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Urban digital twins, morphology and open data: an initial analysis in Madrid

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Abstract

The concept of digital twins first appeared in engineering and has more recently been introduced in the realm of smart city methodologies. The aim to achieve a high degree of integration of an increasingly large array of different information sources scattered among the different public and private agents is usually driven by an engineering efficiency goal. This is undoubtedly relevant as it can become a tool for more sustainable cities. The intersection of that approach with the open data policies is relevant, as these are meant to allow a more transparent city management. As a working hypothesis, an urban digital twin should be transparent in its inputs, and the analytical methodology used should also be open as it is a tool for public policy. This paper shows that the current data infrastructure in Madrid, given its granularity and consistency, can become a foundation for a future urban digital twin.

Keyword: *Digital twin, Morphology, Madrid*

Introduction

The concept of digital twin was introduced by Michael Grieves less than 20 years ago in the realm of product lifecycle management. It is based on the premise that a physical system can be represented through a virtual system which is updated during its lifetime with input from the real-world twin. This means that over time it can bring predictive capabilities covering such issues as maintenance, repairs, upgrades... that would improve performance, reliability, and availability of the physical system to fulfil its role.

Initially applied to such realms as aerospace and military, the digital twin has become a research subject in the urban field, as it provides a wider framework for the concept of smart city. But a digital twin in aerospace, or a submarine or any other complex vehicle, operates in a highly coercive environment. The untimely opening of a hatch in one of such vehicles is surely contemplated in their digital twins, due to potentially serious effects. In such systems the situation prior to the existence of the twinned system is often deemed irrelevant, and there is a finite lifetime. Conversely, in a city there are individual actions weighting on its environmental impact, as opening windows while heating is on, or watering lawns during a drought, which are much more softly, if ever, coerced. A city has no pre-defined shelf life, and legacy systems are, but for new foundation cities and just during a limited number of years, often central to their functionality. The degree of uncertainty is linked to weaker coercion and more complex social interactions.

Table 1. The digital twin: engineering vs urban. Source: authors

	Aerospace, military, engineering	Cities
Coercion to users of the physical twin regarding contour conditions	High (military, company rules, litigation, physical survival, insurance…)	Variable, often loose or subject to personal perception, as utility prices
Publicity of coercion rules	Limited (military secrecy, terrorism prevention, intellectual property)	Public law
Time dimension	Limited lifespan, variable relevance of precedents	Unlimited lifespan and high relevance of precedents
Purpose of the object and performance definition	Clearly quantified from its inception	Broadly and qualitatively defined

Background

Urban digital twins have been a subject of research during recent years. In the European context the digital twin is often associated to climate resilience, carbon neutrality and sustainability, along with the generation of knowledge that can lead to intellectual property that can be marketed to cities. All over Europe similar initiatives are taking shape. In France the experience with the Rennes Digital twin, aimed at improving governance and citizen involvement, is included in the Programme for Industrial Demonstrators for the Sustainable City organized by the Ecological Transition Ministry, and is related to an interesting approach to the built city through cadastral data (Poquet, J, 2019) which is closely related to similar studies of the built urban form linked to energy (Defay et alts, 2019; Cordeau et alt, 2016) . In Germany there are also such local initiatives, as the digital twin of the city of Herrenberg (Dembsky et alt, 2020), in the Stuttgart area. The British case is of special interest by its depth of research, since the Center for Digital Built Britain (CDBB) released in 2018 the Gemini Principles Paper, which can be applied to prototypes of multi-asset digital twins for such large scales as cities. The design attributes relevant roles in sense making to such tools as big data analysis and data mining, and places in the sphere of decision-making others as rule based automation, machine learning and optimisation algorithms. The CDBB has instituted a National Digital Twin programme that has developed into the Digital Twin Hub, which integrates researchers and industry.

In Spain the concept of urban digital twins has been less developed until now. The national Ministry in charge of transportation and the urban agenda has tested the digital twin methodology for transportation infrastructures through its INECO consulting firm. Although there is no specific provision, the Spanish Urban Agenda is consistent with such an approach. Madrid, as the national capital and most populated city, has specific information sources of interest for such a project.

The purpose

Building on the hypothesis that urban digital twins will be formed by integrating sectoral information systems, this paper aims to test to which degree the current systems in place in the city of Madrid can contribute to that end. Figure 1 shows such a preliminary definition of the structure of an urban digital twin, considering the physical city as the field in which the flows of finite quantities of resources among a wide set of agents, each with a different degree of leverage over public policy making, with results in terms of quality of life for each of these agents. The regulatory framework is far from irrelevant in this matter.

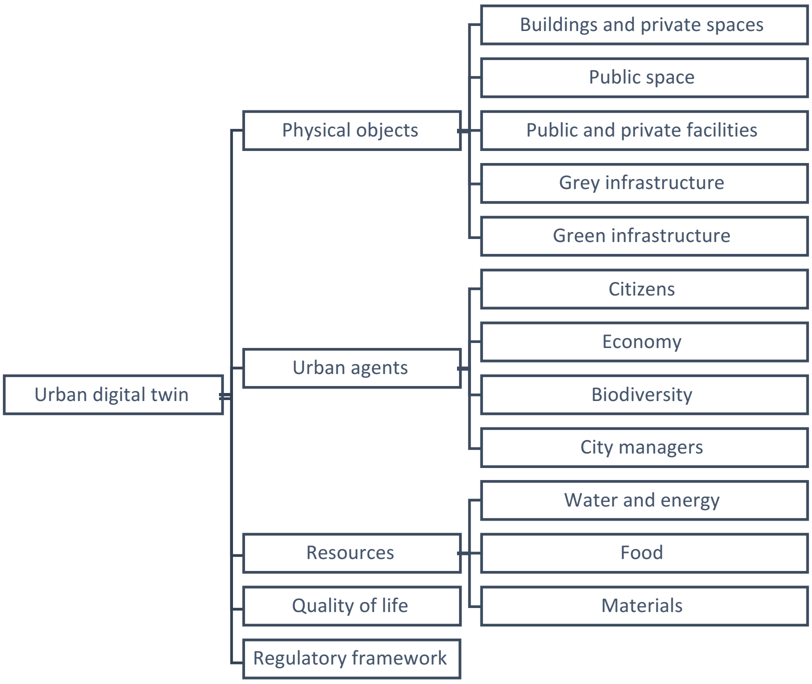

Figure 1*. The urban digital twin as model of physical objects and urban agents. Source: authors*

This paper focuses in a part of the task of implementing and updating an urban digital twin: building and private spaces data. This is due to its links to urban morphology as a disciplinary field, but also to the fact that in Spain overall, and in the case study of Madrid specifically, the already existing data systems provide what seems a foundation, which has already been described and tested by academia (Carpio et alt, 2021; Martínez Navarro et Alt, 2019; Martín-Consuegra Ávila, 2019) and in previous work by the authors (Barros and Ezquiaga, 2019, 2020).

Methodology

Case study

The municipality of Madrid covers an area of 604 sq km, with a population over 3,3 million as of 2020. It is the most populated municipality in Spain and the core of its most populated metropolitan area. This analysis focuses on what the cadastre names as urban land close to 66% which covers existing tissues, on which a diverse set of urban fabrics, densities and use mixes exist (Bataller Enguix et al., 2004). The focus on plots is inherent to morphological analysis, with recent studies of interest in the field (Kropf, 2018).

Data sources

The General Directorate for Cadastre of the Spanish Government publishes its data on the web using a variety of means. The shapefile edition includes a set of history layers for plots, buildings and other features that allow to trace changes in the physical configuration of the properties back to November 2001 in the oldest case, so it has been privileged for this study. History layers include, for each version of the feature, a field showing the date in which it was drawn (fechaalta) and that in which it was replaced (fechabaja). The system uses a cadastral code (referencia catastral) that is 14 characters long for plots and 21 characters long for each property inside a plot.

134.120 plots are included in the January 2021 shapefile version of the Madrid cadastral urban database. The history layer for plots includes 216.579 geometries, and 34.181 plot cadastral codes have more than one geometry associated. Some are limited to improved accuracy in measurements, but there are also larger changes, as for instance in land rearrangement operations. Changes can be the result of documents provided by the owners because of building works, but also come from updates produced by the General Directorate for Cadastre using field work. The last general update for Madrid was published in 2011, with partial updates published in 2013 (airport area, modifying a previous 2008 partial update for that same area) and 2016 (southern districts).

The Madrid City Council has an open data website with 491 datasets as of may 2021. This paper focuses on those concerning urban planning management areas (expedientes de gestion), close to what in the UK would be large area planning applications that been implemented.

Data preparation

The history shapefile layers for plots (parcela) and buildings (constru) have been processed so for each cadastral plot code the number of times it was drawn (fechaalta) and deprecated (fechabaja), as well as whether the cadastral plot code is in use (fechabaja=99999999) or it has been deprecated. The management areas shapefile layer was used as an overlay that allows for the selection of the plots included in that category. The alphanumeric dataset has been processed to extract data about current uses and built areas in properties related to the analyzed features. Figure 2 in this article reproduces the map of the plots as of January 2021, and the number of times each has been subject to geometry changes. PostgreSQL 10 and QGIS 3.18 were used for data edition, consolidation and mapping

Data processing results and consistency analysis

Table 1: Current plots vs history layer plots in Madrid, January 2021. Source: authors, using Spanish Cadastre open data

	Plot geometries	Distinct cadastral plot codes	Deprecated plot codes
Current plots shapefile	137.237	136.545	0
History plots shapefile	216.579	159.141	22.596

Table 1 shows that the current plots shapefile represents on average 1,005 polygons for each plot code, but on the history plots shapefile the ratio is 1,36. This is since some now deprecated plots had many polygons.

Table 2: Number of versions of plot code geometry for the whole city of Madrid, January 2021. Source: authors, using Spanish Cadastre open data

	Number of versions of plot code geometry					
	1 (no changes)	2 or 3	4 to 10	11 to 21	Over 21	Grand total
Number of plot codes	107.582	26.655	2.274	21	3	136.535
% of plots	78,79%	19,52%	1,67%	0,02%	0,00%	
Current area (sq m)	109.537.561	89.952.883	57.398.693	8.598.894	16.671.535	282.159.566
% of current area	38,82%	31,88%	20,34%	3,05%	5,91%	

Table 2 shows that 78,79% of the plots in the January 2021 shapefile, which represent 38,82% of the total plot area in the city, have experienced no changes. This includes 97.889 plot codes without changes since January 2003,, as well as 38.656 that have appeared later with a new code. An additional 19,52% of plots, covering 31,88% of the total plot area, have two or three versions (one or two changes). Higher number of changes are smaller in number of plots, but far from negligeable in terms of area.

The plots in the first category, 1 version (no changes), concentrate (January 2021) 72,1% of residential property units (roughly equivalent to dwelling number) and 58,8% of the overall built area.

Figure 2 shows the number of versions for each current plot. The airport concentrates the highest figures, due to cadastral updates and major extensions. The burial of the M-30 motorway along river Manzanares is not portrayed, as it is not on cadastral plots. Table 3 shows that changes have been more common in management areas, as lower proportions of plots and plot areas are without changes.

Table 3: Number of versions of plot code geometry for management areas in Madrid, January 2021. Source: authors, using Spanish Cadastre open data

	Number of versions of plot geometry- management areas					
	1	2 or 3	4 to 10	11 to 21	Over 21	Grand total
Number of plots	9.938	6.697	1.019	9	2	17.665
% of plots in m.a.	56,26%	37,91%	5,77%	0,05%	0,01%	
Current area (sq m)	49.831.193	65.979.345	48.120.164	2.171.729	2.336.989	168.439.420
% of current area in m.a.	29,58%	39,17%	28,57%	1,29%	1,39%	

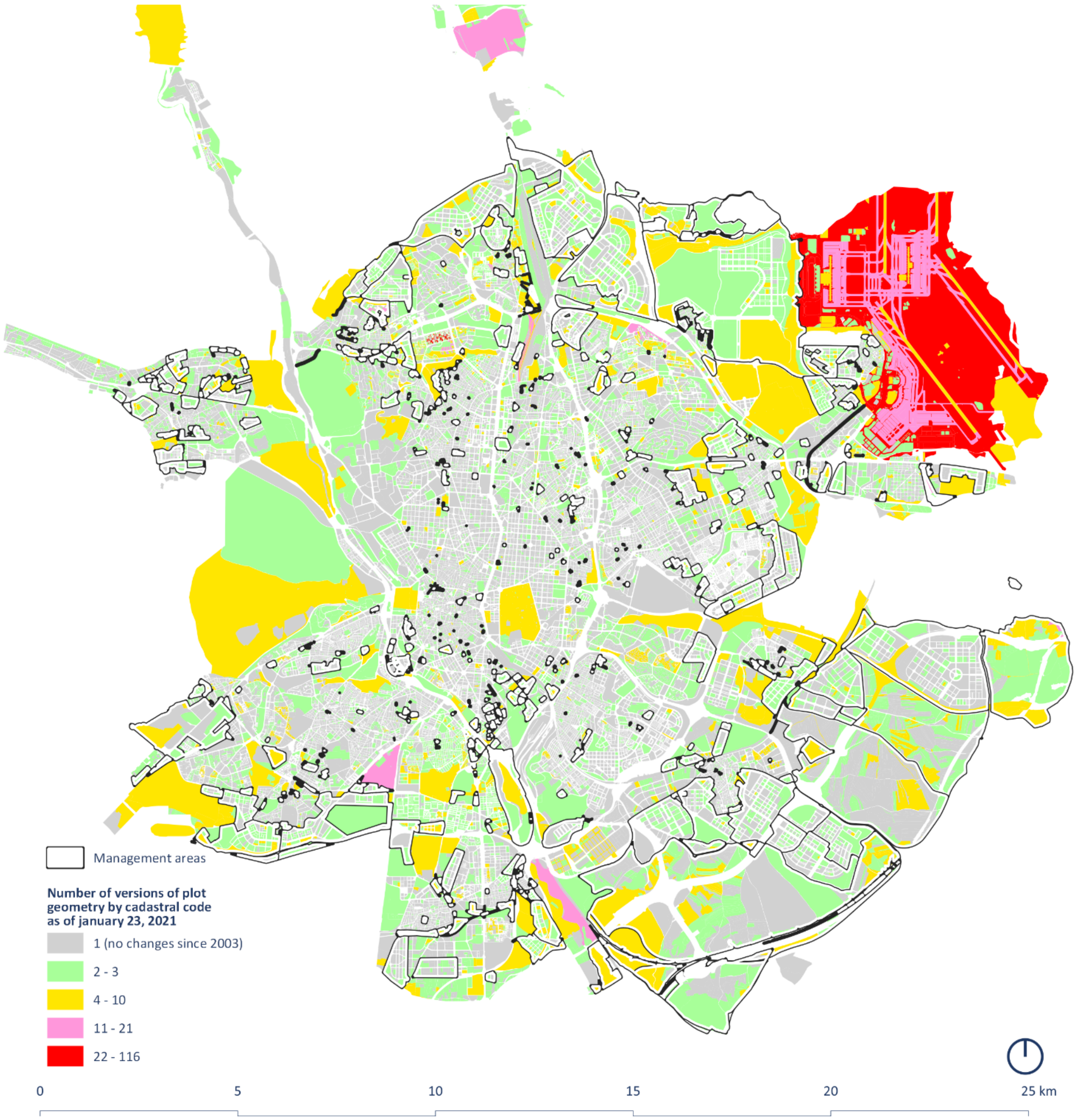

Figure 2*. Madrid plots as of January 2021, and number of times each has been subject to geometry changes. Source: authors, using Spanish Cadastre open data*

Results and Discussions

A first look at the maps shows that the built environment in Madrid has been subject to change dynamics over most of its urban tissue. The start of the open data movement regarding cadastral data in 2003 has coincided with a building boom followed, since the financial crisis initiated in 2008, by an economic crisis. Despite this crisis, change has continued and tissue description through cadastral data has also been fueled by general and zone-specific updates mandated by the cadastral authorities. The evolution of the plot geometry updates shows a dynamic which is close to that of the building production in the city, albeit dampened, as changes in lot configuration and new measurements don't need large budget operations.

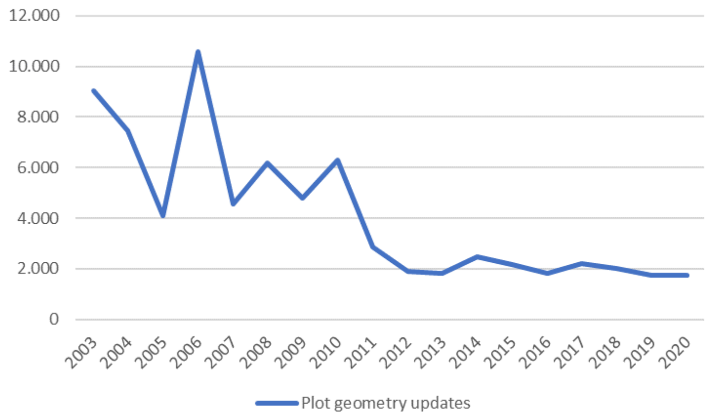

***Figure 4**. Plot geometry updates by year in Madrid, 2003 to 2020. Source: authors, using Spanish Cadastre open data*

The fact that the management areas have proportionally more changes than average is consistent with the physical transformations implied in such instruments. Close to 80% of the plots have not changed their geometry over 17 years, as despite visible changes, the fabric maintains its basic features, as most of the growth until 2008 was on plots defined with the 1997 plan, just prior to the analysed period. What is more of a surprise is that this stable 80% of plots accounts for slightly less than 40% of the current total plot area. This can be explained by changes in such large plots as the airport, or the Retiro park.

The results are consistent with what other data says about the city. The anomaly in the large number of changes in the airport coincides with a period of growth for this complex infrastructure and the fact that it was reappraised twice during the studied period; conversely, the fact that the large physical transformation along the Manzanares river is invisible comes from the fact that the data does not portray traffic tunnels.

Conclusions

Madrid has, through its cadastral system, a foundation for a future urban digital twin regarding the built environment. Its descriptive detail is limited when compared to systems linked to BIM methodologies, but it is already a reasonable source as changes in buildings and plots can deemed low frequency changes.

The first task for future research will be to evaluate in a more detailed way how the changes in lot and building descriptions have played in urban density. Further future research could explore how variables linked to the physical objects relate to urban agents' dynamics, and two main directions appear, as Madrid has high frequency updated data about population and jobs on one side, and there is a spatially detailed information about the evolution of the COVID 19 pandemic. A joint study of these variables can help provide a view of the dynamics of city use and health.

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