; Swansea, UK; Surat & Kochi, India; Ithaca, US.
 - o If you find that anyone from the Welsh Government is attending, please do let me know as we would like to offer them an opportunity to join the panel discussion for the above event.
3. The purpose of the model or models going forward (i.e. tools to support cities with their transition toward net zero, etc?).
 - o The digital twin of Swansea demonstrates our capability as a joint programme between Augment City and KPMG, which is referred to as the Net Zero Urban Programme. The programme was launched last year at COP27 and is designed to support cities, both nationally and internationally, on their net zero journeys, using digital twin technology to help cities prioritise their interventions to achieve net zero carbon.
 - o Post COP28, it would be great to map the direction of travel together determining whether there is interest from the Welsh Government and Swansea Council to add to this work. I am keen to make sure what is produced is beneficial long term to Swansea as a city and useable post Augment City/KPMG involvement. In this scenario, we would need to ensure that KPMG is involved commercially, so that we could offer



wider services as part of the Net Zero Urban Programme, including business cases, PPPs, blended finance models, implementation support, net zero roadmaps etc.

4. Detail needed from each partner, i.e.
 - o I would love to have some headshots of all team members involved from Swansea to acknowledge everyone's efforts, as well as logos to explore how we could incorporate them into our external materials. It would also be great to have one slide on Swansea's ambition as a city and regeneration plans. Can you provide this by Monday next week, latest?
5. Proposed usage of information provided (i.e. as part of an exhibition panel, part of press release, etc?).
 - o As per the second bullet point.

Appendix B: Questionnaire for Joern Hoffmann, Application Partnership Lead for Destination Earth

The following questions were asked, during a Microsoft Teams conversation, to Joern Hoffmann, Application Partnership Lead for Destination Earth.

The questions were devised by the author of this dissertation.

1. What is Destination Earth and what is your role within it?
2. Could you detail the process that DestinE follows for creating a digital twin?
3. How do you envision your model benefiting the field of architecture?
4. Are there any ethical implications in creating digital twins?
5. In the process of developing a digital twin model, what have been the most significant challenges you've encountered, particularly regarding technological limitations, financial constraints, data privacy regulations like GDPR, and other issues?
6. Where do you see digital twins going in the future?
7. The creation and operational use of digital twins involves extensive data collection and processing. Could you describe any specific data management challenges that DestinE has faced in this context? Furthermore, how has your team effectively navigated these challenges, particularly in terms of data storage, processing efficiency, and ensuring seamless data flow?
8. What strategies do you employ to ensure the accuracy and detail within your model?
9. How do you manage real-time data to ensure that your digital twin stays current?
10. Given the scope of DestinE's digital twin project, which extends far beyond the typical city-wide scale, could you elaborate on any scalability challenges you have faced? How have these been addressed to ensure the seamless integration and functionality of such a complex digital model?
11. What is it that inspired the creation of this project?
12. Though it is still a new technology, digital twins are growing quickly. What makes DestinEs' approach unique compared to other initiatives?
13. In the development of DestinE's digital twin, you are likely dealing with a diverse array of data types, including geospatial, environmental, and urban data. Could you elaborate on the methodologies and technologies employed to integrate these varied data streams into a single cohesive and functional model?

Responses were received during the Microsoft Teams conversation with Joern Hoffmann which was held on 04 December 2023.

Appendix C: Questionnaire for Richard Adewale, Global Business Development Manager for Augment City

The following questions were asked, during a Microsoft Teams conversation, to Richard Adewale, Global Business Development Manager for Augment City.

The questions were devised by the author of this dissertation.

1. Could you tell me the aims and initiatives of Augment City, and your role within it?
2. Could you detail the process that Augment City follows for creating a digital twin?
3. Do you typically use drone surveying technology or pre-existing datasets?
4. In what ways do your models benefit the field of urban design, and how?
5. Could you outline the biggest challenges associated with making the digital twin such as finances, data storage and GDPR?
6. Where do you see digital twins going in the future?
7. How advanced is the technology's ability to perform scenario simulations?
8. Could you discuss a particular use case where your digital twins benefited architecture/urban design?
9. What are your thoughts on digital twin technology being utilised with visual reality?
10. Are any of your twins accessible?

Responses were received during the Microsoft Teams conversation with Richard Adewale which was held on 09 January 2024.

Appendix D: Questionnaire for Matthew Drummond, Technical Demonstrator for ACE

The following questions were asked, during a Microsoft Teams conversation, to Matthew Drummond, Technical Demonstrator for ACE.

The questions were devised by the author of this dissertation.

1. Could you tell me the aims and initiatives of the Swansea digital twin project, and your role within it?
2. Could you detail the process you followed for creating your digital twin?
3. How much were each of the drones?
4. What ethical challenges did you face throughout the surveying phase?
5. Could you outline the biggest challenges associated with making the digital twin particularly regarding weather, technology, and storage?
6. Would it be possible to produce a thermographic scan of a sample building?
7. Could you outline the applications of the Swansea City digital twin?
8. What strategies did you employ to ensure the accuracy and detail within your model?
9. What is it that inspired the creation of this project?
10. Were there any lessons learned from previous projects that you have taken forward?
11. Could you outline the key differences in the 2 different drones that were used. Any potential drawbacks, as well as benefits?

Responses were received during the Microsoft Teams conversation with Matthew Drummond which was held on 16 January 2024.