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The time variable in the Territorial Digital Twin: The case of Guadalajara (Spain)

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Abstract: The growing importance of Territorial Digital Twins (TDT) in the built environment is becoming increasingly apparent. The TDT can play a crucial role in helping governments make informed decisions based on a thorough understanding and interpretation of the evolution of both the physical territory and its urban, social, and economic development. This study develops the Territorial Digital Twin of Guadalajara (Spain), within the knowledge domain of urban planning and architectural and natural heritage. It allows the analysis of the evolution of the city, using the variable time, taking as origin an unpublished flight of Guadalajara from 1934. To be able to count on the widest possible time span, it is essential to recover the unpublished documentation that remains in historical archives. In this sense, aerial images have proved to be invaluable source for the recovery of historical heritage and territorial analysis. During the study, different techniques of image georectification have been combined, and a historical vector graphic base with topology has been created, plus an associated database accompanied by files with town planning and heritage information. As a result, the changes produced in the urban planning of the city are analysed and shown on the open-source website developed for the consultation of Territorial Digital Twin by all the stakeholders (collectivity, public bodies, university, investigation bodies, etc).

Keywords: Territorial Digital Twin, time variable, historical data, Guadalajara (Spain).

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1. Introduction

Digital Twins (DT) have their origins in the industrial field and were quickly integrated into the field of architecture, particularly in construction, due to the great symbiosis between the building environment and DT. Furthermore, in recent times this new technology is increasingly present in the field of historical heritage and territorial management; in fact, Territorial Digital Twins (TDT) are essential for the study of historical heritage, urban planning, analysis climate change, as well as the social and economic evolution, and can play an important role in the preservation of cultural and natural capital, in risk prevention and disaster mitigation (Chioni, 2023). A Digital Twin (DT) can include anything from a 3D model of historical heritage (Kong, 2023) to a large city (Lehner, 2020). For which it requires multi-temporal Digital Twins, which are usually also multi-scale and multi-platform (Gabriele, 2023), and whose main variable is time, to which the shape variable subsists. Figure 1 shows a graphical development of the TDT idea on the three fields of knowledge that we intend to cover in this study, and those documents that can contribute the most value to the time variable, indicating in each of them the estimated start of their production.

In order to have a sufficiently wide time window to provide TDTs with the necessary information, it is essential to have recourse to the documents in historical archives. The documents in these archives are, in many cases, unpublished; they have never been used because their interpretation is complex, because the technology necessary for their implementation was not available, or because it was considered that they did not provide relevant and up-to-date information, due to their age or the outdatedness of their data. Changes in the landscape, at a global level, occur too slowly for the human timescale, but there is a need to show and communicate these changes to the public and to show the impact of, for example, land-use policies, changes caused by urban development or watershed modifications. Satellite imagery is, currently, the most common way for the detection of these changes, but we have a much older source of data such as historical mappings or aerial (Figure 2) and terrestrial images, some of which are almost 200 years old, which should be preserved and recovered for the analysis of landscape changes and territorial studies (Produit, 2017; Produit, 2013).

2. Objectives

The aim of this research is to create a TDT of Guadalajara that allows to analyse the urban evolution and, in the future, with the help of artificial intelligence, to predict it under better conditions for the citizens and the environment. To achieve this, the TDT must be provided with as much graphical information as possible, and the older it is, the greater the model's learning capacity will be. The second objective is to make the TDT of Guadalajara accessible to the entire population through a web developed with open-source code (Figure 3). Through TDT it should be possible to analyse spatial relationships between elements, obtain real time information about some objects and access urban and architectural heritage information, both the elements that currently exist and of those that have disappeared, and for which historical information exists. The Digital Twin should promote knowledge of the environment and show users the city's lost heritage in an immersive way and directly on the actual physical space it used to occupy.

3. State of the art

The idea of replicating a physical object by creating a Digital Twin for its study, although very topical, is not a new phenomenon. This task, according to the computational capabilities of the time, has been going on for decades, although the term Digital Twin was only coined in 2002 by Professor Dr. Michael Grieves (Kumar, 2022). What is new in the field of TDTs is the application of the concept of relationship with other models, through geo-referencing, and the non-deterministic concept, which evolves the idea of Digital Twins into the concept of Living Models (Allen, 2021). However, Territorial Digital Twins are still an underexplored field with a weakness in that they have a rather static character (Chioni, 2023), which through the application of the time variable enhancements analysed in this study (Figure 1) we hope to overcome. Furthermore, analysis at a multi-temporal scale helps to define sustainable future management practices and raises awareness among the community and visitors about the importance of preserving both the historical and architectural value and the biodiversity of the site (Gabriele, 2023). Although the digital and information revolution have opened up opportunities for effective multi-level and multi-scale, dynamic and n-dimensional modelling and mapping approaches (Gutiérrez, 2019), Historical TDTs typically employ imagery and mapping produced at the time by topographic or photogrammetric methods (Lehner, 2020), but no case has been found, in the scientific literature consulted, of a TDT of a city, made in the present, day from unpublished historical images, with a graphic base elaborated by current means from this documentation, which makes this TDT, probably, the first of its kind. As Scalas points out (2022), having a precise geometric layer to create the TDT, as in our case, gives it additional capabilities, although its development presents the topological difficulties inherent in vector models with associated information. Complex, multi-scale modelling is essential

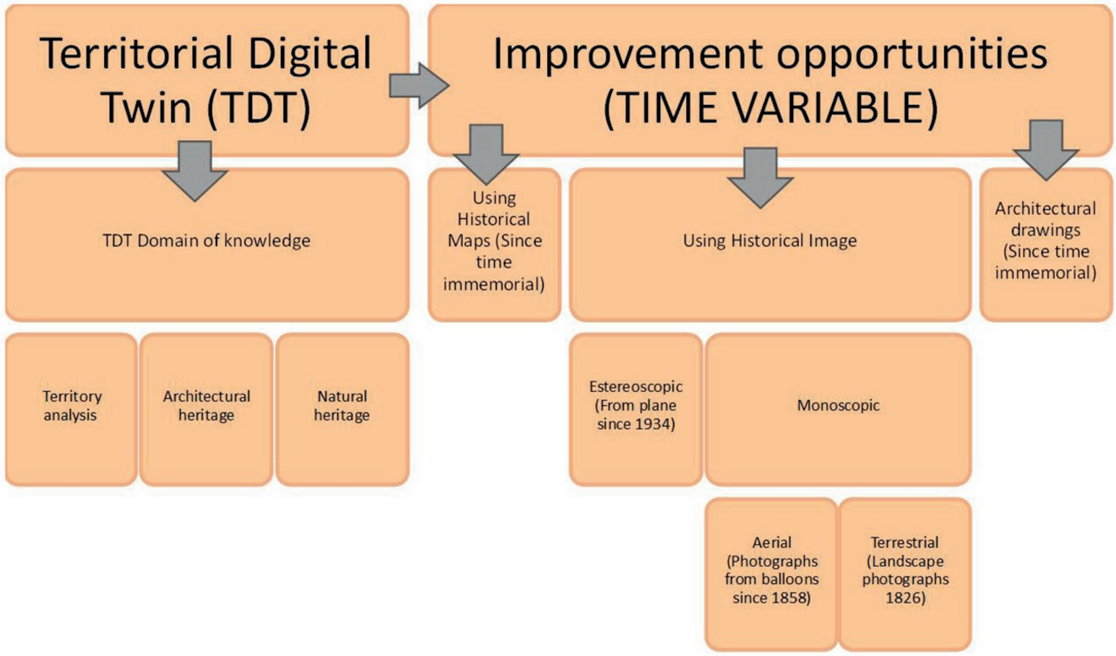


Figure 1 | Time variable improvement opportunities in Territorial Digital Twins (Source: Authors).

for assessing environmental sustainability and biodiversity conservation and transformation (Gabriele, 2023) since human development has come at the expense of natural resources.

On the other hand, as mentioned, one of the key strengths of this TDT is its historical graphical basis from unpublished monoscopic images. As noted above, with the development of aerial photography, terrestrial photography became obsolete for cartographic purposes and was almost forgotten by most photogrammetry specialists (Bozzini, 2012). This has resulted in an excellent opportunity to retrieve from the documentary collections information that had been discarded. The development of image correction capabilities, through increased computing power and the development of new algorithms, is making possible the geometric correction of individual images and other documents.

4. Methodology

The research methodology consists in the following phases:

- Retrieving historical data.
- Processing and incorporating the information into the TDT.
- Development of the vector base with topology to answer spatial queries.
- Connecting the TDT with external static and real-time databases.
- Building the TDT and its publication in a web viewer.
- Establish an immersive process of the TDT exploitation in the field.
- Analysis the urban and territorial evolution of the TDT according to the variables of time and shape.

4.1. Data location and processing choices

There is a wealth of graphic information located in the historical archives that is available to the public, in digital format and ready to be used in any project, such as the American flight of the A (1945), B (1956) and C (1967) series, the IRYDA flight (1980), the GIS Oleícola flights (1997) or the historic flights of the National Aerial Orthophotography Plan. All these images have something in common, they all have overlapping, which gives them stereoscopic capability. On the other hand, there are graphic documents of great value, usually older than the previous ones, which have not received digital geometric correction and have not been used previously, they are unpublished (Figure 2). These documents also have something in common, they

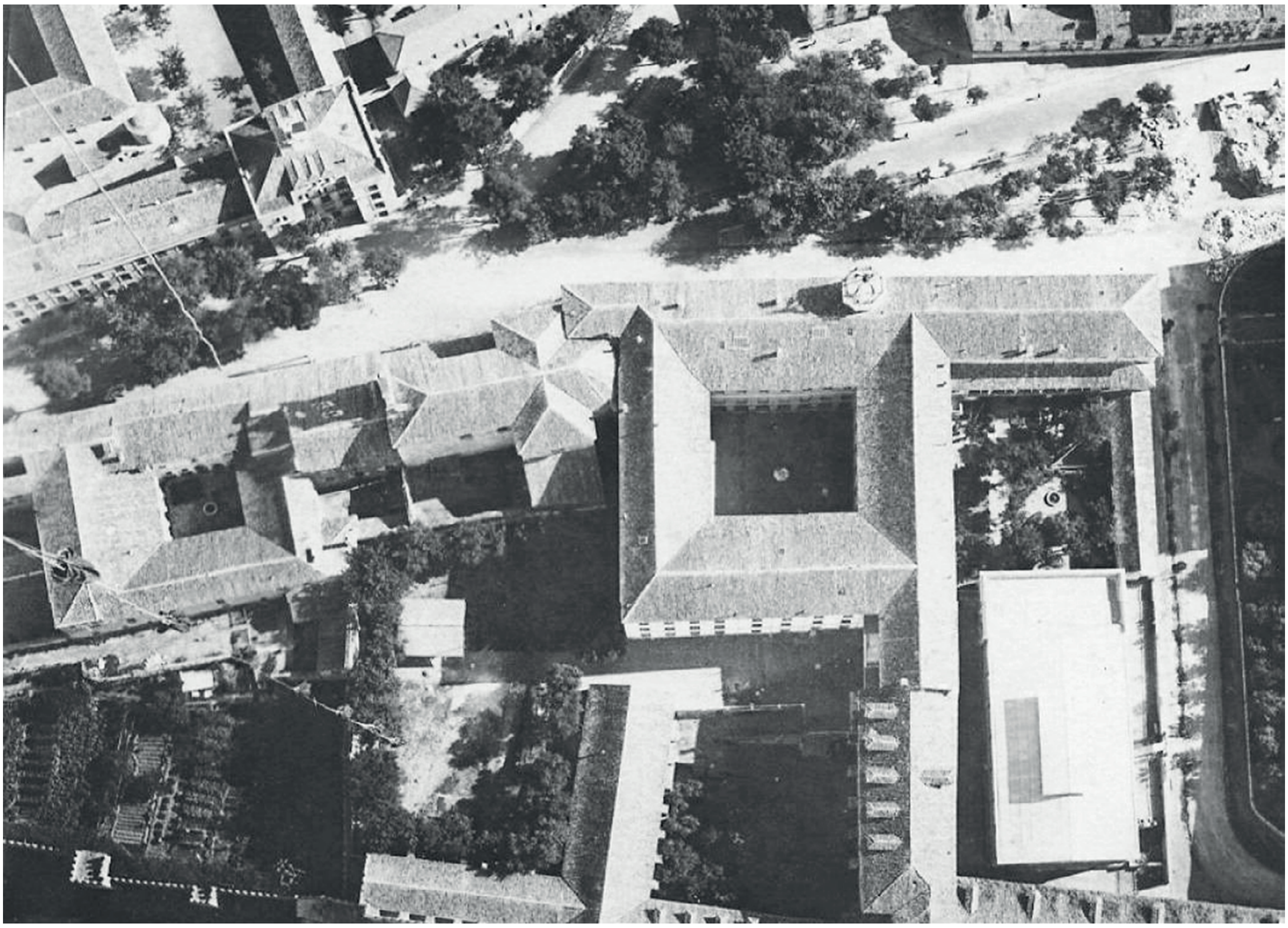


Figure 2 | Photograph from a balloon (1905) of the Academy of Engineers. The ropes for the balloon's ballast can be seen on the left side of the image (Source: Gobierno de España. M. de Defensa. CC BY 4.0).

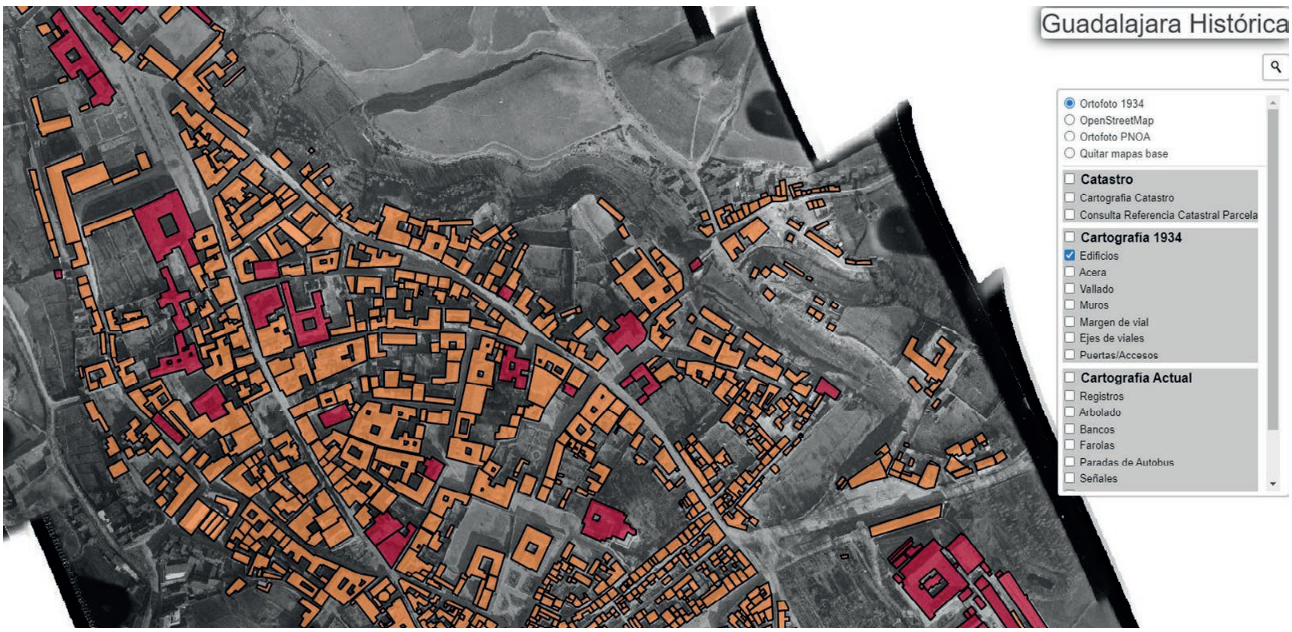


Figure 3 | Appearance of the viewer via the web portal developed in open-source code (Source: Authors).

Figure 4 | Raster Design Toolset Georeferencing Interface. GRS ETRS89 UTM H30N (Source: Authors).

are single images whose correction requires a special process, outside the standard lines of work. Since the aim of the research is to provide the TDT with as broad a time frame of reference as possible, the necessary tasks for the recovery of this type of documentation must be undertaken. To overcome the technical barrier of incorporating these images into TDTs, various methodologies for geometric correction have been evaluated, analysing working methods from different fields, of which we review here four, as the ones that have obtained the best results and are of greatest scientific interest: AutoCAD, very present in the field of architecture, ERDAS, from the field of remote sensing, from which Fissore (2023) has created a prototype of a Digital Twin of alpine glaciers; and the last two, ad hoc scientific developments specialised in the processing of terrestrial images, Pic2MAP, developed by Milani (2015), and the WSL-Monoploting Tool (Bozzini, 2012; Marco, 2018; Hart, 2021), developed by the Swiss Federal Institute for Forest Snow.

4.2. Geometric image correction

Working with AutoCAD all operations were carried out using the Raster Design Toolset module (Figure 4), which allows the images to be georectified using various methods, including polynomial and triangulation methods. It should be noted that the triangulation method, being a piecewise differential method, forces the document to occupy the specified position at each point, the residue in the transformation is always zero. ERDAS, by processing the image as if it were a satellite image, it allows us to incorporate a Digital Surface Model (DSM) and correct the distortion of the target to improve the results, i.e. we are generating an orthophotography, unlike ACAD

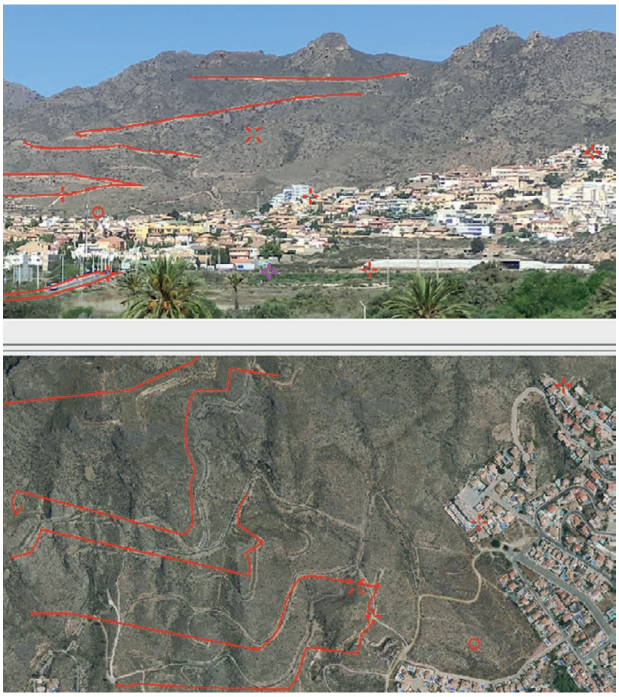


Figure 5 | Top, track layout on the terrestrial photograph. Bottom, the result of the plan drawing, on current orthophotography (Source: Authors).

Figure 6 | Top, georeferenced land image on Google Earth. Bottom, Field of view of ground plan image from the DSM (Source: Authors).

which only deformed the image point by point and does not perform a differential correction taking into account the DSM and the internal parameters of the camera. The scientific tool, developed by Bozzini, WSL-Monoploting Tool (MPT) has provided very interesting results (Figure 5). The working environment and the calculation process are typical of a scientific project, with numerous options and a working process that requires prior training. The result of the paths traced on the test terrestrial image (Figure 5 top side) shows that the elements that are perpendicular to the line of sight of the observer, with little variation in depth, maintain a much greater precision than the elements that follow vanishing lines, whose error can be very large, as can be seen at the bottom of figure 5. The Pic2Map programme is designed exclusively for the treatment of terrestrial photography (Figure 6). The ultimate goal of the tool is not the georectification of the image or the vector plotting of elements, but the export of the georeferenced and scaled image for visualisation in a 3D environment (Figure 6 Top). It brings a very interesting point of view to the field of research on the use of non-metric terrestrial photographs and includes a viewer of the image footprint from a zenith view, which gives an idea of the area covered by the photograph having regard to the DMS (Figure 6 Bottom side).

4.3. Working out of the vector base

The vector base (Figure 7) was created both by digitisation on the monoscopic image and by photogrammetric compilation on the flight part with stereoscopic overlay. The criteria for the extraction of the entities have been the same in both cases. For their tracing, it has been considered that each section of the element will be represented by a series of coordinates of points that identify as faithfully as possible the variations of curvature of the same and selecting them in such a way that, except in areas of very small radius of curvature, the criterion can be established that, given two consecutive points, the next one must be recorded when its distance to the prolongation of the rectilinear segment that passes through the previous ones is greater than 10 centimetres measured in the field. According to the definitions of leg and node, which are required by the topological rules, all intersections of linear map objects with other linear objects or with perimeters of surface objects have given rise to nodes and, consequently, will generate legs. In other words, component legs of linear objects or surface contours may not intersect with any points other than the start or end nodes of another leg. To meet the topological requirements, in addition, there must be analytical continuity in all linear

Figure 7 | View of the vector layer made from the historical images (Source: Authors).

map objects and contours of map objects composed of legs, so that the start node of a leg must exactly match the end node of the leg that precedes it in the object description. The property divisions have been drawn individually using the dividing lines that can be seen on the roofs. On the other hand, the design of the information databases associated with the vector model complies with the semantic rules defined for the TDT and for the creation of metadata, according to the ISO 19139 standard, and in compliance with the recommendations of the Spanish Metadata Core and the INSPIRE regulations, the metadata management programme CatMDEdit version 4.5 has been used for the most part.

4.4. Building TDT using open source

Leaflet, a JavaScript library, has been chosen for the development of the web-based TDT viewer using open source software. It is an application that is widely used in the geographic field for the creation of interactive maps in web applications. Leaflet uses overlapping layers to display geospatial information and is compatible with Web Map Services (WMS), which has allowed us to work with external layers such as the PNOA, the cartography of the General Directorate of Cadastre (Figure 9), the city's Municipal Management Plan, water quality maps, archaeological information, seismic hazard data, etc. To load the raster images, it has been necessary to divide the images into smaller objects, which is called tiling. Tiling divides the map into smaller tiles, which improves efficiency and speed of response. Leaflet also allows connection to real-time services, enabling the TDT to be dynamically updated in response to changes in the underlying data, as the AEMET real-time data overlay. For loading vector geospatial information, the GeoJSON format, an extension of JSON, has been chosen, which is used to represent structured geospatial data. It defines geometry types such as Point, Line and Polygon organised in data collections. In addition to geometry, GeoJSON allows the inclusion of additional properties associated with each geographic entity. This format is a standard for the representation of geographic information due to its simplicity, interoperability, and ability to describe complex data, such as sets of polygons or lines.

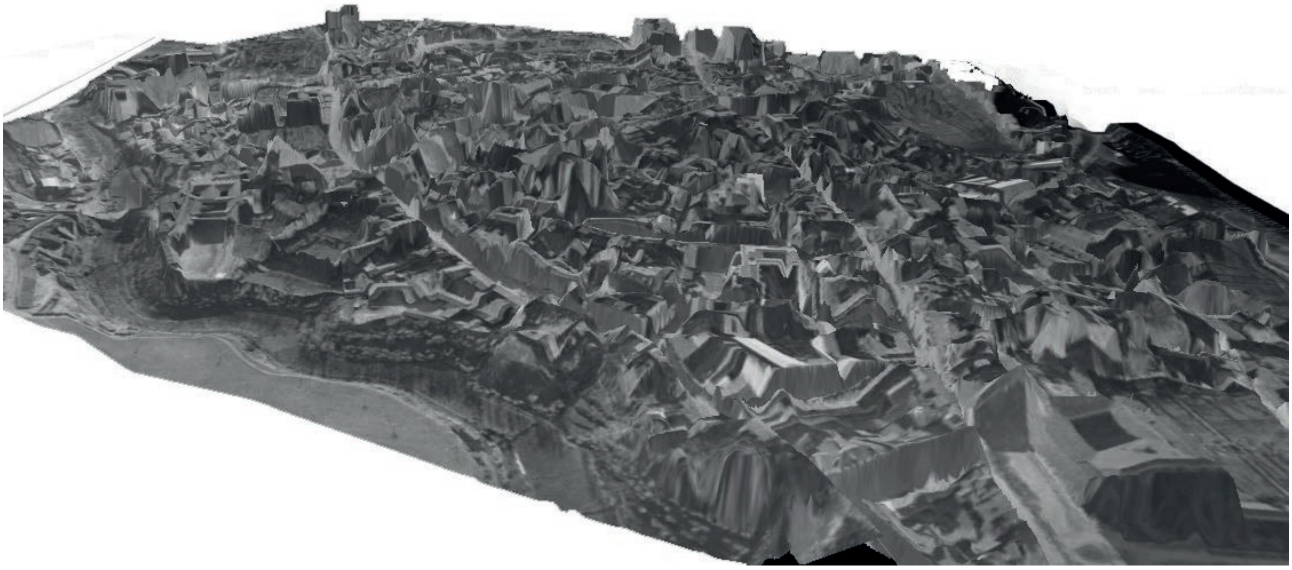


Figure 8 | 3D view of the TDT textured with the image of 1934 (Source: Authors).

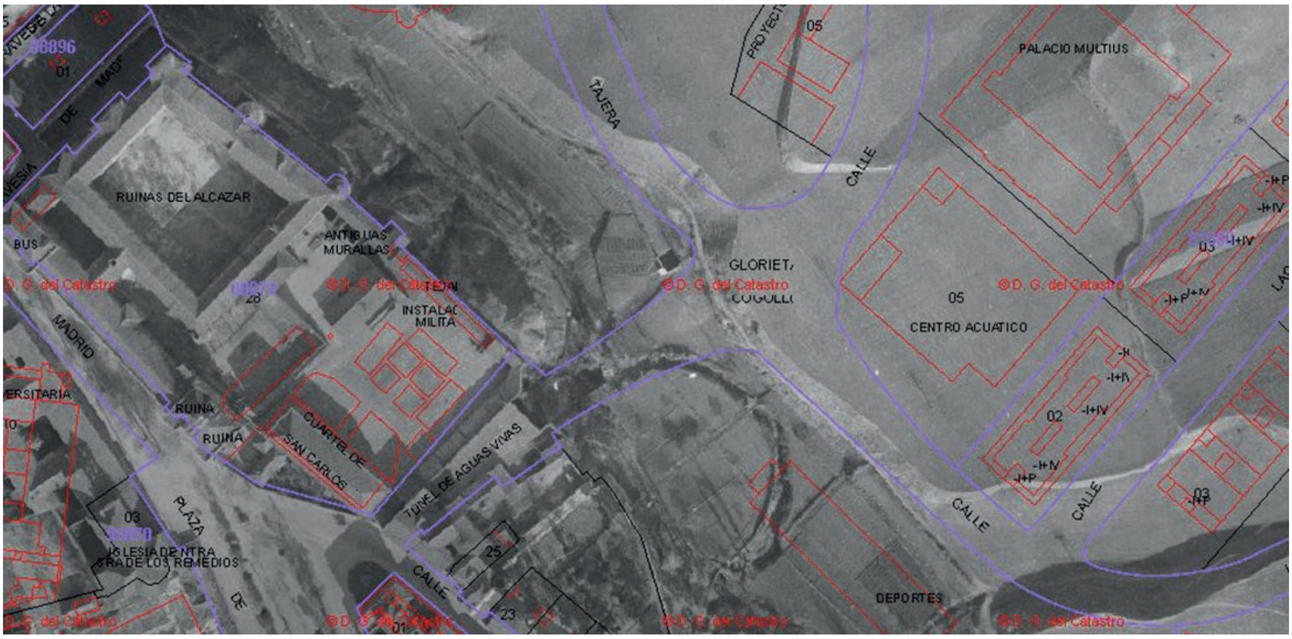


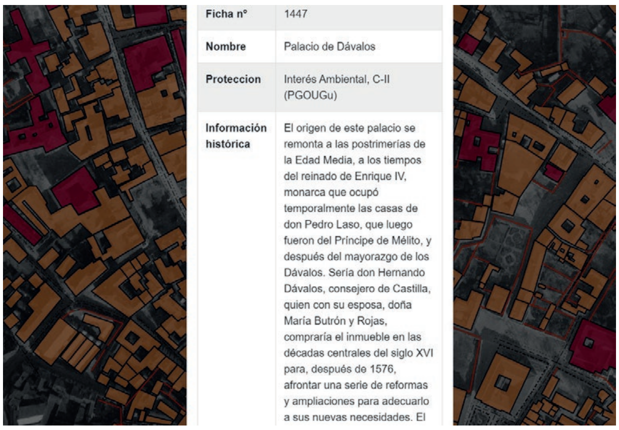
Figure 9 | WMS services on the TDT (Source: Authors).

5. Results

The result of the work carried out is the Territorial Digital Twin of Guadalajara in the field of knowledge of urban planning, territory and historical heritage. It has the analysis variables time and form. The time variable has an observation window corresponding to the last 89 years in 100% of the TDT coverage, and up to 118 years in some areas. The shape variable is linked to the digital terrain model (Figure 8) for the analysis of the topographic surface and to the digital surface model for the analysis of the construction layer. Figure 10 shows nine images representing the time variable observed in the Guadalajara TDT. The information provided by this time

Figure 10 | Time variable on the TDT (Source: Authors).

series is otherwise inaccessible. In this series it is possible to observe not only a great urban development, but also a profound change in the topography of the terrain. In the 1934 image, the Alzcazar Real de Guadalajara is visible in the western part, with its complete roofs, on the edge of the Barranco del Alamín which runs north of the city. To the north of the ravine, there are several cultivated areas with wide watercourses that flow into the ravine. In 1956 the Alcazar was practically in ruins, as can be clearly seen in the 2003 image. In the 1934, 1956 and 1966 images, the watercourses to the north, which flow into the ravine in the centre of the image, are clearly visible. In 1997, the area to the north of the ravine was urbanised by filling in the watercourses to create a hillside on which several blocks of flats have been built. This process of modifying the territory will continue until these hydrographic elements have completely disappeared. In 2003, a bridge was built over the ravine to connect the two sides of the town. The TDT can be seen on the website www.guadalajarahistorica.es (Figure 3), where, thanks to the topology of the vector layer, it is possible to analyse and make queries on the elements displayed. A file has been created for the architectural heritage elements, both those that still exist today and those that have disappeared (Figure 11), which have been assigned a different colour to the rest of the constructions. It is possible to search directly in the database for heritage elements (Figure 12) for output to



Ficha nº	1447
Nombre	Palacio de Dávalos
Proteccion	Interés Ambiental, C-II (PGOUGu)
Información histórica	El origen de este palacio se remonta a las postrimerías de la Edad Media, a los tiempos del reinado de Enrique IV, monarca que ocupó temporalmente las casas de don Pedro Laso, que luego fueron del Príncipe de Mélito, y después del mayorazgo de los Dávalos. Sería don Hernando Dávalos, consejero de Castilla, quien con su esposa, doña María Butrón y Rojas, compraría el inmueble en las décadas centrales del siglo XVI para, después de 1576, afrontar una serie de reformas y ampliaciones para adecuarlo a sus nuevas necesidades. El

Figure 11 | Heritage information on the TDT (Source: Authors).

Figure 12 | Search for items in the database (Source: Authors).

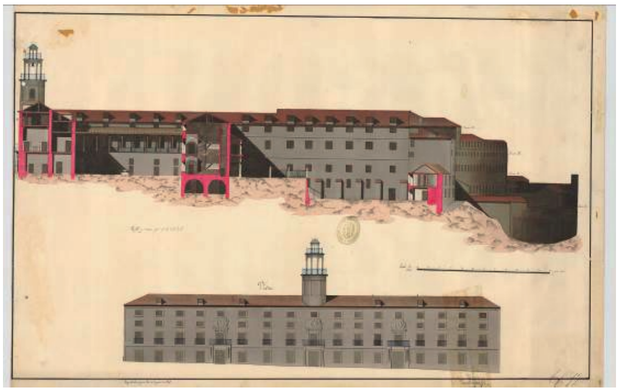


Figure 14 | architectural plans 1834 of the Academy (Source: G. de España. M. de Defensa. CC BY 4.0).

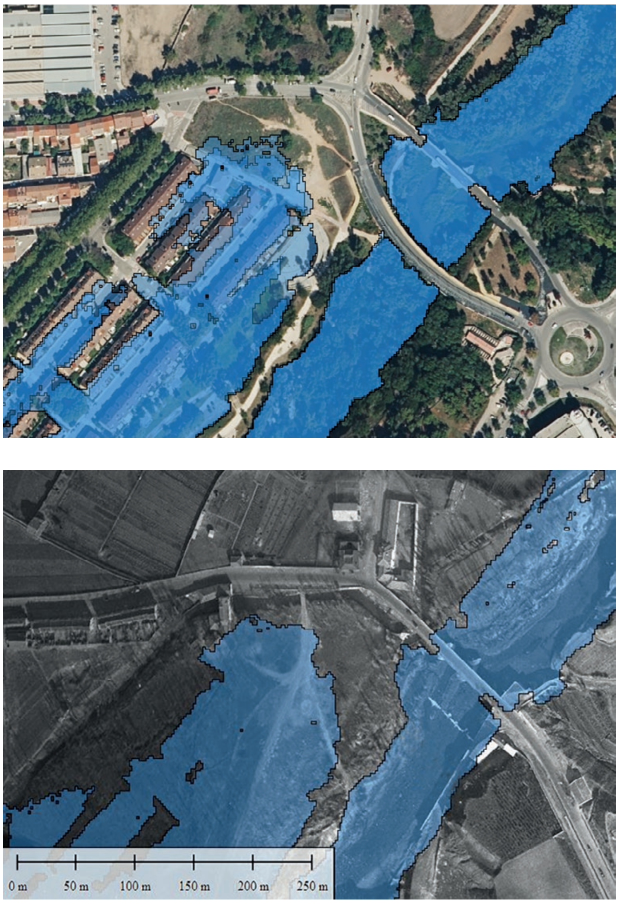


Figure 13 | Top side. 2021 Simulation of flooding on the TDT. Bottom side 1934 Simulation of flooding on the TDT (Source: Authors).

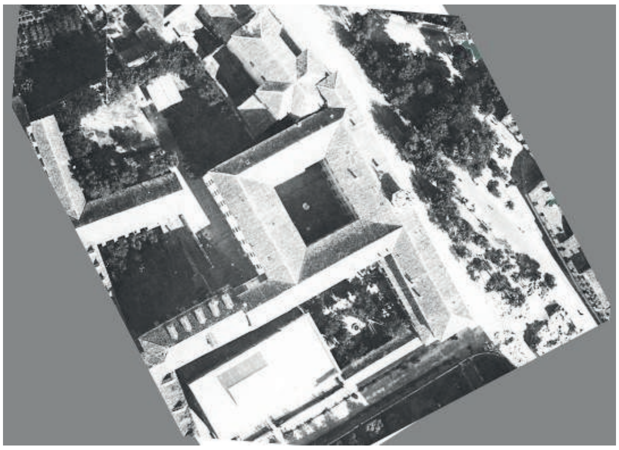


Figure 15 | Image from 1905 of the Academy (Source: G. de España. M. de Defensa. CC BY 4.0).

PDF, take measurements, draw vectors and load CAD files on the TDT. A feature, that endows the TDT with special capabilities and feedback, is the possibility to geolocate on it using a GPS-enabled mobile phone and an Android application specially developed for the project. Geolocation allows the user to locate himself on the ground at missing heritage elements and become aware of their dimensions, consult archives and take measurements. In the northwest part of the city, next to the Arab bridge over the river Henares, we can see architectural elements that no longer exist, such as the mill and its waterwheel, which took water from the river upstream of the bridge and returned it to its course downstream of the Henares. The TDT also makes it possible to simulate the behaviour of the water in this area (Figure 13), which is usually flooded when the river level rises. It can be seen that the former mill area is now an urbanised area, but the topographic conditions of the terrain have not changed much.

Figure 16 | Image from 1934 of the Academy area (Source: Authors from Provincial Historical Archive of Guadalajara).

Figure 17 | Image from 2021 of the Academy area (Source: Gobierno de España. M. Fomento. IGN).

Figure 15 (1905) shows in the centre of the image, taken from a balloon, the Academy of Engineers, executed as described in the elevation plans of 1834 (Figure 14). However, in Figure 16, it can be seen how, after a fire, part of the academy has been devastated, while figure 17, shows that the area is now a garden, with no memory of that building, where, however, the green area essentially coincides with the plan of the Academy.

6. Conclusions and discussion

The ability of the Territorial Digital Twin of Guadalajara to transmit the evolution of the territory leaves no doubt about the need to incorporate as many historical documents as possible into the time variable of the TDTs.

This study shows that geometrically corrected documents can be integrated into the TDTs using commonly used architectural software, such as ACAD, with almost the same level of geometric accuracy as when using specific photogrammetric software.

It confirms the need for an accurate vector layer with a topology that allows spatial analysis between the elements themselves and their relationship with other layers, for which the georeferencing of the TDT in an appropriate geodetic reference system is essential**.** With these premises, the TDT of Guadalajara is a Living Model that can be linked to other nearby TDTs. The Raster Tools add-on to ACAD, a popular desktop programme in the field of architecture, has given good results with a high number of points and when chunk transformations are applied. WSL-Monoploting Tool (MPT) can be very useful for the analysis of terrestrial photographs or old portraits of large elements on the landscape such as glaciers, snowfields, lagoons, forest masses, and incorporate this wealth of information into the TDTs. Pic2Map an interesting idea for incorporation into augmented reality environments of historical photographs or architectural drawings.

7. Future work

Regarding the TDT of Guadalajara, of the five levels of geometric and semantic detail (LOD) defined by CityGML (Lehner, 2020), the current state of the graphic base is LOD1, so progress must be made towards higher levels. Among other things, work remains to be done on how to improve and the digital twin on the Arab Bridge, northwest of the city, to analyse its temporal evolution based on historical images and complemented with current methods such as photogrammetry and laser scanning, as opposed to a sensorised model as proposed by Kong (Kong, 2023).

As for the historical data sources that still need to be studied and incorporated into the model, it is necessary to go deeper into the adjustment and correction of old cartographies, taking into account different altimetric datums for the combination of different techniques, since altimetry is an aspect that has not been dealt with in the literature consulted, and to apply the methods analysed to numerous documents that are not yet georectified in the archives.

In the future, it will be possible to use augmented reality for the three-dimensional visualisation of missing heritage elements recovered and modelled through historical documentation.

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