smart cities

Article

An Open-Source Urban Digital Twin for Enhancing Outdoor Thermal Comfort in the City of Huelva (Spain)

Victoria Patricia Lopez-Cabeza *, Marta Videras-Rodriguez and Sergio Gomez-Melgar

Research Centre for Technology, Energy and Sustainability (CITES), Universidad de Huelva,
21071 Huelva, Spain; marta.videras@pi.uhu.es (M.V.-R.); sergio.gomez@dimme.uhu.es (S.G.-M.)
* Correspondence: victoria.lopez@pi.uhu.es

Highlights

What are the main findings?

- A functional Urban Digital Twin prototype was developed to assess outdoor thermal comfort using real-time data and open-source tools.
- The system integrates spatial modeling, microclimate simulation, and web-based 3D visualization in a modular, replicable architecture.

What are the implication of the main findings?

- Urban thermal comfort analysis can be made more accessible and transferable using public data and new technologies.
- The prototype sets the basis for future interactive tools that support climate-sensitive urban planning.

Abstract

Climate change and urbanization are intensifying the urban heat island effect and negatively impacting outdoor thermal comfort in cities. Innovative planning strategies are required to design more livable and resilient urban spaces. Building on a state of the art of current Urban Digital Twins (UDTs) for outdoor thermal comfort analysis, this paper presents the design and implementation of a functional UDT prototype. Developed for a pilot area in Huelva, Spain, the system integrates real-time environmental data, spatial modeling, and simulation tools within an open-source architecture. The literature reveals that while UDTs are increasingly used in urban management, their application to outdoor thermal comfort remains limited and technically challenging, especially in terms of real-time data, modeling accuracy, and user interaction. The case study demonstrates the feasibility of a modular, open-source UDT capable of simulating mean radiant temperature and outdoor thermal comfort indexes at high resolution and visualizing the results in a 3D interactive environment. UDTs have strong potential for supporting microclimate-sensitive planning and improving outdoor thermal comfort. However, important challenges remain, particularly in simulation efficiency, model detail, and stakeholder accessibility. The proposed prototype addresses several of these gaps and provides a basis for future improvements.

Keywords: urban digital twin; outdoor thermal comfort; microclimate analysis; simulation; GIS

Academic Editors: Songnian Li and Zhen Chen

Received: 31 July 2025
Revised: 7 September 2025
Accepted: 25 September 2025
Published: 29 September 2025

Citation: Lopez-Cabeza, V.P.; Videras-Rodriguez, M.; Gomez-Melgar, S. An Open-Source Urban Digital Twin for Enhancing Outdoor Thermal Comfort in the City of Huelva (Spain). *Smart Cities* **2025**, *8*, 160. https://doi.org/10.3390/smartcities8050160

1. Introduction

The global context is framed by the climate emergency and rapid population growth, both of which pose significant threats to the quality of life in cities [1]. Urbanization is placing additional pressure on urban environments, with a majority of the world's population expected to live in cities by 2050 [2]. Global warming is intensifying environmental challenges in urban areas, particularly through the Urban Heat Island (UHI) effect, caused by factors such as impervious materials, anthropogenic heat, and lack of vegetation, which causes significantly higher temperatures in cities compared to surrounding rural areas [3]. This combination exacerbates heat stress, making cities more vulnerable to extreme heat events and negatively impacting outdoor thermal comfort, human health, social interactions, and the use of public spaces. Addressing these challenges requires effective urban planning and management, with a central role in climate-responsive strategies aimed at mitigating the UHI effect and enhancing both thermal comfort and urban resilience.

1.1. Digital Twins in Urban Planning

To address these challenges, cities are increasingly adopting innovative technologies enabled by the digitalization of urban environments. This digital transformation is accelerating with the advancement of emerging technologies that support real-time data integration, spatial analysis, and system optimization [4]. In this context, Digital Twins (DTs) have emerged as key tools for simulating and improving urban management, made possible by the convergence of these technological developments.

A Digital Twin (DT) is a virtual representation of a physical object, system, or environment that continuously updates with real-time data, enabling advanced simulation, analysis, and optimization [5]. It is a precise virtual copy of machines, systems, or assets that features a dynamic nature and a bidirectional interaction and data flow between the physical entity and its digital replicas, allowing for continuous or periodic synchronization. The foundational DT model includes three core components: the physical entity, its digital counterpart, and the data connections that enable real-time synchronization and interaction between the two.

Building upon the concept of Digital Twins and the digitalization of urban environments, Urban Digital Twins (UDTs) have emerged as essential tools in modern urban development. UDTs are dynamic, digital replicas of a city or specific urban area that integrate real-time data, spatial models, and simulation capabilities to support planning, management, and decision-making [6]. It connects physical urban systems with their virtual counterparts through continuous data exchange, enabling scenario testing, performance monitoring, and predictive analysis for more sustainable and resilient urban development. Their use in urban planning is closely linked to the concept of Smart Cities, as both aim for similar goals, such as improving city governance through informed decisions, enhancing citizens' well-being, managing disasters, and reducing operational costs.

UDTs offer significant promise for supporting decision-making processes at the city scale. Among the primary uses of UDTs in modern urban development is smart building management, urban planning, management of mobility and transportation, energy and water management, environmental and carbon management, and risk mitigation and management [6,7]. However, their specific application to environmental and microclimate analysis is still limited.

1.2. UDT for Assessing Thermal Comfort

In this context, UDTs hold significant potential for advancing microclimate analysis and improving outdoor thermal comfort (OTC) through a citizen-centered perspective. By integrating real-time environmental data, spatial modeling, and predictive simulations, UDTs can support urban design strategies aimed at mitigating heat stress and enhancing the everyday experiences of people in public spaces. This human-focused approach is particularly relevant in the context of rising temperatures and increasing vulnerability to extreme heat events in cities. However, while the concept of Digital Twins is gaining traction in urban planning, their specific application to OTC remains relatively unexplored [7]. Among the main applications related to OTC, UDTs are used for environmental monitoring, analysis, and management, including air quality [8,9], noise pollution [9–11], and microclimate analysis [12,13]. This often includes UHI effects [14], assessing the impact of greenery [15–17], and simulating wind flow [17–19]. They also support evaluating strategies for urban resilience, climate adaptation, and decarbonization [20]. However, the specific application of assessing thermal comfort from a user perspective is less common, although emerging. For instance, some studies propose or develop human-centric UDTs that leverage sensor data, crowdsourced data, computer vision, and machine learning to predict outdoor comfort on sidewalks or assess heat exposure [21,22]. These approaches aim to capture dynamic interactions between the environment and individuals or groups and provide personalized predictions or visualize collective heat exposure [23]. These UDT frameworks are being developed to integrate microclimate simulations (like PET or UTCI) into UDTs for assessing the impact of urban interventions on thermal conditions [17,24,25]. These often involve integrating 3D city models with thermal or meteorological data and using simulation tools or machine learning as surrogates for computationally expensive methods like CFD, or developing models for walkability that integrate thermal comfort aspects is also a relevant application area. Table A1 in the Appendix summarizes the main UDTs aimed at thermal comfort assessment found in the literature and their characteristics.

1.3. Enabling Technologies and Research Advancement

Several key technological components support the development of UDTs for OTC assessment, aligned with the typical layers of a digital twin architecture. Three-dimensional city modeling forms the geometric backbone of UDTs. Most projects rely on open-access cadastral data and LiDAR point clouds to create simplified 3D models of buildings, terrain, and vegetation [9,11,19,24], often using formats like CityGML [9,18,26–28]. GIS and CAD tools are standard [11,16,17,24,29], while BIM integration remains limited [15,28]. These models provide spatial context for simulating physical processes, but their resolution is often constrained by data availability. Recent advances aim to improve accuracy through automated 3D reconstruction [30], the integration of thermal imagery [13], and hybrid BIM–GIS approaches [31,32].

The environmental data collection is crucial to ensure that UDTs reflect current urban conditions. Weather stations, IoT environmental sensors, and satellite imagery supply continuous measurements of key variables (e.g., temperature, radiation, wind), while wearables and mobile sensors provide subjective and physiological data to support human-centered assessments. Some projects incorporate crowdsourced or street-level data enhanced by GeoAI to monitor thermal comfort in real time [22,25].

On the other hand, simulation tools represent the core of the analytical layer. Physics-based models like ENVI-met, SOLWEIG, or UrbClim simulate microclimatic variables and thermal comfort indices (e.g., UTCI, PET). However, their computational demands limit scalability. In response, emerging approaches use machine learning and surrogate models to generate faster predictions, integrating sensor inputs and spatial data for near real-time analysis [33,34].

Finally, integration platforms and user interfaces bring these components together through interactive environments built with platforms and engines like Cesium [35], Unity [36], Unreal Engine [37], or Rhinoceros/Grasshopper. These platforms support data streaming, spatial analysis, and interactive visualization of thermal comfort conditions. Web-based dashboards, immersive VR/AR tools, and decision support systems (DSS) aim to make UDTs accessible to planners, stakeholders, and citizens [14,26,27]. Participatory platforms are increasingly common, enabling real-time scenario exploration and collaborative decision-making [20,38–40].

1.4. Key Challenges

The literature presents numerous examples of technological challenges encountered by the research community when addressing the development of UDT. Among the technological challenges remains the lack of robust real-time data integration. While some systems incorporate live sensor or satellite data, many still rely on static datasets or infrequent updates, limiting their responsiveness to rapid environmental changes [15,18,29]. Additionally, the absence of common standards and interoperability between platforms complicates the integration of diverse data sources such as GIS, BIM, and IoT networks, leading to fragmented systems that are difficult to scale or replicate [4,5]. High computational demands also remain a concern, especially when detailed simulations (e.g., CFD or radiative transfer models) are used. These simulations are resource-intensive and often unsuitable for routine or large-scale applications. Beyond performance, digital twins often lack comprehensive validation [41], and the uncertainties in data, model assumptions, or simplifications are rarely quantified. Finally, many DTs are tailored to specific cities or datasets, making it difficult to generalize or transfer them to new urban contexts without significant adaptation.

When applied to outdoor thermal comfort, these challenges become more specific and pronounced. Physically based simulations are often required to capture the complexity of microclimatic interactions, such as wind flow, solar exposure, and radiative exchange, but these models are computationally expensive and slow. To simplify workflows, many studies rely on thermal comfort indices that neglect important human factors such as age, gender, activity level, clothing, or acclimatization [42]. Additionally, detailed microclimatic variations such as transient shading or surface-specific thermal properties are frequently omitted or oversimplified, which undermines the accuracy of thermal assessments. In parallel, emerging data-driven models, particularly those using machine learning, offer an appealing alternative by reducing computational overhead. However, as previous studies have noted [43,44], these models are typically trained on localized datasets, and their performance tends to degrade when transferred to different locations, climates, or urban morphologies. This sensitivity to the training context underscores the need for site-specific retraining or domain adaptation strategies, which limit their immediate applicability and transferability.

Beyond technical and modeling challenges, implementation challenges such as costs, governance, and data privacy have also been highlighted in the literature, implementation barriers that affect the adoption of digital twins for OTC assessment [5]. The interdisciplinary nature of DT implementation, which spans data science, urban planning, environmental modeling, and social sciences, adds additional complexity [45]. Finally, the absence of shared definitions, success metrics, and clear value propositions limits communication among researchers, practitioners, and policymakers, making it difficult to evaluate outcomes or justify continued investment in these systems.

1.5. Research Objectives

Based on the previously revised literature gaps and challenges, this study aims to develop and implement a prototype Urban Digital Twin focused on assessing and visualizing outdoor thermal comfort in urban environments. The proposed system integrates public geospatial data, real-time environmental monitoring, microclimate simulation, and interactive 3D visualization within an open-source and modular architecture. This study builds on the previous literature overview, identifying key technological challenges that inform the design choices of the prototype and introduces several distinctive contributions:

- Open-source stack and open standards: exclusive use of open-source tools (QGIS, UMEP, PostGIS, GeoServer, and Cesium), with OGC-compliant services (WMS/WFS) ensuring transparency and interoperability.
- Real-time data ingestion: continuous sensor integration through Node-RED into a spatial database, directly linked with the model.
- Open data pipeline: reliance solely on public cadastral and LiDAR datasets, enabling reproducibility and transferability to other cities.
- Thermal comfort focus: open-source physics-based digital twin for high spatial resolution and accuracy.
- Browser-based user interface: interactive 3D environment, open-source and license-free, designed for deployment in any standard web browser.
- Connection layer for modularity: explicit design of a connection layer that synchronizes real-time data, simulations, and visualization, facilitating future extensions (user-triggered simulations, participatory planning).

In contrast, some previous UDT projects (listed in Table A1 of the Appendix A) provide advanced frameworks but rely on proprietary tools, large-scale infrastructures, or simplified surrogate models that limit transparency, reproducibility, or fine-grained comfort analysis. Our prototype explicitly addresses these gaps by demonstrating the feasibility of a low-cost, open-source, and transferable UDT tailored for outdoor thermal comfort analysis at high spatial resolution. These novelties are further detailed in the methodological description of the next section. They are also compared with previous studies in the discussion section. The combination of characteristics of our proposed UDT makes the system accessible and reproducible for medium-sized cities and local institutions, while still enabling detailed assessment of outdoor thermal comfort through microclimate simulations and interactive 3D visualization. This work demonstrates the feasibility of a low-cost, transferable, and user-centered UDT for climate-aware urban planning, using the El Carmen campus in Huelva, Spain, as a pilot area where thermal comfort is analyzed through different performance parameters.

The paper is structured into four sections: following this Introduction, the Materials and Methods section explains the framework of the DT prototype and the case study. Then, the Results section provides an example of the use of the DT and its operation. Finally, the Discussion and Conclusion sections offer a comprehensive analysis of the results and outline future work.

2. Materials and Methods

To translate the conceptual advances of digital twins into a functional tool for urban thermal comfort analysis, this section presents the architecture of a digital twin specifically designed for application in real urban environments and describes the case study and performance parameters to analyze the results. Figure 1 presents the research framework adopted in this study, beginning with the identification of urban challenges, progressing through a literature review to find existing gaps, and continuing to the conceptualization and implementation of the digital twin model, which finally leads to the main contributions of this research.

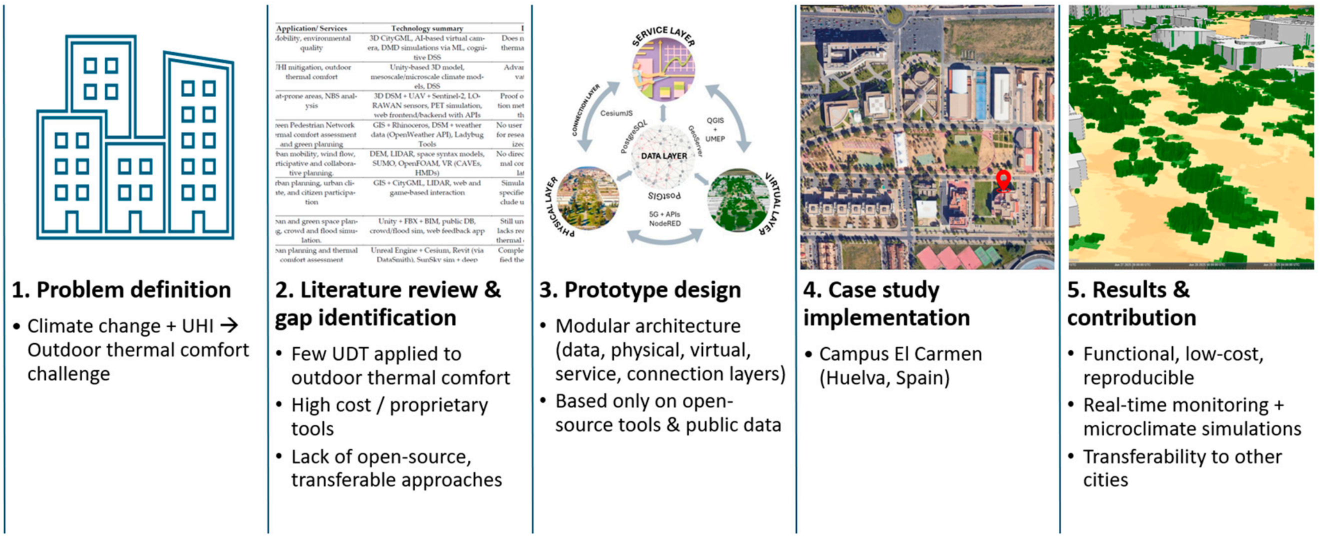


Figure 1. Research framework diagram.

2.1. Digital Twin Proposed Architecture

Responding to the challenges identified in the literature, our methodological approach structures the digital twin into five interrelated layers, each fulfilling a distinct role in the system's operation. These five layers (physical layer, virtual layer, data layer, service layer, and connection layer) are described in detail in the following sections, and their interconnection is represented in Figure 2.

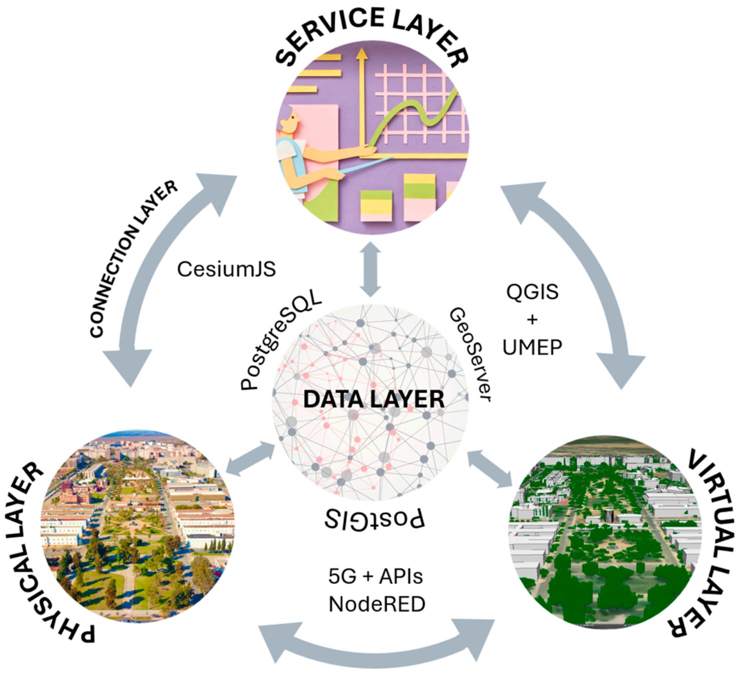


Figure 2. Schematic representation of the urban digital twin layer components.

2.1.1. Data Layer

The data layer collects, stores, and manages all the information datasets required for the operation of the digital twin. Different databases are required due to the varying nature of the data types and sources. A list of data types, sources, and formats used for this DT is presented in Table 1.

Table 1. Data types, sources, and formats.

Parameter	Source	Data Type	Acquisition Method	Frequency	Format
Climate parameters	Weather Stations Bresser 9 in 1	Weather Data	Real-time monitoring	Continuous (every minute)	CSV/JSON
Building footprints	Cadastral information (public)	Spatial Data	Bulk download (manual/API)	Static (periodic updates)	Shapefile
Elevations and land surface classification	Public LiDAR repositories (IGN)	Spatial Data	Bulk download (manual/API)	Static (periodic updates)	LAZ/LAS
Digital Terrain Model	Obtained from LiDAR	Spatial Data	QGIS transformations	Static (periodic updates)	Raster (GeoTiff)
Digital Surface Model	Obtained from LiDAR	Spatial Data	QGIS transformations	Static (periodic updates)	Raster (GeoTiff)
Canopy Digital Surface Model	Obtained from LiDAR	Vegetation Data	QGIS transformations	Static (periodic updates)	Raster (GeoTiff)
Thermal comfort	UMEP processing	Simulation Data	QGIS + UMEP simulations	User selected	Raster (GeoTiff)

The climate data was temporally referenced in Central European Time (UTC+1) with explicit marking of daylight-saving transitions (UTC+2 in summer). The building footprints were provided by the Spanish Cadastral Agency, which complies with the INSPIRE European Directive [46], providing that information as open data in Shapefile format. The LiDAR point cloud data of elevations is part of the Spanish National Plan of Aerial Orthophotography [47] (PNOA, by its Spanish initials) provided by the Instituto Geográfico Nacional (IGN). These data are available in the LAZ format, a compressed version of the LAS file format. The more recent data for Andalucia were collected in 2020, with a vertical accuracy of less than 20 cm and an average point density ranging from 0.5 to 2 points per square meter. The points in the files are automatically classified into their land surface class [48]. The original geodesic reference system of the files was ETRS89.

To achieve the handling of geographical and temporal information, we implement a PostgreSQL database enhanced with the PostGIS spatial extension [49], enabling robust management, analysis, and querying of spatial datasets. On the other hand, to make GIS data available online through web services, Geoserver [50] is used. This open-source server establishes a direct connection with the PostgreSQL/PostGIS database, facilitating the real-time distribution of spatial information through widely adopted standards such as WMS (Web Map Service) and WFS (Web Feature Service). This way, any type of spatial data (raster or vector layers) is available, as Geoserver allows the storage of inputs from different sources and makes them accessible online.

2.1.2. Physical Layer

This layer represents the physical counterpart of the digital twin, encompassing both the real-world urban environment and the network of physical sensors responsible for real-time data acquisition. In this case, aiming to develop an urban digital twin for thermal comfort assessment, the physical layer includes the ground, buildings, and vegetation, with detailed information of materials and geometry, the most influential parameters for thermal comfort assessment. On the other hand, the physical sensors are weather stations that provide real-time meteorological data to perform the analysis. The characteristics of the weather stations used in this study are represented in Table 2. During field campaigns, the weather stations were installed following best practice for microclimate monitoring, selecting buildings on the site to ensure spatial representativity. The exact coordinates (latitude, longitude) of the stations are (37.27434406149676, −6.925154429369391), (37.26893907652284, −6.923644031340186), and (37.267106520144594, −6.9220211487966585). The installation was carried out on the roof of the buildings, separated from it to avoid overheating from roof materials, ensuring that no nearby obstacles altered the sun radiation or wind speed sensors. Images of the stations are shown in Figure

3. A maintenance protocol was followed, consisting of weekly inspections. Sensor performance was verified against records from the nearest official meteorological station operated by AEMET (the Spanish official meteorological agency). Systematic deviations were observed, with slightly higher temperatures and lower wind speeds at the urban sites compared to the reference station, which is consistent with expected urban heat island effects and local roughness influences [51]. These deviations reflect real spatial variability rather than sensor bias.

(**a**) Weather station mounted on the southern building. (**b**) Weather station mounted on the northern building.

Figure 3. Location of the weather stations on the roofs of the buildings.

Table 2. Weather station technical specifications.

Model	**Wi-Fi Standard**	**Wi-Fi Frequency**	**Transmission Interval**
Bresser 9 in 1	802.11 b/g/n	2.4 GHz	12 s
Variable	**Range**	**Accuracy**	**Resolution**
Pressure	540~1100 hPa	(700~1100 hPa ± 5 hPa) (540~696 hPa ± 8 hPa)	1 hPa
Temperature	−20~80 °C	0.1~60 °C ± 0.4 °C −19.9~0 °C ± 0.7 °C −40~−20 °C ± 1 °C	0.1 °C
Relative Humidity	1–100%	1~9% ± 5% 10~90% ± 3.5% 91~99% ± 5% (at 25 °C)	1%
Wind speed	0–50 m/s	<5 m/s: +/−0.8 m/s; >5 m/s: +/−6% (whichever is greater)	0.1 m/s
Rain	0~19,999 mm	± 7% or 1 tip	0.254 mm
Light intensity	0~200 Klux	Not defined	0.01 Klux

2.1.3. Virtual Layer

The digital representation of the urban environment is the virtual layer. To build the urban model, QGIS software [52] is used to process geospatial data. The datasets, including building geometry, land use, vegetation, and terrain, are processed and refined to construct a comprehensive virtual representation of the city. LiDAR data, provided as classified point clouds in .laz format, is transformed into four key raster layers essential for analysis: the Digital Elevation Model (DEM), the Digital Surface Model (DSM), the Canopy Digital Surface Model (CDSM), and the Land Cover classification. Figure 4 summarizes the main QGIS processes used with the input files to obtain the raster files mentioned. In parallel, vector datasets, such as building footprints and elevation attributes, are processed to support the digital twin framework and enable further simulations, as detailed in the next section. Upon completion of these transformations, all resulting layers are uploaded to the spatial databases to ensure structured storage and facilitate future retrieval and analysis.

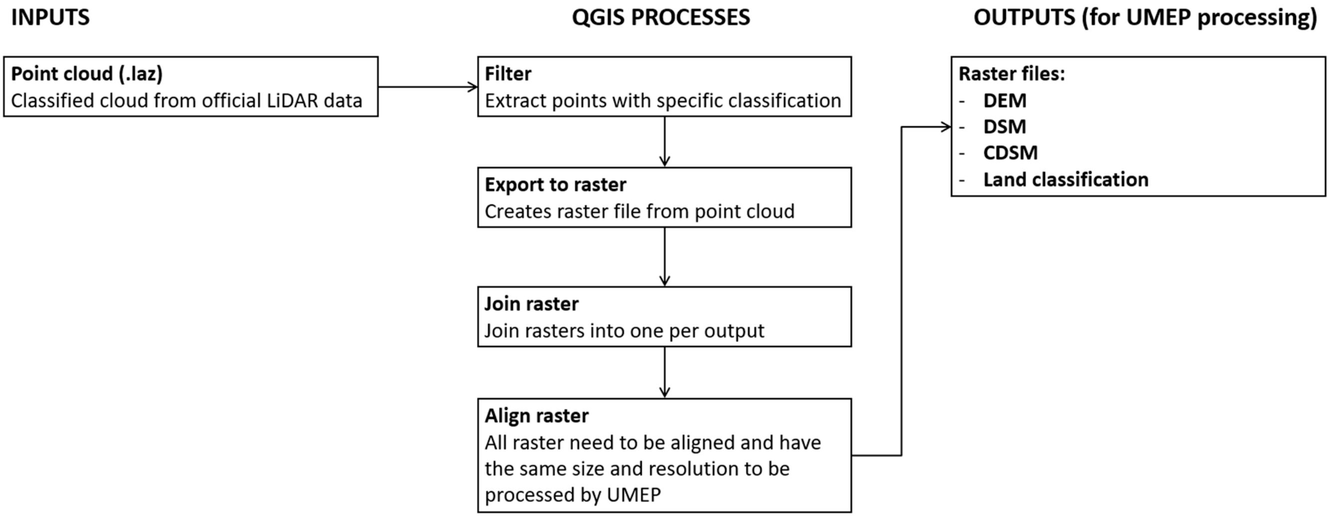


Figure 4. QGIS processing of input data.

2.1.4. Service Layer

The service layer in a digital twin architecture is the component that provides functional capabilities to end users and other systems, enabling interaction with the digital twin's data and models. It acts as the interface between the underlying data/virtual layers and the applications or services built on top of the twin. This layer provides the analytics and simulation models and the visualization and user interface.

- Simulation models.

The simulation component of the service layer is primarily implemented in QGIS, which serves as the central platform for modeling and analyzing the urban environment. Within this framework, the Urban Multi-scale Environmental Predictor (UMEP) plugin [53] is employed to support simulations related to outdoor thermal comfort, urban energy fluxes, and climate change mitigation strategies. UMEP operates directly within QGIS, leveraging spatial datasets to compute a range of environmental parameters. In the context of this digital twin, UMEP is primarily used to simulate and evaluate outdoor thermal comfort conditions.

The core thermal simulations rely on two integrated models: SOLWEIG v2022a [54], which calculates Mean Radiant Temperature (MRT), and URock v2023a [55], which estimates wind speed and direction at the pedestrian level. MRT calculations are based on the previously high-resolution raster data derived from LiDAR (the DEM, DSM, CDSM, and land cover classifications). The SOLWEIG model performs pixel-by-pixel calculations at a 1 m^2 resolution, generating spatially explicit MRT maps of urban open spaces. This model has been previously validated in numerous studies [56,57], justifying the selection for the digital model. The data input and key model parameters used in the UDT are specified in Table 3, separated into the processes needed to perform the analysis (first the Urban Geometry: Sky View Factor process and then the Outdoor Thermal Comfort: SOLWEIG process).

Table 3. UMEP MRT input parameters.

Process: Urban Geometry: Sky View Factor	
Building and Ground DSM	Processed raster file from LIDAR data
Vegetation Canopy DSM	Processed raster file from LIDAR data
Transmissivity of Light Through Vegetation	3%
Vegetation crown base height	25% of the crown top height
Anisotropic sky	True
Process: Outdoor Thermal Comfort: SOLWEIG	
Simulation period	30 May 2025 from 1:00 h to 23:00 h
Time step	1 h
Spatial data	
Building and Ground DSM	Processed raster file from LIDAR data
Vegetation Canopy DSM	Processed raster file from LIDAR data
DEM	Processed raster file from LIDAR data
Transmissivity of Light Through Vegetation	3%
Vegetation crown base height	25% of the crown top height
First day of year with leaves	97
Last day of year with leaves	300
Conifer trees	True
Input land cover classification	Processed raster file from LIDAR data
Anisotropic model	Output from Urban Geometry: Sky View Factor process
Meteorological data	.met file built from weather station data
Environmental parameters	
Albedo (Buildings)	0.35
Albedo (Ground)	From land cover classification (standard values)
Emissivity (Buildings)	0.9
Emissivity (Ground)	From land cover classification (standard values)
Human exposure parameters	
Absorption of shortwave radiation	0.70
Absorption of longwave radiation	0.95
Consider human as cylinder	True
Posture of the human body	Standing

Wind modeling is handled by URock model, which applies the methodology proposed by Röckle [58] to estimate 3D airflow patterns in urban canyons. This tool has been validated in previous studies [55] against other widely validated models such as QUIC-URB [59]. The model integrates 2.5D representations of buildings and vegetation and is implemented using Python libraries in conjunction with the H2GIS spatial database [60]. It requires building footprint and vegetation vector datasets, both derived from the same LiDAR-based processing pipeline used for raster inputs, through the process URock prepare before the main simulation with the process URock; Urban Wind Field. The main data inputs and key parameters for running the URock processes are defined in Table 4.

Table 4. URock input parameters.

Process: URock Prepare	
Building footprints	Vector data from public cadastral information
Building raster DSM	Processed raster file from LIDAR data
DEM	Processed raster file from LIDAR data
Vegetation raster DSM (3D canopy)	Processed raster file from LIDAR data
Tree height/tree crown radius ratio	0.75
Process: Urban Wind Field: URock V2023a	
Building polygons and height field	Vector data from URock prepare outputs
Vegetation polygons and crown top height	Vector data from URock prepare outputs
Vegetation crown base height	25% of the crown top height
Vegetation wind attenuation factor	1.00
Vertical wind profile type	Urban
Height of the reference wind speed (m)	10 m
Wind speed at the reference height (m)	Hourly data from the weather station
Wind direction (° clockwise from North)	Hourly data from the weather station
Horizontal resolution (m)	1 × 1 m
Vertical resolution (m)	2 m
Output wind height (m)	1.5 m

After obtaining the MRT and wind fields, thermal comfort is assessed using the UMEP Outdoor Thermal Comfort processor, which calculates the Universal Thermal Climate Index (UTCI). This post-processing tool synthesizes radiation and wind data to deliver a fine-scale spatial representation of thermal comfort across the modeled urban area. The main parameters used in this study are summarized in Table 5.

Table 5. UTCI calculation parameters.

Process: Outdoor Thermal Comfort: Spatial Thermal Comfort	
Mean Radiant Temperature	Output from Outdoor Thermal Comfort: SOLWEIG
Wind speed and direction	Output from Urban Wind Field: URock V2023a
Thermal comfort parameter	UTCI
Age	35 years
Activity	80 W
Clothing	0.9 clo
Weight	75 kg
Height	180 cm
Sex	Male

- User interface.

Accessibility of users to the UDT is provided through a web-based application. All spatial data, simulation outputs, and processed layers are stored in the PostgreSQL/PostGIS database and published online via GeoServer as previously described. Then, to provide an intuitive and immersive experience, the front-end of the platform incorporates a 3D interactive visualization built using the CesiumJS library [35], an open-source JavaScript framework for rendering high-performance 3D globes and maps in a web browser. This interface allows users, including planners, researchers, and the general public, to explore the digital twin environment directly in their browser, with the ability to navigate, inspect, and interact with the city model. The 3D representation integrates building geometries, terrain models, vegetation layers, and simulation results, enabling a more comprehensive understanding of spatial and environmental dynamics.

By leveraging web standards and open-source technologies, this setup ensures cross-platform accessibility, real-time data querying, and the potential for future extensions such as user feedback collection, scenario testing, or participatory planning modules.

2.1.5. Connection Layer

The connection layer provides the infrastructure that enables seamless communication and data flow across all components of the digital twin, linking the physical, data, virtual, and service layers. It ensures the integration and synchronization of real-time and static data sources, supporting the coherence and responsiveness of the entire system.

A key element in this layer is the real-time connection between environmental sensors and the PostGIS database. Sensor data is transmitted via Wi-Fi and processed using Node-RED [61], a flow-based development environment that formats and uploads the data in real time. Node-RED functions as a middleware, automating the acquisition and structuring of incoming data streams before storing them in the geospatial database.

The virtual layer, built in QGIS, maintains a live connection with the PostGIS database, allowing for the continuous updating and transformation of spatial layers as new data becomes available. These updated layers are subsequently published through GeoServer, which acts as the central dissemination hub, delivering both raster and vector datasets via standard OGC web services such as WMS and WFS.

On the front end, the Cesium-based web interface interacts with GeoServer to provide real-time 3D visualization of the digital twin. Users can access and explore both static representations and dynamic simulation outputs. Furthermore, the connection layer anticipates future functionalities in which users will be able to initiate simulations directly from the web viewer. This planned feature would allow server-side execution of Python-based scripts within QGIS via user-generated requests, enabling on-demand environmental analyses and significantly enhancing the interactivity of the digital twin.

2.2. Case Study Description and Scenarios

The architecture of the DT described, aiming to assess thermal comfort in urban environments, is tested in a case study located in the city of Huelva. The city is located on the southwest coast of Spain and has a Csa climate according to the Koppen classification [62], meaning mild winters and hot and dry summers. The El Carmen university campus was selected as it involves a medium-sized sector of the city, including 28 buildings (academic buildings, student residences, and cafeterias) distributed in a surface area of approximately 375,000 m^2, with not only varied vegetated open spaces that are frequently used by students but also many parking lots. Figure 5 shows an aerial view of the study area.

Figure 5. An aerial view of El Carmen campus and the location of the weather stations.

This university campus opened in 1994, with a maximum building age of 30 years, many modern buildings, and some areas that are still under development. This means an opportunity to test the possibilities of the proposed DT. The mean height of the buildings is 10 m (3 floors), the percentage of area occupied by buildings is 16%, and 17% of the area is covered by low to medium-sized vegetation.

2.3. Performance Parameters

The objective of this study is to describe the design and application of a UDT specialized in assessing outdoor thermal comfort. To this end, the model construction and the operation will be described. In addition, in order to describe thermal comfort analyses that can be performed with the DT, a specific day, 30 May 2025, was selected. This day was selected as it was one of the hottest days of the academic course 2024/25, reaching up to 36 °C air temperature and a minimum of 21 °C. The day was completely clear, and the relative humidity oscillated between 20 and 55%. The wind speed was low, reaching only 10 km/h in the evening hours. The monitored climatic variables used in the model are described in Figure 6.

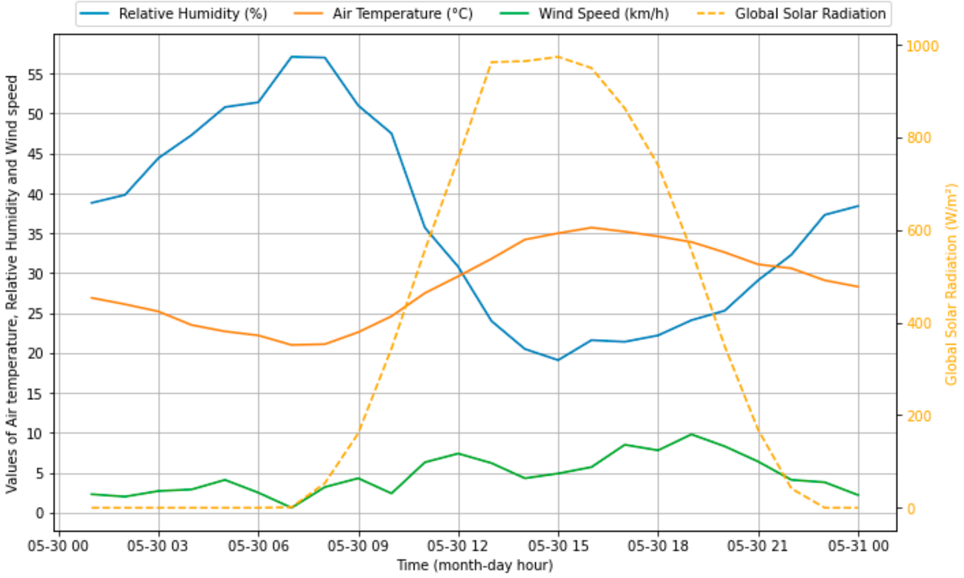


Figure 6. Monitored climatic variables used in the simulations.

The specific performance parameter used in this study to assess outdoor thermal comfort is the Universal Thermal Climate Index (UTCI). This index was selected due to its wide acceptance in the literature and its strong physiological foundation, which models the human body's dynamic response to environmental conditions [63,64]. UTCI integrates air temperature, wind speed, humidity, and mean radiant temperature into a single equivalent temperature value that reflects how conditions are actually perceived. Its universality makes it suitable for application across different climates and urban contexts, and its sensitivity to both heat and cold stress allows for consistent comparisons in diverse settings [65]. Recent reviews have confirmed UTCI's reliability and growing use in both climate-responsive urban design and health-oriented studies [66]. How the model calculates and represents these results has been described in the previous Section 2.1.4.

2.4. Hardware and Software Specifications

In this section, to ensure reproducibility of the digital twin prototype and associated analyses, we provide a detailed description of the hardware, software, and computational environment used. The system was run on a Windows 11 machine with 64 GB DDR5 RAM, an Intel Core Ultra 9 285K CPU, an NVIDIA RTX 4070 Ti GPU (16 GB), and 2 TB NVMe storage. Software components include QGIS 3.40 LTR, UMEP for Processing 2.1.7, SOLWEIG v2022a, URock v2023a, PostGIS 3.5.3, GeoServer 2.26.1, and Node-RED 4.0.

The Python environment for reproducible workflows includes key dependencies such as Python 3.9, Spyder, NumPy, Pandas, SciPy, Matplotlib, Seaborn, StatsModels, GeoPandas, Rasterio, Rasterstats, Fiona, Shapely, GDAL, PyThermalComfort, Requests, and Boto3. QGIS-specific libraries are provided with the QGIS installation.

3. Results

This section presents the model construction and UDT operation. It focuses on the results of the analysis of thermal comfort that it can perform.

3.1. Model Construction

Public official data was used for modeling the case study virtual layer. From the LIDAR files in .laz format, the data was processed using a Python script and QGIS tools to obtain the DEM, DSM, and CDSM raster layers (Figure 7A), and the point classification was used to produce the Land Classification raster layer (Figure 7B). With this information, the Sky View Factor (SVF) was computed, as one of the main parameters used for thermal comfort calculations (Figure 7C).

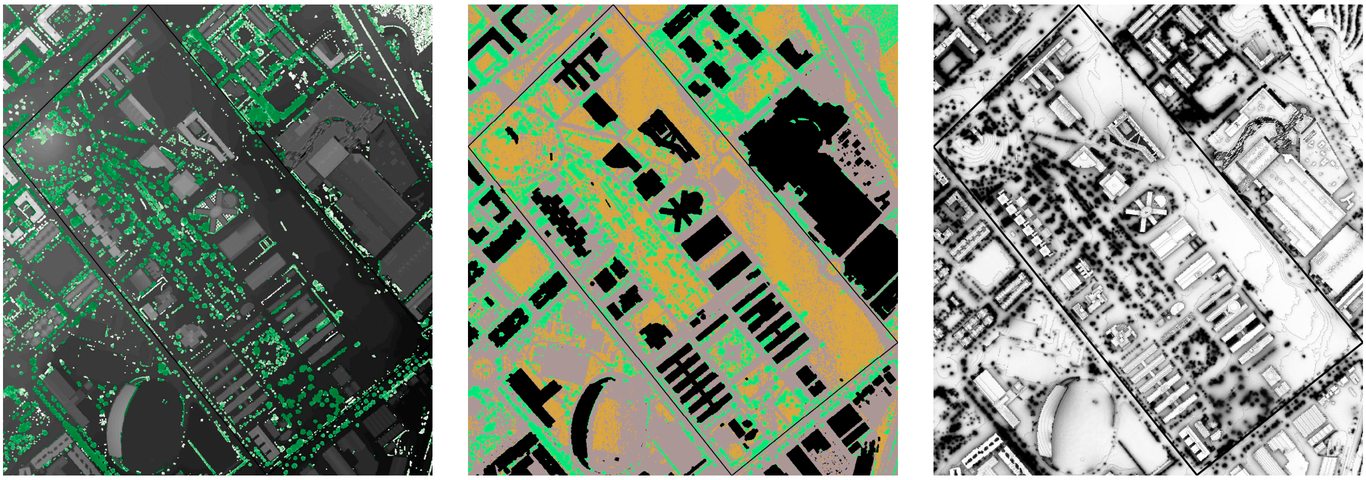

(**A**) DSM and CDSM (**B**) Land Classification (**C**) SVF

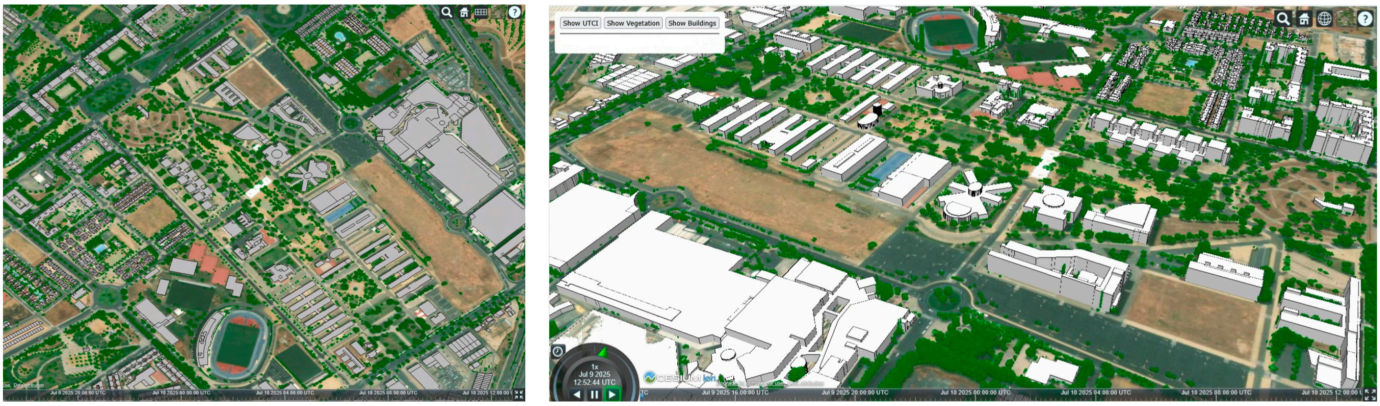
Figure 7. Digital model layers used to build the UDT and perform the simulations.

These raster files were produced at a 1 × 1 m resolution, providing high spatial definition. However, the identification of vegetation canopy and land features is based on the metadata from public LIDAR files, which allows for fast file generation but may introduce some inaccuracies that require manual correction if necessary. The classification was performed automatically according to the ASPRS standard, assigning classes such as ground, low vegetation, high vegetation, and buildings, without any manual post-editing [48]. A Python code has been included that allows the modification of the raster files to not only include other options in the simulations but also correct the inaccuracies detected.

3.2. Model Operation and Visualization

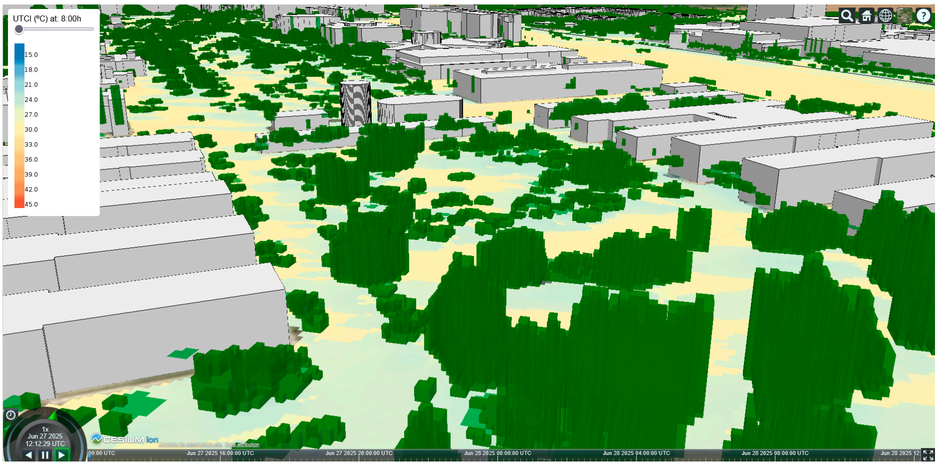
The previously generated layers are further processed using UMEP algorithms to extract vector data representing building footprints and heights. These are then exported as GeoJSON files, which proved to deliver the most accurate and efficient rendering results within Cesium. Based on this data, the 3D model is constructed using HTML and integrated into a web-based interface for interactive visualization and user interaction. This method allows for the construction of the model with a LoD1 according to CityGML standard [67], meaning that the model is limited to a definition of building heights with flat roofs.

The web-based interface provides 2D or 3D views of the model (Figure 8). A side panel allows the user to manage the visualization of different layers and comfort results at different times of the day. Figure 9 shows examples of the 3D view in three areas of the campus, showing UTCI results at different times of the day.

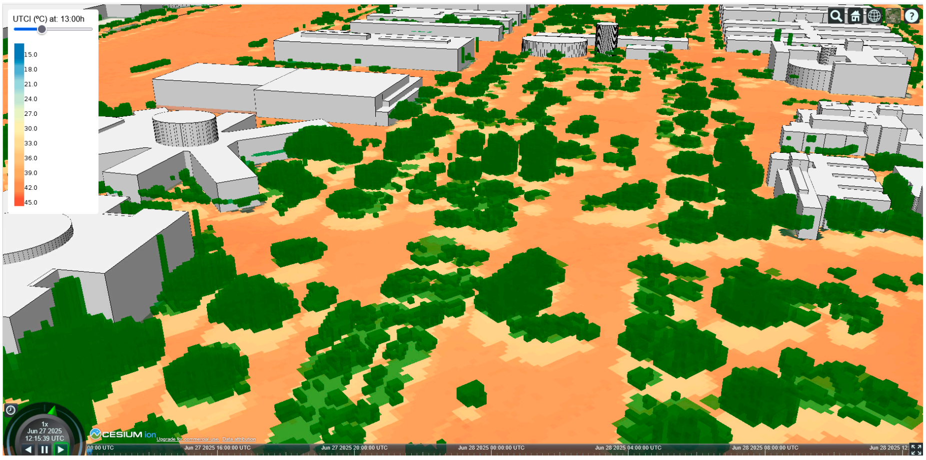


(**a**) 2D view of the model. (**b**) 3D view of the model.

Figure 8. (**a**) 2D and (**b**) 3D views of the UDT model.



(**a**) UDT showing the UTCI results in the southern area of the campus at 8 h on 30 May 2025.



(**b**) UDT showing the UTCI results in the middle area of the campus at 13 h on 30 May 2025.

(**c**) UDT showing the UTCI results in the northern area of the campus at 18 h on 30 May 2025.

Figure 9. Images of the web-based interface of the Digital Twin.

3.3. Thermal Comfort Analysis Applications

The Digital Twin allows for the assessment of the thermal comfort on the El Carmen campus, through the analysis of the different parameters that influence the UTCI. The air temperature and relative humidity are monitored and updated in real time in the model. The data from the selected day are included in the input for the UTCI simulation. Then, the mean radiant temperature and wind speed are also computed. Figure 10 shows the wind speed computed using the mean wind speed and directions recorded on 30 May. Wind speed remains low, with a mean value of 0.4 m/s and a standard deviation of 0.3 m/s. Areas around buildings are those with the highest values. Figure 11 shows the average MRT results per time frame of the day, and the maximum of the day. MRT reached up to 75.5 °C in completely sunny areas. In contrast, shaded areas only reached 35.6 °C. This close to 40 °C difference emphasizes the benefits of vegetation or other shading infrastructures in ensuring thermal comfort in outdoor spaces, especially when wind speed is low and relative humidity remains at medium values, as in this case.

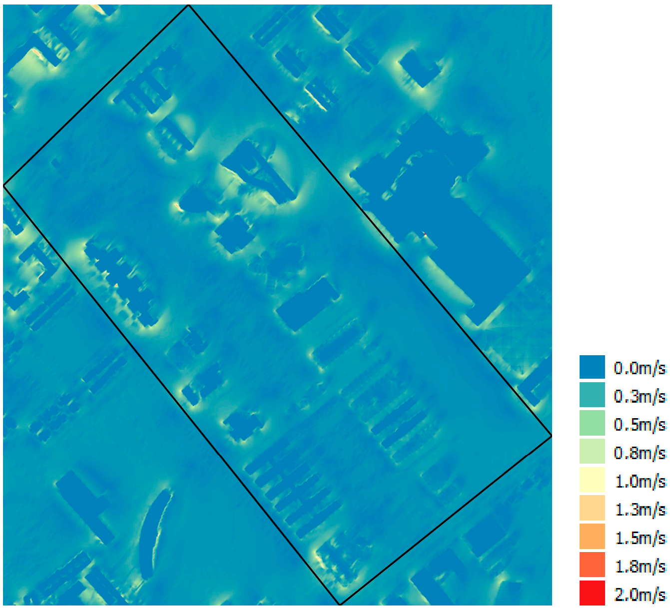


Figure 10. Wind speed in the case study on 30 May. Meteorological input data: Wind speed = 6.5 km/h, Wind direction = 40° from North (clockwise).

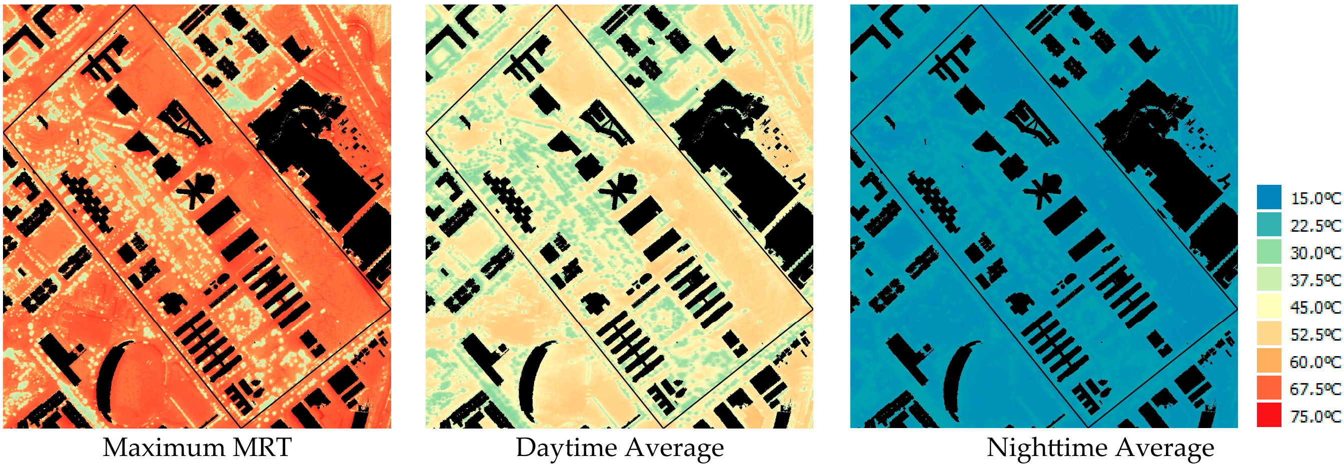
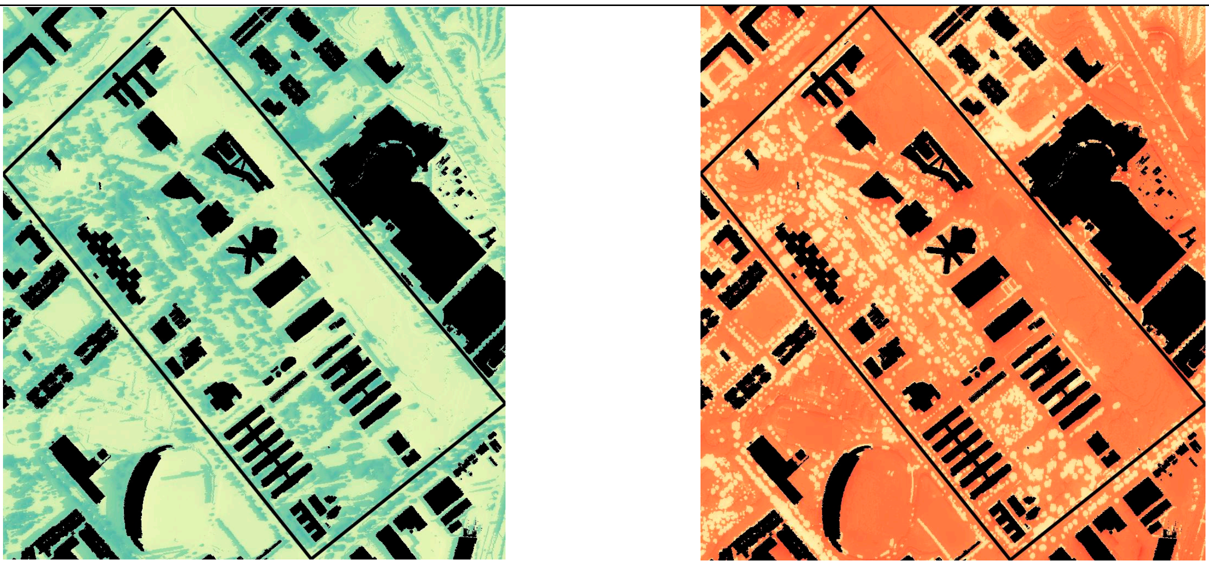


Figure 11. Mean Radiant temperature results on the campus on the 30 May 2025.

The previously described data is used to compute the UTCI. Figure 12 shows the results at four hours of the selected day, in addition to some statistical data (minimum, maximum, mean values, and standard deviation), and the climate input data from the weather station as a reference (note that the wind and solar radiation are spatially computed by the previous MRT process). Minimum UTCI values reached 23.0 °C at 8:00 h, while the maximum values reached 43.0 °C at 13:00 h. Despite the huge differences in MRT between sunny areas and shaded ones, the UTCI value differences are lower, up to 10 °C. However, there is still a great difference that influences thermal comfort significantly. During the night, the UTCI values are less variable in the area.

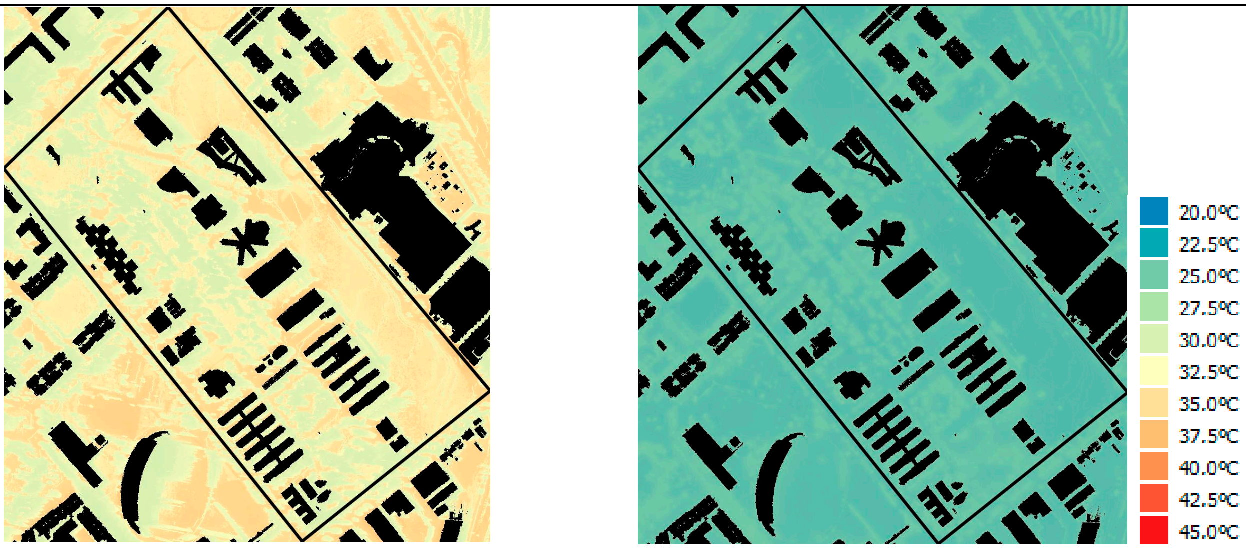
min	max	mean	std	min	max	mean	std
23.0	31.6	28.2	2.5	33.3	43.0	39.4	2.3



Ta = 21.4 °C, RH = 57%, WS = 3.2 km/h, SR = 53 W/m²
8:00 h

Ta = 31.8 °C, RH = 24%, WS = 6.2 km/h, SR = 962 W/m²
13:00 h

min	max	mean	std	min	max	mean	std
30.0	36.8	32.7	1.8	23.8	25.1	24.4	0.3



Ta = 34.6 °C, RH = 22%, WS = 7.8 km/h, SR = 739 W/m²
18:00 h

Ta = 29.1 °C, RH = 37%, WS = 3.8 km/h, SR = 0 W/m²
23:00 h

Figure 12. UTCI results on the campus on the 30 May 2025 at different hours.

Figure 13 shows the distribution of UTCI values throughout the day, clearly highlighting the contrast between shaded and sunlit areas. The most frequent UTCI values in each condition are significantly distinct, with shaded zones consistently exhibiting lower thermal stress. At night, due to the absence of solar radiation, UTCI values converge around 24 °C, showing minimal variation across the area. The highest thermal stress occurs at 13:00, when UTCI values reach up to 40 °C in sun-exposed areas, while shaded areas remain closer to 35 °C. By 18:00, the bimodal distribution peaks around 31 °C in shaded zones and 35 °C in sunlit ones, both occurring with similar frequency. In the early morning (08:00), the shaded areas peak around 26 °C, whereas sunny areas reach approximately 31 °C, again with comparable distributions. These patterns underscore the critical role of shade in mitigating heat stress and maintaining more favorable thermal comfort conditions throughout the day.

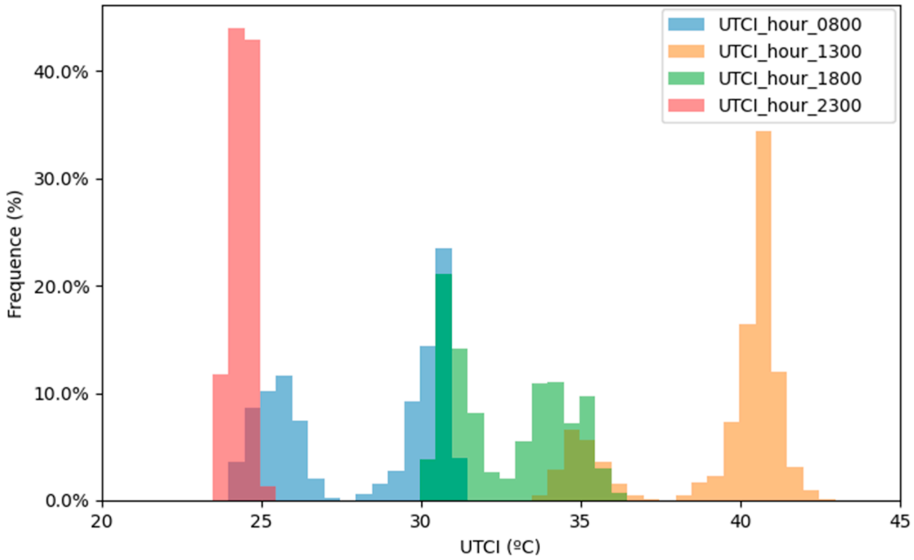


Figure 13. Histograms of the distribution of UTCI values at different hours.

4. Discussion

This study develops a modular, open-source prototype of UDT implemented in the city of Huelva for the analysis of outdoor thermal comfort. The case study provides a concrete example of how emerging tools can be adapted to support microclimate-sensitive urban planning, while also revealing critical challenges still present in this field.

First, the modeling of the urban environment relied entirely on public data sources such as cadastral footprints and LiDAR point clouds. This reflects the approach observed in many reviewed projects, like Matera [26,27], Enschede [24] or Zurich DTs [9], among others, where open-access datasets allow for rapid prototyping but constrain the level of geometric and semantic detail. The resulting model achieves a basic LoD1 representation, sufficient for simplified simulations, but inadequate for capturing finer urban features like material properties, stepped roofs, or dynamic shading. This limitation, shared by many UDTs, affects the accuracy and applicability of simulation results in real design scenarios, emphasizing the widespread concern in the literature about the need for more efficient and accurate urban modeling [30]. In addition, relying on publicly available data, while an advantage of accessibility, also limits the definition of the model, being dependent on public updates of the datasets and their quality. Many existing DTs combine public data with field campaign data to improve the definition of their models [18,46]. The option of modifying the model online would allow for the introduction of private data, aiming for both model definition and future scenario prediction.

Second, the integration of real-time data was partially achieved through a set of weather stations connected to a PostGIS database. This enables continuous updates of key meteorological variables, improving the temporal resolution of the model. However, as noted by other authors [68], the spatial representativeness of this data remains a challenge, particularly in heterogeneous urban environments. Using machine learning algorithms to downscale climate parameters would allow for faster and more precise DTs if combined with real-time monitoring at some points. However, most current UDTs still lack robust real-time environmental data feeds, limiting their ability to respond dynamically to changing conditions. As an example, the DTs of the Docklands area in Dublin [15], Tokyo in Japan [29], or Kalasatama in Helsinki [18] lack real-time data integration. The literature found that this is an increasingly interesting research topic, in which different techniques are being used to improve the spatial resolution of weather data [23].

Third, the simulation tools used (SOLWEIG for radiant temperature and URock for wind fields) enabled high-resolution, spatially explicit comfort assessments using physical principles. Yet, these physics-based models are computationally intensive, making them unsuitable for rapid scenario testing. This reproduces a common limitation in the reviewed literature: the tension between accuracy and responsiveness [33]. This trade-off is consistently acknowledged in the reviewed studies, which point to the pressing need for strategies that optimize simulation performance without compromising accuracy. Data-driven surrogate models are emerging as a solution, although it should be noted that their transferability remains an open challenge, as their performance often degrades outside the training domain. While not addressed in this study, future research in urban digital twins will need to consider strategies for improving cross-site generalization.

Finally, the user interface built with Cesium offers a 3D visualization of the digital model and simulation outputs. While intuitive and visually effective, the interface is currently limited to predefined outputs and lacks interactive simulation capabilities. This reflects a broader trend in the literature: most UDTs are designed primarily for experts and planners (the DTs of Hangzhou in China [11], Imola in Italy [16,17], or the project Cooling Singapore [14] are some examples), with a few examples enabling participatory exploration or user-initiated analyses [9]. In this case, the full capability of the DT is only accessible through QGIS, an expert tool. The literature calls for more user-centric approaches that enable intuitive interaction, real-time feedback, and participatory use, capabilities that are still largely missing from existing platforms [20]. As such, while the case study makes progress in implementing an open and modular framework, it also illustrates the gap between current prototypes and the full vision of a responsive, interactive, and autonomous digital twin.

This study contributes to the emerging field of urban digital twins in two main ways. First, it demonstrates that a working prototype of UDT for outdoor thermal comfort assessment can be implemented exclusively with open-source software and open data, enhancing transparency, accessibility, and transferability to medium-sized cities that often lack proprietary resources, unlike large-scale projects such as Cooling Singapore [14], which rely on proprietary platforms. Second, it advances beyond previous digital twin applications for comfort analysis, such as Padua DT [46] or Busan [28], which relied on simplified indices or surrogate models, respectively. By integrating physics-based microclimate simulations at high spatial resolution, the proposed framework delivers a more robust and process-oriented understanding of outdoor thermal comfort dynamics, thereby supporting climate-sensitive urban planning.

The proposed prototype, as a proof of concept, presents several limitations. Its results have not been formally validated, which hinders the applicability of the prototype. Future work will focus on systematic validation using in situ measurements of MRT, wind speed, and UTCI across different microclimatic conditions on the campus. This will allow the computation of error metrics and a deeper analysis of uncertainties, thereby strengthening the applicability of the proposed framework. Another aspect to consider is the reliance on publicly available geospatial data, which constrains replication in cities with limited data access. The system has an architecture ready to implement all DT capabilities, although it still functions more like a digital shadow. Simulations are computationally demanding, limiting scalability and constraining the potential for seamless web-based operation. Broader challenges, such as data privacy, long-term maintenance, and stakeholder engagement, were beyond the scope of this study but remain critical for future deployment. Finally, an important limitation is the absence of empirical performance benchmarks (latency, cache efficiency, or scalability), since the system, as a prototype, has not yet been deployed in a production environment. Future work will include load-testing and user trials to generate a full performance profile and assess operational robustness.

Despite these limitations, the prototype addresses important research gaps. It demonstrates a functional and reproducible workflow for building an operational UDT using only open-source tools and public data for OTC management. It also establishes a layered architecture that enables modular expansion, whether by incorporating new data sources, upgrading simulation engines, or introducing participatory mechanisms. Beyond the evaluation of outdoor thermal comfort at the microclimate scale, the proposed UDT framework is aimed at informing material-related and vegetation planning decisions in urban planning and design. The thermo-physical properties of pavements (albedo, emissivity, and thermal conductivity) directly influence surface temperatures, radiative exchange, and therefore mean radiant temperature and UTCI values. Moreover, the soil/ground heat flux determines the capacity of urban surfaces to store and release heat, shaping diurnal comfort patterns and the severity of heat stress during heat waves. By explicitly mapping and simulating these effects, this UDT's outputs can support practitioners in the selection of pavement materials, the design of vegetation, and the assessment of the performance of different heat mitigation strategies under extreme climatic events. This highlights the potential of the framework not only as a monitoring and visualization tool but also as a decision-support system for sustainable material and infrastructure strategies in cities facing climate change.

5. Conclusions and Future Research

This study presents and tests a prototype urban digital twin for analyzing outdoor thermal comfort on the El Carmen campus (Huelva, Spain). In the context of rising urban temperatures, the tool illustrates how climate-sensitive planning can support citizens' well-being.

The main contribution of this study lies in demonstrating that a complete workflow, integrating open data, real-time monitoring, physics-based simulations, and 3D visualization, can be implemented entirely with open-source solutions. The architecture demonstrates how modular open-source components can be combined into a coherent workflow: QGIS and PostGIS for data integration, environmental models (UMEP, SOLWEIG and URock) for physics-based simulations, and Cesium for interactive 3D web visualization. This modular design reinforces transparency and replicability, enabling other cities to adapt the approach with minimal proprietary barriers. To our knowledge, this is the first urban digital twin fully dedicated to urban thermal comfort, using physics-based simulations to analyze the influence of environmental parameters such as material properties or vegetation distribution on thermal conditions. Applied to the El Carmen campus, the model identified OTC challenges: shaded versus unshaded areas displayed up to an 8 °C difference in UTCI at peak hours. The results emphasize the need for mitigation strategies focused on providing shade, preferably by vegetation, although other strategies could be investigated.

Nevertheless, the current prototype remains at an early stage, with limitations related to output validation, computational efficiency, modeling accuracy, and user interface interactions. These challenges reflect broader barriers identified in the literature on digital twins for urban climate adaptation. Despite this, the model contributes to bridging research and practice and provides a foundation for more responsive, participatory, and climate-aware urban planning tools.

Future work will focus on three main directions: (1) accelerating simulation workflows by integrating AI-based models for thermal prediction; (2) enhancing the spatial detail and realism of the model through drone-based imagery and automated urban feature extraction; and (3) enabling full bidirectional interaction between the web interface and the simulation engine, allowing users to initiate comfort analyses and scenario testing online. These steps will consolidate the role of digital twins as climate-adaptation tools in urban planning.

Author Contributions: Conceptualization, V.P.L.-C. and S.G.-M.; methodology, V.P.L.-C.; software, V.P.L.-C.; validation, V.P.L.-C. and M.V.-R.; formal analysis, V.P.L.-C.; investigation, V.P.L.-C.; resources, S.G.-M.; data curation, V.P.L.-C. and M.V.-R.; writing—original draft preparation, V.P.L.-C. and M.V.-R.; writing—review and editing, V.P.L.-C.; visualization, V.P.L.-C.; supervision, S.G.-M.; project administration, S.G.-M.; funding acquisition, S.G.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been supported by the project AVADTUS (PID2023-146213OA-I00) funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe", and by the National Government of Spain, Ministerio de Ciencia, Innovación y Universidades through a Juan de la Cierva Postdoctoral Fellowship granted to V.P. L.-C. (JDC2023-050880-I).

Data Availability Statement: The official public data was derived from the public domain source described in each case in the paper. Further inquiries can be directed to the corresponding author.

Acknowledgments: During the preparation of this manuscript/study, the authors acknowledge the use of OpenAI's ChatGPT-5 to assist in the drafting and editing of portions of this manuscript, particularly for improving language clarity and structure. All ideas, data interpretation, and critical analysis are the author's own. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

UHI	Urban Heat Island
DT	Digital Twin
UDT	Urban Digital Twin
OTC	Outdoor Thermal Comfort
DEM	Digital Elevation Model
DSM	Digital Surface Model
CDSM	Canopy Digital Surface Model
UMEP	Urban Multi-scale Environmental Predictor (QGIS plugin)
LoD	Level of Detail (CityGML standard)
MRT	Mean Radiant Temperature
UTCI	Universal Thermal Climate Index
STD	Standard deviation
SVF	Sky View Factor
WMS	Web Map Service
WFS	Web Feature Service
Ta	Air temperature
RH	Relative Humidity
WS	Wind Speed
SR	Solar Radiation

Appendix A

Table A1. Key examples of Urban Digital Twins in the literature.

City/Project	Application/Services	Technology Summary	Limitations
Matera, Italy [26,27]	Mobility, environmental quality	3D CityGML, AI-based virtual camera, DMD simulations via ML, cognitive DSS	Does not directly model thermal comfort indexes
Cooling Singapore [14]	UHI mitigation, outdoor thermal comfort	Unity-based 3D model, mesoscale/microscale climate models, DSS	Advanced DT, but privately available
Padua, Italy [46]	Heat-prone areas, NBS analysis	3D DSM + UAV + Sentinel-2, LORAWAN sensors, PET simulation, web frontend/backend with APIs	Proof of concept; simulation methods could be further enhanced
Imola, Italy [16,17]	Green Pedestrian Network thermal comfort assessment and green planning	GIS + Rhinoceros, DSM + weather data (OpenWeather API), Ladybug Tools	No user interface; designed for researchers and specialized practitioners
Herrenberg, Germany [19]	Urban mobility, wind flow, participative and collaborative planning.	DEM, LIDAR, space syntax models, SUMO, OpenFOAM, VR (CAVEs, HMDs)	No direct modeling of thermal comfort; focus on related variables
Zurich, Switzerland [9]	Urban planning, urban climate, and citizen participation	GIS + CityGML, LIDAR, web and game-based interaction	Simulation methods not specified; future plans include urban climate integration
Docklands area, Dublin, Ireland [15]	Urban and green space planning, crowd and flood simulation.	Unity + FBX + BIM, public DB, crowd/flood sim, web feedback app	Still under development; lacks real-time updates; no thermal comfort simulation
Busan, South Korea [28]	Urban planning and thermal comfort assessment	Unreal Engine + Cesium, Revit (via DataSmith), SunSky sim + deep learning (MoE)	Complete DT with surrogate thermal comfort prediction
Hangzhou, China [11]	Inform landscape planning of waterfront environments	Rhino 3D, UAV + LIDAR + IoT, statistical analysis	Research-oriented; includes citizen data on thermal comfort
Enschede, Netherlands [24]	Urban planning, PET-based thermal comfort	3D GIS, PET simulation using LIDAR + remote data	Limited wind data integration; unclear PET model adaptation to surroundings
Tokyo, Japan [29]	Urban heat and pedestrian exposure	GIS + Rhino/Grasshopper, ArcGIS web UI, path/heat simulation	Limited to transportation and heat stress; lacks real-time data integration
DUET (EU project) [10]	Urban system modeling and integration	T-cell architecture, API-based cloud of models for traffic, air quality, noise	Ongoing project; emphasis on secure data sharing, not specific to thermal comfort
Kalasatama, Helsinki, Iceland [18]	Built environment lifecycle management	CityGML, Ladybug, Ansys Fluent, Unity + Umbra + Cesium	Immersive experience; lacks real-time data integration
Wuppertal City, Germany [69]	UHI mitigation and planning support	LIDAR + GIS, Unreal Engine (via City Engine), LST sim with ML	Prototype with limitations: computational load, data availability, GIS–Unreal interoperability, ML model limits

References

1. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2021.
2. United Nations. SDG Goal 11 Indicators. Available online: https://unstats.un.org/sdgs/report/2023/goal-11/ (accessed on 14 February 2025).
3. Kim, S.W.; Brown, R.D. Urban heat island (UHI) intensity and magnitude estimations: A systematic literature review. *Sci. Total Environ.* **2021**, *779*, 146389. https://doi.org/10.1016/j.scitotenv.2021.146389.
4. Qi, Q.; Tao, F.; Hu, T.; Anwer, N.; Liu, A.; Wei, Y.; Wang, L.; Nee, A.Y.C. Enabling technologies and tools for digital twin. *J. Manuf. Syst.* **2019**, *58*, 3–21. https://doi.org/10.1016/j.jmsy.2019.10.001.
5. Mylonas, G.; Kalogeras, A.; Kalogeras, G.; Anagnostopoulos, C.; Alexakos, C.; Munoz, L. Digital Twins From Smart Manufacturing to Smart Cities: A Survey. *IEEE Access* **2021**, *9*, 143222–143249. https://doi.org/10.1109/ACCESS.2021.3120843.
6. Peldon, D.; Banihashemi, S.; LeNguyen, K.; Derrible, S. Navigating urban complexity: The transformative role of digital twins in smart city development. *Sustain. Cities Soc.* **2024**, *111*, 105583. https://doi.org/10.1016/j.scs.2024.105583.
7. Lopez-Cabeza, V.P.; Videras-Rodriguez, M.; Gomez-Melgar, S.J.; Andujar-Marquez, J.M. The Role of Digital Twins in Enhancing Outdoor Thermal Comfort: A systematic review. In Proceedings of the INCREaSE 2025, Faro, Portugal, 1–4 July 2025.
8. Park, J.; Yang, B. GIS-enabled digital twin system for sustainable evaluation of carbon emissions: A case study of Jeonju city, south Korea. *Sustainability* **2020**, *12*, 9186. https://doi.org/10.3390/su12219186.
9. Schrotter, G.; Hürzeler, C. The Digital Twin of the City of Zurich for Urban Planning. *PFG–J. Photogramm. Remote Sens. Geoinf. Sci.* **2020**, *88*, 99–112. https://doi.org/10.1007/s41064-020-00092-2.
10. Raes, L.; Michiels, P.; Adolphi, T.; Tampere, C.; Dalianis, A.; McAleer, S.; Kogut, P. DUET: A Framework for Building Interoperable and Trusted Digital Twins of Smart Cities. *IEEE Internet Comput.* **2021**, *26*, 43–50. https://doi.org/10.1109/MIC.2021.3060962.
11. Luo, J.; Yuan, Z.; Xu, L.; Xu, W. Assessing the Impact of Waterfront Environments on Public Well-being through Digital Twin Technology. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2025**, *18*, 4536–4553. https://doi.org/10.1109/JSTARS.2025.3530762.
12. Liu, T.; Fan, C. A Digital Twin Framework to Simulate Urban Microclimates, ASCE Inspire. 2023. Available online: https://ascelibrary.org (accessed on 18 February 2025).
13. Ramani, V.; Ignatius, M.; Lim, J.; Biljecki, F.; Miller, C. A Dynamic Urban Digital Twin Integrating Longitudinal Thermal Imagery for Microclimate Studies. In Proceedings of the 10th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation, Istanbul Turkey, 15–16 November 2023; ACM: New York, NY, USA, 2023; pp. 421–428. https://doi.org/10.1145/3600100.3626345.
14. Singapore, C. Available online: https://sec.ethz.ch/research/cs.html (accessed on 1 February 2025).
15. White, G.; Zink, A.; Codecá, L.; Clarke, S. A digital twin smart city for citizen feedback. *Cities* **2021**, *110*, 103064. https://doi.org/10.1016/j.cities.2020.103064.
16. Gholami, M.; Torreggiani, D.; Barbaresi, A.; Tassinari, P. *Smart Green Planning for Urban Environments: The City Digital Twin of Imola*; Springer: Berlin/Heidelberg, Germany, 2024; pp. 133–150. https://doi.org/10.1007/978-3-031-35664-3_10.
17. Gholami, M.; Torreggiani, D.; Tassinari, P.; Barbaresi, A. Developing a 3D City Digital Twin: Enhancing Walkability through a Green Pedestrian Network (GPN) in the City of Imola, Italy. *Land* **2022**, *11*, 1917. https://doi.org/10.3390/land11111917.
18. KIRA-digi. The Kalasatama Digital Twins Project. Available online: https://www.kiradigi.fi/en/experiments/ongoing-projects/kalasatama-digital-twins.html (accessed on 23 February 2025).
19. Dembski, F.; Wössner, U.; Letzgus, M.; Ruddat, M.; Yamu, C. Urban Digital Twins for Smart Cities and Citizens: The Case Study of Herrenberg, Germany. *Sustainability* **2020**, *12*, 2307. https://doi.org/10.3390/su12062307.
20. Maiullari, D.; Nageli, C.; Rudena, A.; Isacson, Å.; Dokter, G.; Ellenbroek, I.; Wallbaum, H.; Thuvander, L. Digital twin for supporting decision-making and stakeholder collaboration in urban decarbonization processes. A participatory development in Gothenburg. *Environ. Plan B Urban Anal. City Sci.* **2024**, 1–25. https://doi.org/10.1177/23998083241286030.
21. Liu, X.; Gou, Z.; Yuan, C. Application of human-centric digital twins: Predicting outdoor thermal comfort distribution in Singapore using multi-source data and machine learning. *Urban Clim.* **2024**, *58*, 102210. https://doi.org/10.1016/j.uclim.2024.102210.
22. Liu, P.; Zhao, T.; Luo, J.; Lei, B.; Frei, M.; Miller, C.; Biljecki, F. Towards Human-centric Digital Twins: Leveraging Computer Vision and Graph Models to Predict Outdoor Comfort. *Sustain. Cities Soc.* **2023**, *93*, 104480. https://doi.org/10.1016/j.scs.2023.104480.
23. Pan, X.; Mavrokapnidis, D.; Ly, H.T.; Mohammadi, N.; Taylor, J.E. Assessing and forecasting collective urban heat exposure with smart city digital twins. *Sci. Rep.* **2024**, *14*, 9653. https://doi.org/10.1038/s41598-024-59228-8.

24. Cárdenas-León, I.; Morales-Ortega, R.; Koeva, M.; Atún, F.; Pfeffer, K. Digital Twin-based Framework for Heat Stress Calculation. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2024**, *X-4-2024*, 67–74. https://doi.org/10.5194/isprs-annals-X-4-2024-67-2024.
25. Ignatius, M.; Lim, J.; Gottkehaskamp, B.; Fujiwara, K.; Miller, C.; Biljecki, F. Digital Twin and Wearables Unveiling Pedestrian Comfort Dynamics and Walkability in Cities. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2024**, *X-4/W5-202*, 195–202. https://doi.org/10.5194/isprs-annals-X-4-W5-2024-195-2024.
26. Castelli, G.; Cesta, A.; Ciampi, M.; De Benedictis, R.; De Pietro, G.; Diez, M.; Felici, G.; Malvezzi, R.; Masini, B.; Pellegrini, R.; et al. Urban Intelligence: Toward the Digital Twin of Matera and Catania. In Proceedings of the 2022 Workshop on Blockchain for Renewables Integration (BLORIN), Palermo, Italy, 2–3 September 2022; IEEE: Piscataway, NJ, USA, 2022; pp. 132–137. https://doi.org/10.1109/BLORIN54731.2022.10028437.
27. Corrado, S.; Scorza, F. Towards Sustainable Urban Development: Matera's Urban Digital Twin and Challenges in Data Integration. In *Lecture Notes in Civil Engineering*; Springer Science and Business Media: Deutschland, Germany, 2024; pp. 230–236. https://doi.org/10.1007/978-3-031-54118-6_22.
28. Lam, H.-K.; Lam, P.-D.; Ok, S.-Y.; Lee, S.-H. Digital Twin Smart City Visualization with MoE-Based Personal Thermal Comfort Analysis. *Sensors* **2025**, *25*, 705. https://doi.org/10.3390/S25030705.
29. Garrett, A.; Ginensky, K.; Wang, X.; Ahmed, H.; Shen, J.; Yoshida, T.; Murayama, A.; Yang, P.P.J. Leveraging a Digital Twin Interface for Multimodal Transportation Resilience, Connectivity, and Equity—A Case Study of Toyosu, Tokyo. *Energy Proc.* **2025**, *51*. https://doi.org/10.46855/ENERGY-PROCEEDINGS-11460.
30. Pađen, I.; Peters, R.; García-Sánchez, C.; Ledoux, H. Automatic high-detailed building reconstruction workflow for urban microscale simulations. *Build. Environ.* **2024**, *265*, 111978. https://doi.org/10.1016/j.buildenv.2024.111978.
31. Kim, Y.; Ham, Y. Spatio-temporal heat risk analysis in construction: Digital twin-enabled monitoring. *Autom. Constr.* **2024**, *168*, 105805. https://doi.org/10.1016/j.autcon.2024.105805.
32. Miller, C.; Abdelrahman, M.; Chong, A.; Biljecki, F.; Quintana, M.; Frei, M.; Chew, M.; Wong, D. The Internet-of-Buildings (IoB)—Digital twin convergence of wearable and IoT data with GIS/BIM. *J. Phys. Conf. Ser.* **2021**, *2042*, 012041. https://doi.org/10.1088/1742-6596/2042/1/012041.
33. Ahn, J.; Kim, J.; Kang, J. Development of an artificial intelligence model for CFD data augmentation and improvement of thermal environment in urban areas using nature-based solutions. *Urban For. Urban Green.* **2024**, *104*, 128629. https://doi.org/10.1016/j.ufug.2024.128629.
34. Wang, H.; Ma, W.; Niu, J.; You, R. Evaluating a deep learning-based surrogate model for predicting wind distribution in urban microclimate design. *Build. Environ.* **2024**, *269*, 112426. https://doi.org/10.1016/j.buildenv.2024.112426.
35. CesiumJS–Cesium. Available online: https://cesium.com/platform/cesiumjs/ (accessed on 20 June 2025).
36. Unity. Available online: https://unity.com/es (accessed on 3 February 2025).
37. Unreal Engine. Available online: https://www.unrealengine.com/es-ES (accessed on 3 February 2025).
38. Gonzalez-Caceres, A.; Hunger, F.; Forssén, J.; Somanath, S.; Mark, A.; Naserentin, V.; Bohlin, J.; Logg, A.; Wästberg, B.; Komisarczyk, D.; et al. Towards digital twinning for multi-domain simulation workflows in urban design: A case study in Gothenburg. *J. Build. Perform. Simul.* **2024**, *18*, 311–332. https://doi.org/10.1080/19401493.2024.2320112.
39. Kolokotsa, D.; Lilli, A.; Tsekeri, E.; Gobakis, K.; Katsiokalis, M.; Mania, A.; Baldacchino, N.; Polychronaki, S.; Buckley, N.; Micallef, D.; et al. The Intersection of the Green and the Smart City: A Data Platform for Health and Well-Being through Nature-Based Solutions. *Smart Cities* **2023**, *7*, 1–32. https://doi.org/10.3390/SMARTCITIES7010001.
40. Arif, Y.M.; Kusumadewi, T.; Karami, A.F.; A'rof, B.G.F.; Wijayanti, L.; Mulyadi, M. A Novel Digital Twin Framework for Adaptive Urban Weather Visualization Using IoT and Fuzzy Logic. *Int. J. Intell. Eng. Syst.* **2024**, *17*, 494–507. https://doi.org/10.22266/ijies2024.1031.39.
41. Elnabawi, M.H.; Raveendran, R. Meta-pragmatic investigation of passive strategies from 'UHI– climatology' nexus perspective with digital twin as assessment mechanism. *J. Urban Manag.* **2024**, *13*, 332–356. https://doi.org/10.1016/j.jum.2024.03.002.
42. Zheng, L.; Lu, W. Urban micro-scale street thermal comfort prediction using a 'graph attention network' model. *Build. Environ.* **2024**, *262*, 111780. https://doi.org/10.1016/j.buildenv.2024.111780.
43. Seleem, O.; Ayzel, G.; Bronstert, A.; Heistermann, M. Transferability of data-driven models to predict urban pluvial flood water depth in Berlin, Germany. *Nat. Hazards Earth Syst. Sci.* **2023**, *23*, 809–822. https://doi.org/10.5194/NHESS-23-809-2023.
44. Prasad, A.; Harder, P.; Yang, Q.; Sattegeri, P.; Szwarcman, D.; Watson, C.; Rolnick, D. Evaluating the Transferability Potential of Deep Learning Models for Climate Downscaling. 2024. Available online: https://arxiv.org/pdf/2407.12517 (accessed on 6 September 2025).

45. Sukma, A.I.; Koeva, M.N.; Reckien, D.; Bockarjova, M.; da Silva Mano, A.; Canili, G.; Vicentini, G.; Kerle, N. 3D City Digital Twin Simulation to Mitigate Heat Risk of Urban Heat Islands. *ISPRS Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2024**, *XLVIII-4/W*, 129–136. https://doi.org/10.5194/isprs-archives-XLVIII-4-W11-2024-129-2024.
46. Spanish Ministry, CARTOGRAFÍA CATASTRAL-INSPIRE. Available online: http://www.catastro.minhap.gob.es/webinspire/index.html (accessed on 7 July 2022).
47. MITMA, Plan Nacional de Ortografía Aérea (PNOA). Available online: https://pnoa.ign.es/web/portal/pnoa-imagen/visualizadores-y-servicios-web (accessed on 4 July 2023).
48. Procesamiento de los datos-Plan Nacional de Ortofotografía Aérea. Available online: https://pnoa.ign.es/pnoa-lidar/procesamiento-de-los-datos (accessed on 7 July 2025).
49. PostGIS. Available online: https://postgis.net/ (accessed on 30 May 2025).
50. GeoServer. Available online: https://geoserver.org/ (accessed on 30 May 2025).
51. García, D.H. Analysis of Urban Heat Island and Heat Waves Using Sentinel-3 Images: A Study of Andalusian Cities in Spain. *Earth Syst. Environ.* **2021**, *6*, 199–219. https://doi.org/10.1007/S41748-021-00268-9.
52. Open Source Geospatial Foundation (OSGeo), QGIS. Available online: https://www.qgis.org/en/site/ (accessed on 1 July 2022).
53. Lindberg, F.; Grimmond, C.S.B.; Gabey, A.; Huang, B.; Kent, C.W.; Sun, T.; Theeuwes, N.E.; Järvi, L.; Ward, H.C.; Capel-Timms, I.; et al. Urban Multi-scale Environmental Predictor (UMEP): An integrated tool for city-based climate services. *Environ. Model. Softw.* **2018**, *99*, 70–87. https://doi.org/10.1016/J.ENVSOFT.2017.09.020.
54. Lindberg, F.; Holmer, B.; Thorsson, S. SOLWEIG 1.0–Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. *Int. J. Biometeorol.* **2008**, *52*, 697–713. https://doi.org/10.1007/s00484-008-0162-7.
55. Bernard, J.; Lindberg, F.; Oswald, S. URock 2023a: An open-source GIS-based wind model for complex urban settings. *Geosci. Model Dev.* **2023**, *16*, 5703–5727. https://doi.org/10.5194/gmd-16-5703-2023.
56. Lindberg, F.; Grimmond, C.S.B. The influence of vegetation and building morphology on shadow patterns and mean radiant temperatures in urban areas: Model development and evaluation. *Theor. Appl. Climatol.* **2011**, *105*, 311–323. https://doi.org/10.1007/S00704-010-0382-8.
57. Colaninno, N.; Salvati, A.; Lopez, J.; Morganti, M. District-Scale Cumulative Heat Stress Mapping Using Very-High-Resolution Spatiotemporal Simulation. *Sustain. Cities Soc.* **2025**, *130*, 106498. https://doi.org/10.1016/J.SCS.2025.106498.
58. Rockle, R. *Bestimmung der Stomungsverhaltnisse im Bereich Komplexer Bebauungsstrukturen*; Technischen Hochschule Darmstadt: Darmstadt, Germany, 1990.
59. Girard, P.; Nadeau, D.F.; Pardyjak, E.R.; Overby, M.; Willemsen, P.; Stoll, R.; Bailey, B.N.; Parlange, M.B. Evaluation of the QUIC-URB wind solver and QESRadiant radiation-transfer model using a dense array of urban meteorological observations. *Urban Clim.* **2018**, *24*, 657–674. https://doi.org/10.1016/J.UCLIM.2017.08.006.
60. GitHub-orbisgis/h2gis: A Spatial Extension of the H2 Database. Available online: https://github.com/orbisgis/h2gis#readme (accessed on 26 May 2025).
61. OpenJS Foundation & Contributors, Node-RED. Available online: https://nodered.org (accessed on 20 June 2025).
62. Beck, H.E.; Zimmermann, N.E.; McVicar, T.R.; Vergopolan, N.; Berg, A.; Wood, E.F. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci. Data* **2018**, *5*, 180214. https://doi.org/10.1038/sdata.2018.214.
63. McGregor, G.R. Special issue: Universal Thermal Climate Index (UTCI). *Int. J. Biometeorol.* **2012**, *56*, 419–419. https://doi.org/10.1007/s00484-012-0546-6.
64. Fiala, D.; Havenith, G.; Bröde, P.; Kampmann, B.; Jendritzky, G. UTCI-Fiala multi-node model of human heat transfer and temperature regulation. *Int. J. Biometeorol.* **2011**, *56*, 429–441. https://doi.org/10.1007/s00484-011-0424-7.
65. Blazejczyk, K.; Epstein, Y.; Jendritzky, G.; Staiger, H.; Tinz, B. Comparison of UTCI to selected thermal indices. *Int. J. Biometeorol.* **2012**, *56*, 515–535. https://doi.org/10.1007/S00484-011-0453-2.
66. Romaszko, J.; Dragańska, E.; Jalali, R.; Cymes, I.; Glińska-Lewczuk, K. Universal Climate Thermal Index as a prognostic tool in medical science in the context of climate change: A systematic review. *Sci. Total. Environ.* **2022**, *828*, 154492. https://doi.org/10.1016/J.SCITOTENV.2022.154492.
67. CityGML Standard | OGC Publications. Available online: https://www.ogc.org/standards/citygml/ (accessed on 30 May 2025).

68. Chajaei, F.; Bagheri, H. Machine learning framework for high-resolution air temperature downscaling using LiDAR-derived urban morphological features. *Urban Clim.* **2024**, *57*, 102102. https://doi.org/10.1016/j.uclim.2024.102102.
69. Afzalinezhad, A. *Digital Twin-Based Planning Support System for Urban Heat Island Mitigation*; University of Twente: Enschede, The Netherlands, 2024.