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A Digital Twin of a University Campus from an Urban Sustainability Approach: Case Study in Madrid (Spain)

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Abstract: The development of geographic information systems has grown significantly over the past decade. Simultaneously, the concept of smart cities based on the management of large volumes of data has also spread worldwide. The digital twin concept has recently been incorporated into the technological domain of urban management. However, currently, phases such as technological integration, standardization, data and process interconnection, the development of tools and utilities, professional training, and the application of digital urban development in real-world situations are converging. This paper presents the experience developed on a university campus, detailing each of the phases carried out from the initial design to a fully operational pilot phase model. The article highlights the importance of certain aspects to consider in each phase, demonstrating that there are barriers and limitations and at the same time, great strengths and opportunities in applying the digital twin model in urban management, considering aspects such as mobility, accessibility, energy management, and involving students and university administrators in the process.

Keywords: digital twin; geographic information system; sustainability; university campus; living lab; smart city

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1. Introduction

Geographic information systems (GIS) have been transformed over the last decade, expanding their capacity to store information, perform spatial analysis and implement related services [1,2]. At the same time, advances in spatial analysis tools together with the incorporation of 3D models have opened up new fields of study and monitoring, even in dynamic scenarios such as ecosystems [3].

Infrastructure management, together with the incorporation of real-time data has become a current demand, linked to the development of intelligent infrastructure management in areas such as building information modeling (BIM) [4]. BIM provides a highly detailed digital 3D model of a building or infrastructure, which is meant to be useful throughout its entire lifecycle: from design and construction to maintenance. BIM contains both geographic and semantic information; in a sense, it can be thought of as a GIS for an isolated structure.

Recently, the development of digital twins (DTs) has garnered significant attention from the scientific and industrial communities, and it may be the next step linking GIS and BIM technologies [5]. GIS provides the spatial context in which infrastructure will be installed. Virtually placing a building in its actual location enables various types of analysis, such as visibility or shadow (considering trees and neighboring buildings), noise, traffic, and service areas, among others. The potential of combining BIM with GIS lies in the capability to simulate the interaction between the new structure and its environment. This capability can be effectively leveraged in the creation of DTs, especially for simulations.

Another advantage of using GIS in the creation of DTs is its capability to integrate a wide variety of data. GIS enables the incorporation of vector-based spatial information, such as cadastral data, census data, administrative units, road networks, public transport systems, points of interest, and utilities, into a single database. Additionally, it allows for the integration of raster data, such as digital elevation models (DEMs), slope maps, or interpolations of climatic variables (temperature, precipitation, etc.). All this information is crucial to create realistic 3D models of both built and natural environments for DTs.

However, the definition of a digital twin still varies between being considered an object and being considered a technology [6], depending on its application in different fields [7]. Park et al. [8] define a digital twin as a virtual representation of a physical object used to optimize performance using real-time data. In line with this, Lehtola et al. [5] add that a digital twin is a 3D model extended with certain properties, including (1) the lifecycle management of objects; (2) simulations of different scenarios; and (3) incorporation of real-time data from sensors.

There are different types of sensors used to implement these functionalities in a digital twin [5]. Sensors installed across cities to record temperature, ambient noise, traffic intensity, or air quality can transmit their data in real time, but pre-processing is required before the data can be integrated into the digital twin. Additionally, image and LiDAR sensors are used to capture 3D data of both the interior and exterior of buildings and other real-world objects. The identification and vectorization of features in these objects, such as walls, roofs, or tree trunks, are usually performed using artificial intelligence (e.g., [9]) or geometry-based algorithms (e.g., [10]). These analyses are time-consuming, so the data cannot be incorporated immediately to update the 3D model on which a digital twin is based. Therefore, despite the demonstrated utility of these technologies, challenges remain in terms of autonomous data collection and its integration to keep a digital twin up-to-date and operational [5].

The smart city model, in which everything is connected, is advancing in parallel to DTs. However, the goal of a smart city is not merely to automate everything, but rather to serve as a methodological framework for resource management and the optimization of citizens' quality of life [11]. In this context, the digital twin provides a platform to implement the smart city model, whose aim can be to deliver a powerful and realistic 3D representation, and additionally offer information derived from the analysis of geospatial patterns that are imperceptible to the human eye at such a scale.

The possibility of combining different areas of information, e.g., mobility, air quality and carbon footprint per trip, could lead to a better analysis of societal patterns and help public authorities in their decision making. An understanding of these patterns is crucial to the evolution of cities in a more sustainable and intelligent way. Before starting with an area as big as a city like Madrid (Spain), the concept of a smart campus comes to mind as a trial for city management.

A smart campus applies the same concept as a smart city but in a rather smaller area, such as a university campus. University students and workers are a perfect example of a city and its patterns. This type of group, given their large number, can be considered a demonstration group for further analysis which can be applied to urban society as the group contains a wide variety of ages, economic statuses, ethnic backgrounds, genders, concerns and abilities.

The smart campus concept is still at an early stage, where research and reasoning are ongoing [12]. There are examples in countries such as South Korea [13], where nine university buildings with fifty-five classrooms were evaluated in terms of saving light energy. The conclusion was that 60% of the energy consumed could be saved by means of an infrared sensor with a switch-off strategy and the installation of LED lights.

Another study conducted in Italy focused on the incorporation of the Internet of Things with a dynamic strategy applied to university buildings [14]. This could lead to a real-time evaluation of resources from the user's point of view, extending the lifecycle of the building.

Also, in Europe, a digital twin model is being developed in the city of Kaunas (Lithuania) through the Kaunas University of Technology [15]. In this project, one of the key aspects is the analysis of building energy efficiency and heat loss, with the aim of estimating the future response of buildings over the years.

In Spain, a more extensive study has been carried out. The project is called SIGEUZ (Geographic Information System of the spaces of the University of Zaragoza). In this experience, the University of Zaragoza has developed a smart campus concept via the creation of two models for different users (https://smartcampus.unizar.es (accessed on 20 June 2023)). One of the models was used to help students with orientation and location, using 3D photos of the classrooms and basic information. A second model was created with restricted access for university management, where university staff have access to basic information about equipment inventories, security and facilities management.

Although these cases show that progress is being made in the smart campus model, there is still a long way to go.

In this study, we present the digital twin of the Technical University of Madrid (UPM) South Campus. In this first stage, we have focused on the creation of a comprehensive 3D model that serves as a platform for the development of the digital twin. In addition to data specific to university management, we have incorporated other data related to mobility, sustainability and accessibility. The primary functionalities that we have exploited are web visualization and a simulation of photovoltaic energy exploitation. The digital twin model is undergoing continuous improvement and evolution, and is thus intended to accommodate future extensions, such as applications to simulate different scenarios (the location of new facilities, design of new pedestrian paths, bicycle lanes, green areas, etc.), and integrate real-time data (vehicle traffic, energy demand, classroom occupancy, etc.). With respect to other campus digital twins, with the present study we have made the following contributions:

- It is the first digital twin of a university campus open to students in Madrid, a city with almost 30 university campuses.
- As recommended by [16], it not only incorporates university facilities, but also additional information encompassing the entire campus, including mobility (access points, public transport, parking spaces), sustainability (water and energy consumption, green areas), and accessibility (street gradients, elevators).
- We have demonstrated the feasibility of integrating data from a wide variety of sources, including data generated specifically for this project, as well as data from Spanish public institutions and the University Rectorate.
- The development shown is the result of joint research by professors and students, without the involvement of private companies. The design enables the incorporation of further research and future developments.

The following sections of the article present the results of the experience carried out on a university campus with the development of a digital geographic model as a basis for a digital twin. This research is innovative for its development involving students, generating an open-access model, into which new technological developments can be incorporated, expanding the digital twin. In the Spanish university environment, there are previous experiences already mentioned but no open digital developments at this level, which also incorporate elements such as sustainable mobility, air quality and accessibility in alignment with national and European policies.

The Materials and Methods section describes the area of work and the methodology followed to design each of the study areas. It also describes the process of data capture, classification and processing.

In the Results and Findings section, the digital model creation phase is explained, and then, the different analyses carried out are presented by area as examples to support decision making.

The Discussion reviews the barriers and limitations to carrying out the work, and the lines of research to be strengthened. And the Conclusions section highlights the main achievements of the research and the importance of connecting digital development with sustainable transition.

2. Materials and Methods

2.1. Description of Area of Interest

The project is located in the south campus of the Technical University of Madrid (Universidad Politécnica de Madrid, UPM) in the city of Madrid (Spain). It is a university area with a surface of about 30 Ha, composed of faculties, research centers and service facilities (Figure 1). Campus users are students, professors, university staff and other workers, reaching more than 5100 people (4724 students and approximately 400 faculty staff, according to data from the academic year 2020–2021).

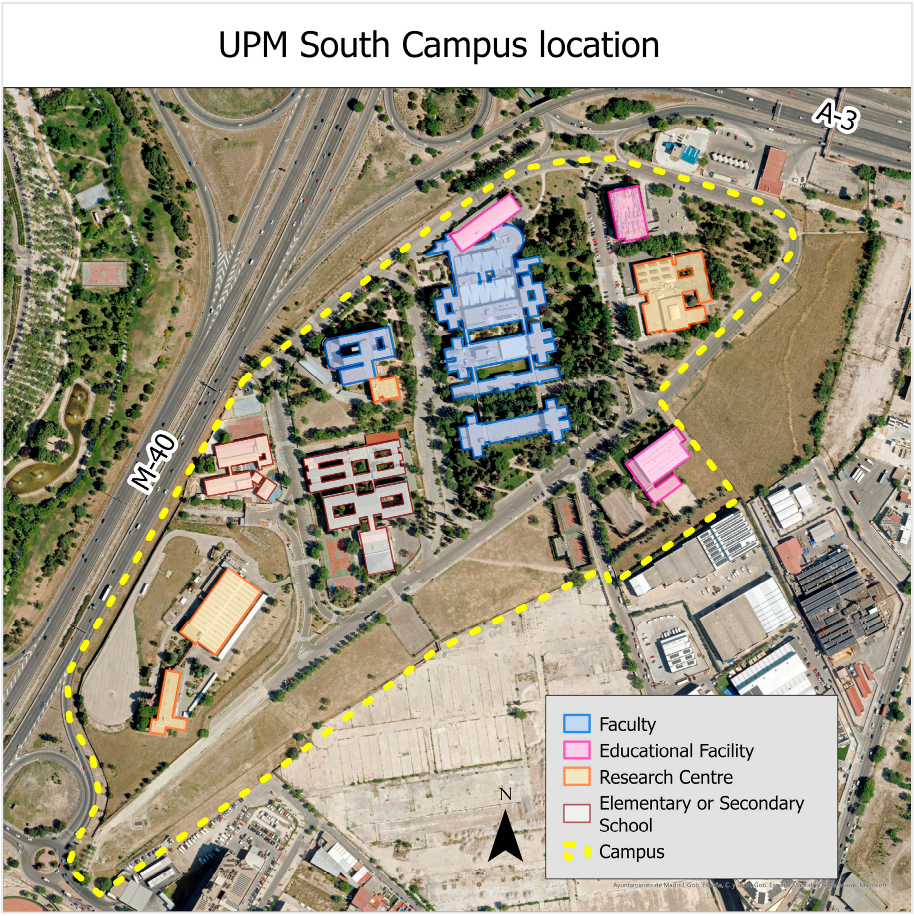

Figure 1. Map of the university campus, classification of buildings and main roads. Source of orthoimage: National Geographic Institute of Spain—free access and distribution.

The university campus is served by public transportation, including a city bus with 5 stops and an intercity bus with 1 stop. Both an underground station and a commuter train station are located within a 10 min walk. All public transportation connects the campus with the city center and its surrounding districts. The campus also has numerous parking spaces for private vehicle access.

On the campus, there is a large number of green areas and trees, as well as pedestrian paths. However, the campus is bordered by two major highways (M-40 and A3). This information is relevant for the analysis of air quality and acoustic impact.

The area, population, buildings and facilities of the UPM South Campus allow for the development of a pilot project to identify and evaluate the barriers and limitations, as well as the strengths and capabilities of the development of a digital twin for an urban area.

2.2. Methodology

Phase 1: Modeling

The approach followed to create the UPM South Campus digital twin is shown in Figure 2. The first step was to create the digital 3D model in a geographic information system, with both geometry and semantics. To achieve this, all available data sources had to be homogenized. They were clipped to the extent of the study area, standardized in terms of formats and data types, and all layers were transformed to the same reference system. WGS84 was chosen for cloud upload compatibility. The numerical data were incorporated into Microsoft Excel and the geographic data into ArcGIS Pro. As the data sources were diverse, the pre-processing steps and the integration strategy were very important to ensure the quality of the data geometry. The geometry of the buildings was created in 3D, whereas the geometry of the roadway, pavements, pedestrian crossings, cycle lanes, waste collection areas, and green spaces was created using 2D polygons, whose elevation was interpolated from a 3D digital elevation model (DEM). Trees, bus stops and underground and train stations were represented as point features.

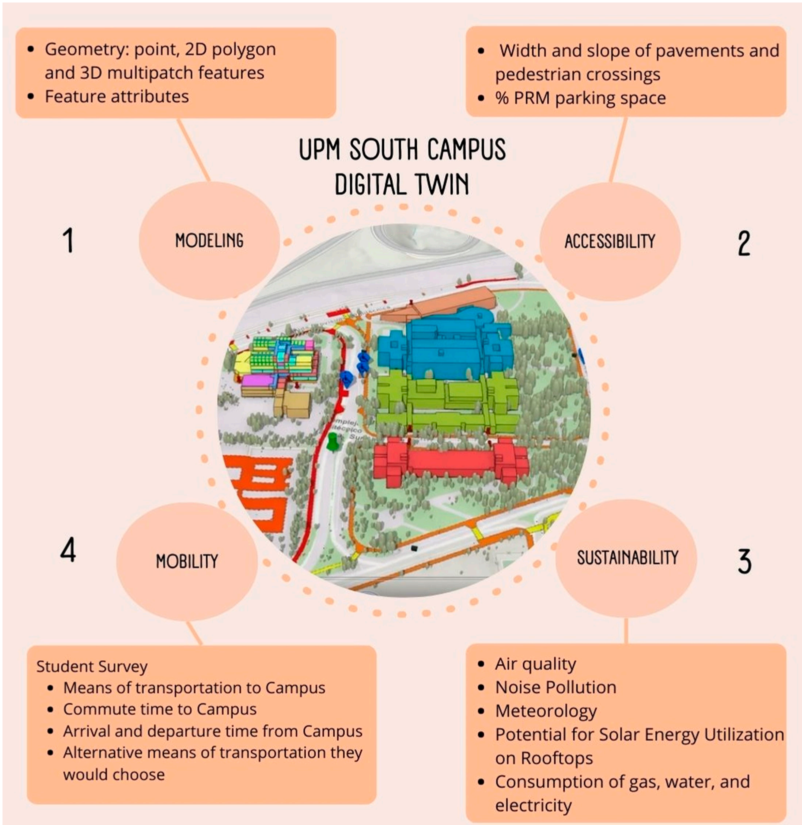

Figure 2. Workflow designed to create the UPM South Campus digital twin.

Once the geographic features were created, they were provided with semantics. Faculties, research centres, and facilities were given their names, built area, and other specific data, such as the number of students in the faculties or the number of seats in the library. Additionally, URLs linking to information of interest for users, such as opening hours and capacity, were included in the database.

The School of Surveying, Geodesy and Cartography Engineering (S.S.G.C.E) was modeled in detail, based on a BIM that we created in a previous project [17]. In an early step of the modeling phase, we considered the incorporation of the BIM in the 3D model; however, after evaluating the main goal of this digital twin, we eventually decided not to integrate it. The rendering of such a heavy object would have been slow, hindering the functionality of the web application. Additionally, the BIM contains highly detailed elements, such as supply lines, furniture, etc., that are not of general interest. Nevertheless, we have used the geometry and part of the BIM's semantics, along with the available plans, to create a more detailed 3D digital model of the school than that of other campus buildings, including the geometry and the name and/or use of each individual room (Figure 3).

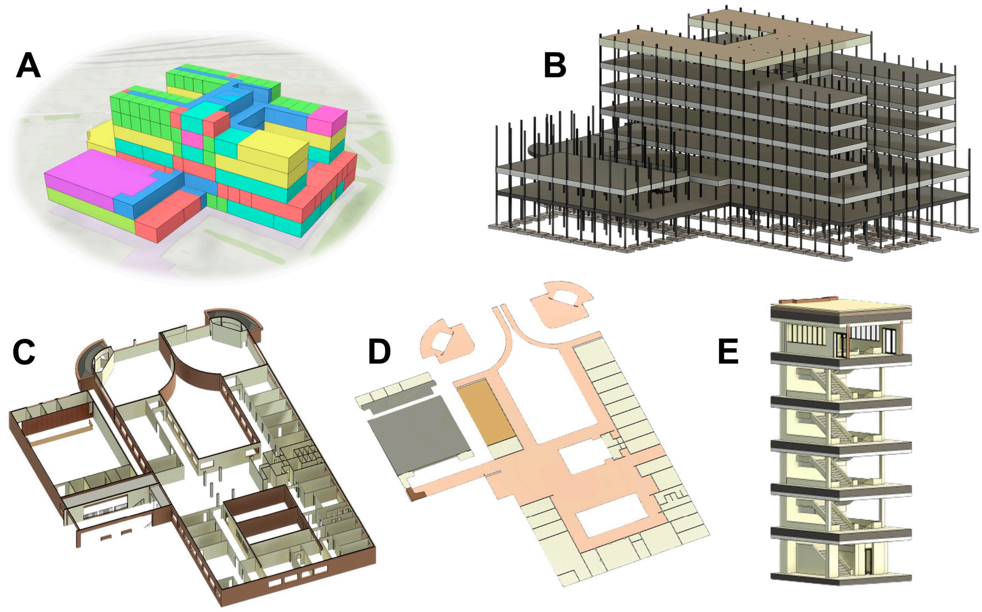

Figure 3. Features of the detailed building information model (BIM) of the School of Surveying, Geodesy and Cartography Engineering: (**B**) building structure; (**C**) 3D model of the main floor; (**D**) plan of the main floor; (**E**) 3D model of a staircase, from the basement to the top floor. The image in (**A**) shows the final, geometrically simplified 3D digital model of the school, which was used to create the digital twin.

The campus also includes other educational buildings, such as a secondary school and a special education school. These were represented in 2D, with attributes similar to those of the other buildings, and were extruded using the number of floors.

The 2D polygon features related to transportation have specific attributes. The roadways, pavements, and cycle lanes have their area and length; the car and bicycle parking areas have the number of spaces; the underground and suburban train stations, as well as the bus stops, have line numbers and URLs for more information.

Regarding point features, the trees were assigned the attribute of height. This was achieved by calculating a normalised digital surface model (nDSM), obtained by subtracting the digital terrain model (DTM) from the digital surface model (DSM).

All this semantic information was incorporated during the modeling phase and expanded upon in subsequent phases.

Phase 2: Accessibility

In phase 2 (Figure 2), data related to the accessibility to the campus were incorporated into the GIS as attributes to the building entrance, pavement, pedestrian crossing, and car park feature layers. All this information was collected through an in-field survey conducted in 2023. The objective was to evaluate accessibility for persons with reduced mobility (PRM) to the buildings on the university campus. Therefore, routes from bus stops and the ratio of parking spaces for PRM were considered. Accessibility of the routes was characterized by the width and slope of pavements and pedestrian crossings, following the accessibility official regulations of Madrid as a reference.

The slope was calculated in ArcGIS Pro from the campus DEM in terms of percentage. ArcGIS includes a Python function designed to compute the slope for each raster cell by comparing its value with those of its eight nearest neighbours. The slope is the first derivative of the DEM and is understood as the ratio of elevation change between one cell and another. Among the eight slope values computed for each cell, the highest value is selected. Percentage slope values range from 0 (in flat areas) to nearly infinite (in vertical terrain), with 100% representing a 45° slope.

In accordance with the official regulations of Madrid, the itineraries were classified as follows: adapted, usable and non-adapted (Table 1).

Table 1. Reference values to classify the route accessibility.

Value	Width (m)	Slope (%)
Adapted itinerary	>1.2	<4
Usable itinerary	0.9–1.2	4–8
Non-adapted itinerary	<0.9	>8

Phase 3: Sustainability

In phase 3, the sustainability data were computed and integrated within the GIS. Five different indicators were analyzed, namely, air quality, noise pollution, meteorology, solar energy, and supplies consumption (Figure 2).

- To evaluate air quality, data were obtained from the Madrid City Council's Air Quality Monitoring Network. This network consists of 24 automated monitoring stations, which are grouped into 5 zones. The study area is located in "Zone 02 Southeast", which includes three stations (Ensanche Vallecas, Moratalaz, and Vallecas). The South Campus is situated nearly equidistant from the three stations (Ensanche Vallecas at 2.25 km, Moratalaz at 2.40 km, and Vallecas at 1.95 km). For this reason, the average data from the three stations were used to calculate air quality. Despite the station being almost equidistant, an inverse distance weighted interpolation (IDW) was performed in ArcGIS Pro instead of computing a simple average. ArcGIS Pro has a python function to compute the IDW interpolation using the inverse of the distance between the calculation point and the samples as weights.
  As a reference indicator, the national Air Quality Index (AQI) defined in Spanish regulations was selected [18]. The AQI defines six air quality categories: good, reasonably good, fair, poor, very poor, and extremely poor, based on the application of the methodology described in the regulations to the concentration of atmospheric pollutants recorded at each station. Table 2 presents the pollutant value intervals and the AQI levels.

Table 2. Reference concentration range for each air pollutant to classify the AQI (values in μg/m^3).

SO_2	PM10	O_3	NO_2	AQI
(0–100)	(0–20)	(0–50)	(0–40)	Good
(101–200)	(21–40)	(51–100)	(41–90)	Reasonably Good
(201–350)	(41–50)	(101–130)	(91–120)	Fair
(351–500)	(51–100)	(131–240)	(121–2030)	Unfavorable
(501–750)	(101–150)	(241–380)	(231–340)	Very Unfavorable
(751–1250)	(151–1200)	(381–800)	(341–1000)	Extremely Unfavorable

For the analysis, data from the three air quality control stations near the South Campus were used for the year 2022, specifically the monthly average concentration values of the pollutants SO_2, PM_{10}, O_3, and NO_2 (measured in μg/m^3). These data are provided by the Madrid City Council, which validates and publishes them as open data for download.

- The analysis of noise pollution was carried out using sound level (Ld = noise emission indices for the day) data from four stations located between 1.9 km and 2.5 km around the campus. In this case, the monthly average of the values measured between 7 a.m. and 7 p.m. every day was used as indicator. As in the case of air quality, the IDW interpolation was used to estimate the sound level. According to the municipal regulations, university campuses are classified as educational zones and therefore the noise pollution limit is set low, at Ld = 50 dB (the sound measurement must not exceed the maximum limit by more than 5 dBA).

- The meteorological conditions were studied using parameters defined by the Madrid City Council: wind speed (m/s), wind direction, temperature (°C), relative humidity (%), and precipitation (L/m^2). Data were collected from a station placed 2.1 km from the campus, which provides hourly data, and monthly averages were calculated.
- Regarding renewable energy resources, a simulation was conducted on the digital twin on the potential of solar radiation on rooftops to assess the feasibility of installing photovoltaic solar panels. The amount of solar radiation received by the buildings on the South Campus in the year 2023 was calculated, along with the potential electricity production by the solar panels. This simulation was conducted using the methodology provided by ESRI [19] with a digital surface model (DSM) of 2.5 m geometrical resolution and the building footprints.
    1. First, the solar radiation (insolation) was computed for each rooftop, following the sequence below:
        (a) Calculation of a viewshed at every location, looking from the rooftop upwards, to the sky. The result is a raster dome with the portion of the sky that is visible from each roof taking into consideration the occlusion with the surrounding topography and other obstacles (such as other roofs or trees).
        (b) Sun map calculation, which is a raster representing the apparent position of the sun along the day and the year. This sun track is computed based on the latitude of the roof and the time configuration, creating numerous sectors that are defined by their zenith and azimuth angles. Finally, solar radiation values are calculated in each sector.
        (c) Calculation of diffuse radiation caused by the atmospheric particles and clouds on a raster divided into sectors, as previously described.
        (d) The three raster layers are overlain: viewshed, sun map, and sky map. The total radiation (in kilowatt hours per square meter) reaching each cell in the roofs is computed as the sum of direct and diffuse solar radiation masked by the viewsheds.
    2. Next, inadequate roofs were eliminated, according to the following criteria:
        (a) Roof slope > 45°. The slope of the roofs was computed using the same function explained in Section 2.2 phase 2, with the DSM as input, and those with a slope higher than 45° were excluded from the analysis.
        (b) North-facing roofs. A python function in ArcGIS was used to calculate the aspect of the DSM. Aspect provides the compass direction of the downslope in each raster cell, with values ranging from 0° to 360°, increasing clockwise from north.
        (c) Roofs receiving +800 kWh/m^2. The raster with the solar radiation computed in the previous step was filtered to keep values exceeding 800 kWh/m^2.
        (d) Roof area > 30 m^2. The installation of solar panels is not economically viable on roofs smaller than 30 m^2.
    3. Finally, the electrical energy that each building could potentially produce was computed using the following steps:
        (a) Calculate the solar radiation in each building. The average solar radiation received by the cells of each roof is multiplied by the area in m^2 and divided by 1000 to convert the units to MWh.

(b) Convert solar radiation into potential energy. To do this, the application considers the efficiency estimate provided by the U.S. Environmental Protection Agency (EPA) for photovoltaic panels. According to the EPA, panels can convert 16% of the solar energy they receive into electrical energy, of which 86% is utilized. These percentages are then applied to the values obtained in the previous step to estimate the potential electrical energy of the roofs on the South Campus buildings.

- Finally, monthly consumption attributes of electricity (kWh), gas (kWh), and water (m^3) for each faculty and academic facility were incorporated. Additionally, an estimation of monthly water consumption for green areas and tree irrigation was made, considering a daily irrigation requirement of 6 L/m^2.

Phase 4: Mobility

For the mobility analysis, data on underground and suburban train stations, as well as bus stops, were gathered from official sources. An in-field survey was conducted to locate all parking spaces on the campus and identify those designated to RMP.

This geographic information was complemented by a student survey to determine their preferred means of transport to campus, frequency of use (days per week), and commuting time.

Online Publication

Once the digital twin was complete, all the layers were published on ArcGIS Online, and a web application was implemented using the Experience Builder module. Therefore, the model becomes publicly accessible, allowing users to access the information, including both geometry and semantics. We decided to create two different models to cover all functionalities and approaches that the different potential users might need. On one hand, a fully publicly accessible model was created, displaying data of interest to campus students. It can be accessed at (https://upmarcgis.maps.arcgis.com/apps/instant/basic/index.html?appid=ef5732871b274bddad0f48051733eb33 (accessed on 1 October 2024)). On the other hand, UPM campus staff responsible for management can access the digital scene, which is restricted and has greater functionalities. In this way, the digital model gains value as a data repository with the ability to perform simulations and expand in the future.

2.3. Data Collection

To conduct all the calculations outlined in the methodology and to integrate all feature attributes, an extensive data collection process was undertaken. This phase represented the longest and most critical step in ensuring the success of the digital twin. Various public institutions offering web services and spatial data infrastructures (SDI) were consulted to obtain relevant data for the South Campus. Additionally, multiple meetings with technical and service staff from the UPM were necessary to gather specific data sources.

Table 3 summarizes the datasets collected or generated, categorizing them by source, data type, extent, and original reference system. The UPM provided data on the buildings, public transport, green spaces, and street furniture. Data related to air quality, climate and noise are available on the Madrid City Council website. The Madrid underground and train services offer information on the stations. The DTM and the DSM were downloaded from the National Geographic Institute. Furthermore, certain data required for the complete GIS implementation did not previously exist, such as dumpster location, lifts inside the buildings or designated parking spots for PRM. This involved its generation using aerial orthoimagery and fieldwork, thereby extending the planned work duration.

Table 3. Description of the data sources used in this study.

Source	Data	Data Type
UPM database Extension: South Campus Reference System: ETRS-89 UTM 30N	BIM of the S.S.G.C.E.	Revit format
	Pavements	Polygon *.SHP
	Water, electricity and gas consumption	Alphanumeric
	Trees	Point *.SHP
	Bicycle lanes	Line *.SHP
	Bus stops	Point *.SHP
	Intercity bus stops	Point *.SHP
	Underground and train station access	Point *.SHP
	Highways	Line *.SHP
	Maps of the S.S.G.C.E.	*.DWG
	Net floor area of buildings	Alphanumeric
	Gross floor area of buildings	Alphanumeric
	Traffic signs	Point *.SHP
	Library users	Alphanumeric
	Streetlights	Point *.SHP
	Library spots data	Alphanumeric
	Library private rooms data	Alphanumeric
	Number of students per school	Alphanumeric
Madrid City Council Extension: City of Madrid Reference System: ETRS-89 UTM 30N	3D buildings	Multipatch *.SHP
	Air quality stations	Point *.SHP
	NO_2 data	Alphanumeric
	SO_2 data	Alphanumeric
	O_3 data	Alphanumeric
	PM10	Alphanumeric
	Climate stations	Point *.SHP
	Climate data	Alphanumeric
	Noise pollution data	Alphanumeric
	Noise pollution stations	Point *.SHP
Madrid Underground Service Extension: Madrid and surrounding cities	Entrances to underground station	Alphanumeric
Madrid Commuter Train Service Extension: Madrid and surrounding cities	Commuters in train station	Alphanumeric
National Centre for Geographic Information (CNIG) Extension: Spain Reference System: ETRS-89 UTM 30N	Digital terrain model	Raster (2 m geometric resolution)
	Digital surface model	Raster (2.5 m geometric resolution)
Self-generated data Extension: South Campus Reference System: ETRS-89 UTM 30N	Dumpsters	Point *.SHP
	Green areas	Polygon *.SHP
	Lifts	Polygon *.SHP
	Pedestrian crossings	Polygon *.SHP
	Parking spots	Point *.SHP
	Parking spots for PRM	Point *.SHP
	Student survey	Alphanumeric

*: File extension format.

3. Results and Findings

In this section, we show the results obtained after creating the UPM South Campus digital twin.

3.1. Phase 1: Modeling

The result of the campus modeling is shown in Figure 4. The four university buildings can be seen in 3D with different colors, as well as the facilities (library, cafeteria, sports center, and research centers). The S.S.G.C.E. has a more detailed geometry of each classroom, room, and office (Figure 4C). We integrated the CAD plans in *.dwg format provided by the UPM into the GIS to create polygons for each room from the vector lines. Then, the polygons were extruded considering a floor height of 3.5 m and transformed into a 3D format (multipatch). As a result, each room was represented separately. Finally, fieldwork was conducted to complete the geometric model with semantics corresponding to the use and name or number of every room, classified as follows: administration, student associations, classrooms, laboratories, research, toilets/cleaning, mobility (lifts and stairs), cafeteria, offices, and corridors.

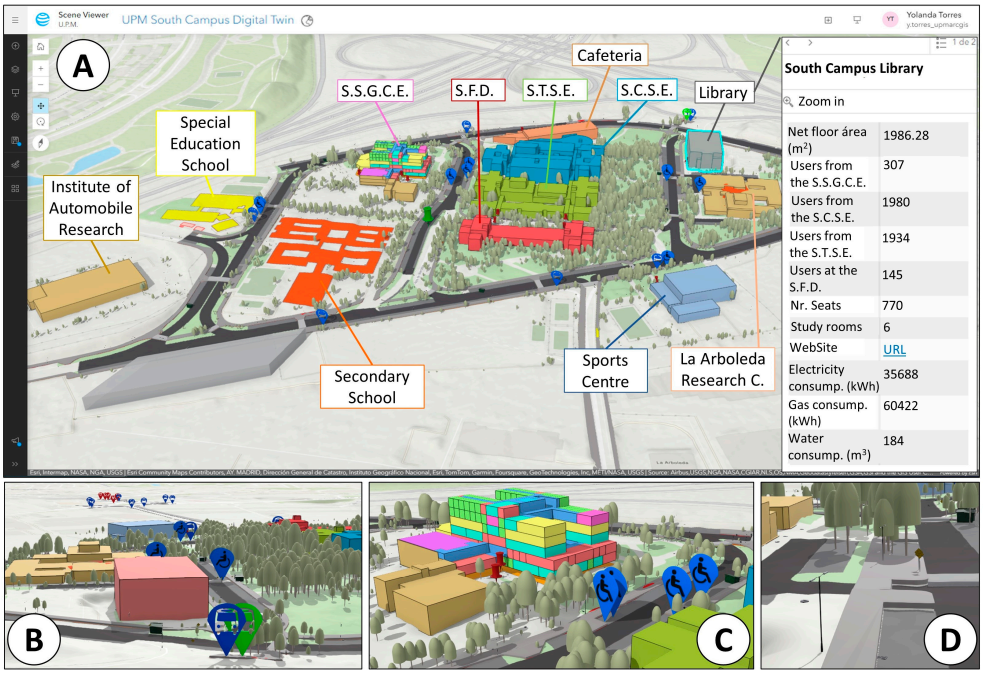

Figure 4. (**A**) General view of the UPM South Campus digital twin on the web application. (**B**) Detailed view from the north. (**C**) View of the School of Surveying, Geodesy and Cartography Engineering. (**D**) Detailed view of a street.

The geometry of the other faculties and facilities associated with university activities (library, sports center, and cafeteria) was also generated from the CAD plans provided by the university. These were extruded based on the number of floors, at 3.5 m per floor. However, detailed layouts for each room were not created due to time constraints. Clicking on one of the elements displays a pop-up window with the semantic information stored in its table. Figure 4A shows an example of the library, which has 770 seats and 6 group study rooms. The School of Computer Systems Engineering (S.C.S.E) has 2249 students; the School of Telecommunications and System Engineering (S.T.S.E.) has 2085 students; the School of Fashion Design of Madrid (S.F.D.M.) has 144 students; and the S.S.G.C.E has 246 students.

The total built area on the campus is 130,492 m^2, of which 35% corresponds to the faculties; 20% to the research centers; 18% to the facilities; and the remaining 27% to the school and secondary school, which are represented in 2D. The entrance of each building is marked with point features, with an attribute indicating whether it is accessible to PRM.

Regarding the street network, it shows the roadway (with a total area of 22,809 m^2), pavements (4975 m^2), pedestrian crossings (21), bus stops (18, 16 of which are for urban buses and 2 are for interurban buses), parking spaces (995, 10 of which are for PRM, making up 1%), and entrances to the underground station (5) and the train station (2), with indications of accessibility. Additionally, streetlights (215), traffic signs (61), manhole covers (251, for lighting, telephony, electricity, irrigation, etc.), and drain covers (55) have been integrated. The large number of trees on the campus (2197), the green areas (48,258 m^2), and the waste collection points (8) are also shown.

All these features are shown in Figure 4. In the foreground of the image (B), there are two bus stops (blue for urban buses and green for intercity buses). To their left, there is a dumpster. In the background, several underground and train station entrances can be seen, located about 700 m from the campus. The high density of trees is also visible in this image. Figure 4C shows the S.S.G.C.E., with rooms represented in different colors. Two red pins indicate the entrances, which include information on accessibility and a photo for better identification. Nearby, between the street and the pavements, there are four parking spaces for PRM. Figure 4D provides a closer view of a street with covers, traffic signs, and lamp posts.

Esri's styles were used for feature symbolization. However, to highlight the bus stops, the underground and train station entrances, and the parking spaces for PRM, custom symbols were designed using 3D Builder software for Windows and exported for use in ArcGIS Pro as 3D Model Markers.

3.2. Phase 2: Accesibility

The accessibility analysis indicates that the width of pavements and pedestrian crossings meet the conditions stipulated by the regulations (Table 1). However, the slope values of the pavements do not comply in some areas of the campus, which are crucial for PRM accessibility. One of the pavements with the steepest slope (Figure 5) is located on Mercator Street, where almost half of the campus parking spaces for PRM are concentrated. These paths would be impracticable for PRM, severely restricting their movement on the campus. It is important to note that neither of the two intercity bus stations are accessible for PRM. This has been confirmed through fieldwork and corroborated with official sources from the Municipal Transport Company (EMT) of Madrid, which manages these buses.

Figure 5. Result of the campus accessibility analysis.

In the analysis of parking spaces for PRM, it was found that all spaces meet the required surface area according to the regulations. However, the ratio of PRM parking spaces to conventional ones, which should be one in every fifty, is significantly lower (0.61 in every 50). It is estimated that eight additional PRM parking spaces would be needed to comply with regulations.

Finally, with regard to building entrances, it has been observed that all buildings have at least one accessible entrance.

3.3. Phase 3: Sustainability

For the sustainability analysis, monthly data for the year 2022 were used. From the average values of the three air quality stations of the Madrid City Council (Figure 6), the monthly Air Quality Index of the South Campus was determined, showing 'good' values in November and December and 'reasonably good' for the rest of the months. Low on-campus traffic intensity, non-intensive use of heating, efficient waste management, a large number of trees and extensive green areas on campus seem to contribute to maintaining clean air. However, noise pollution exceeds acceptable levels (below 50 + 5 dB) throughout the year, with Ld values ranging from 61.6 dB in July and August (holiday period) to 64.6 dB in March. The reason for this may be the adjacent motorway (M-40) with very heavy traffic to the north of the campus. This leads to the conclusion that further work is necessary to isolate the campus from the influence of this traffic, as the current noise pollution is not suitable for an educational environment.

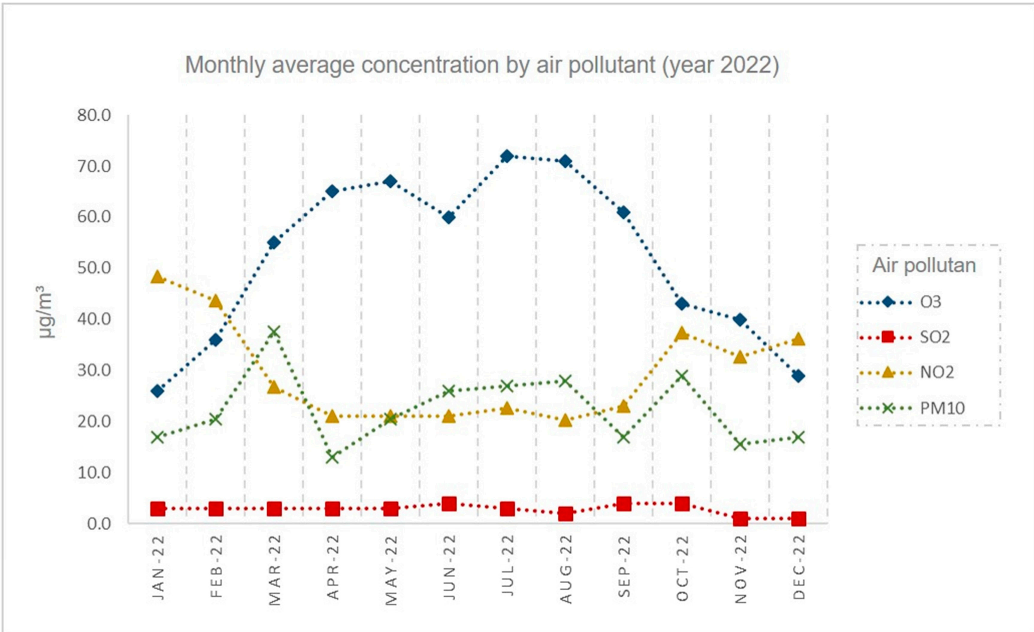

Figure 6. Average monthly concentration value of each air pollutant in the study area (year 2022) (µg/m^3).

Meteorological variables were also analyzed throughout the year 2022, including monthly mean values for wind speed and direction, daily temperature, relative humidity and precipitation. This basic information is considered a fundamental element for further analysis, such as the variation in irrigation water demand as a function of temperature and humidity, or heating fuel consumption in buildings.

The fourth variable in the sustainability study is solar energy utilization. This has been calculated for all the roofs on campus, considering their pitch and the amount of sunlight they receive based on their orientation. The ESRI methodology, implemented in ArcGIS Pro 3.2, has enabled the estimation of the electrical energy that could be produced on the campus if solar panels were installed on all viable roofs. Figure 7 shows these results. It was found that the total energy produced would exceed 2000 MWh per year, with the central campus building, which houses the S.T.S.E. and S.C.S.E., being able to generate the most energy, at over 760 MWh/year.

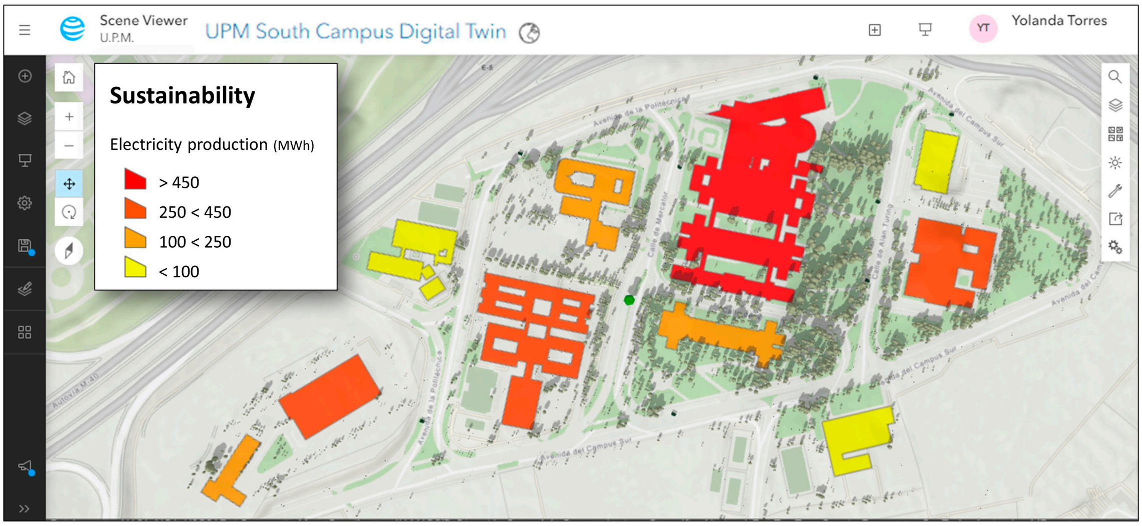

Figure 7. Estimated electricity production (MWh) for the roofs of the campus buildings according to surface area and insolation.

Finally, the total consumption of electricity, gas, and water by the buildings associated with university activities was studied for the year 2023. The library is the building that consumed the most electricity and gas, with 247,000 kWh and 858,400 kWh, respectively. Conversely, it used less water than the others (1000 m^3). The School of Fashion Design has the lowest electricity consumption (247,064 kWh), whereas the Institute of Automobile Research consumed the least gas (44,898 kWh). The building housing the Schools of Computer Systems Engineering and Telecommunications Engineering reported the highest water consumption, with a total of 12,660 m^3.

3.4. Phase 4: Mobility

To analyze mobility, data were collected from public transport services; however, it was not possible to discriminate accurately between general users and students on campus. For this reason, we conducted a survey using Google Forms with four essential questions related to the transportation habits of the students: (1) arrival and departure times to the campus; (2) means of transportation; (3) commute time; (4) alternative means of transportation they would use; the questionnaire consisted of closed questions, and a final open question to suggest improvements to the campus.

A total of 72 surveys were completed, all of which were answered by S.S.G.C.E. students, representing approximately 30% of the total number of students in the faculty. The aim of the survey was also to evaluate the capacity to incorporate social information (opinions, behaviors, habits, etc.) into the digital twin and to assess its usability in decision making.

The analysis of the responses reveals that most students arrive at the campus between 8:30 and 10:30 and leave between 14:00 and 16:30. This aligns with the fact that teaching activities are generally held in the morning. It takes between 30 min and 1 h to reach the campus by bus; however, students using the train or underground need more than an hour. Apparently, students who live further away tend to use the metro and train more as these are more efficient and faster than the bus. However, the use of private vehicles is the main option chosen by students as it reduces travel time by between 15 and 30 min.

Some interesting observations from the analysis of student responses are the following:

- Bicycles: more than 60% of bicycle users do not park their bikes in the designated bike racks on campus;

- Trains: of the total users of the nearby train station, between 40% and 50% are campus students;
- Cars: among those who drive to campus, only 3.19% find it difficult to find a parking space;
- Electric cars: more than 90% of respondents would approve the installation of electric vehicle chargers on campus;

4. Discussion

The development of this pilot project has allowed a better understanding of the importance of designing a coherent information flow diagram, which allows the integration of numerical, alphanumeric and graphical data with geographic information systems. Additionally, the progress of the project in each of its phases has confirmed some of the current limitations and barriers to the development of a digital twin [20].

First, it is important to determine the objective and scope of the digital twin, describing the groups and categories of data and information, and defining the end-user profile. A model designed for a specific organization should be compatible with its tools and data formats; however, a model based on open-source software adds more value and facilitates visualization for public use (students, citizens, public administrators, etc.).

Following the previous step, the development of the software architecture requires selecting a specific application, which involves choosing a data format, standards, and a database system. These decisions may limit interoperability between different data sources and hinder analysis processes, potentially creating future barriers to the growth of the digital twin.

The data used in the project come from public institutions and are openly accessible, demonstrating that it is possible to develop complex digital models using these datasets and the appropriate tools. However, open data is sometimes not updated frequently enough or uses different protocols that are not standardized for automatic loading into a digital twin [21]. This barrier could be overcome by designing automated data capture and standardization systems that allow direct loading into the digital twin's database.

Visualization is an important aspect of a digital twin. It is necessary to balance realistic imagery, user comprehension of the 3D model, and graphic resource demands. Our experience has shown that a conceptual 3D model is easy for users to interpret without affecting processing time, especially if the application is used on mobile devices.

The greatest potential of a digital twin lies in its ability to perform analyses, queries, and simulations that support decision-making processes [22]. Working with different technologies and software applications provides greater computational and visualization capabilities but also makes model management more complex. This limitation is further compounded by the current lack of experience and knowledge among urban management professionals and academic staff of how to incorporate digital twins into their daily tasks. Technological advancement requires parallel training and education programs.

For the digital twin to be a tool in the management of a smart campus or smart city, not only do the facilities have to be incorporated, but also elements of the entire campus [16], with information on access and public transport, water and energy consumption, green areas, car parks, etc. At the next level of complexity, adding data and analysis in real time, thanks to the integration of other technologies such as the Internet of Things, machine learning, or Web Map services could also be incorporated [23].

A major challenge is to connect the digital representation of a city with its social, economic and ecological flows and processes [22]. In many cases, a university campus plays a transformative role in the development of the city in which it is located [24]. In addition to being home to the university community, a campus is a focus for innovation and applied research, a space for reflection and debate, and in alignment with the concept of "living labs", a place for open science and citizen science that serves as an urban demonstration space [25–27]. A digital twin can be understood as a living model, in which users participate in its design and future evolution.

5. Conclusions

The digital twin of the UPM South Campus exemplifies the potential of this technology in urban environments by integrating geographic information, data, and variables from various sources with user activities and habits. It not only enhances result analysis but also serves as a powerful tool for planning and decision making.

The methodology and phases outlined in each section—from model design to data visualization—provide a solid foundation for future research. Furthermore, they highlight that, as the digital twin evolves through successive and aggregated phases, the initial design, system architecture, and data standards play a critical role in ensuring its success.

In public universities, spatial analysis tools are not commonly used for infrastructure and space management. This digital twin offers the UPM full control over its data, along with the analytical capabilities to guide future investments in designs that align with social and environmental objectives. It can also serve as a reporting tool to ensure compliance with environmental quality and sustainability standards.

The results of the accessibility analysis show that the educational facilities and green areas on the campus are accessible to PRM (people with reduced mobility). However, accessibility to transportation options is limited due to the lack of PRM parking spaces and the fact that intercity buses are not adapted.

In terms of mobility, the analysis highlights the need to improve cycling infrastructure to promote greater use of bicycles as a mode of transportation. Additionally, the sufficient number of parking spaces presents an opportunity to evaluate whether some could be repurposed into pathways, green spaces, or student meeting areas.

The geographical analysis, combined with transportation habits for both public and private transport, enhances the digital twin as a tool for analysis and decision-making support. Its objectives include assessing parking demand, identifying peak times that require increased public transport capacity, and strategizing connectivity improvements to reduce travel times and promote public transport usage. Furthermore, the tool's analytical capabilities extend to estimating the carbon footprint per trip and per student, based on transport type and distance travelled.

Finally, recognizing that a university campus differs from a city, this research enables operation under the living lab model, fostering connections between technology and people. Additionally, in future steps, students can take on the role of developers of the digital twin, adopting an open-access and collaborative approach.

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