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Application to a deprived quarter in Madrid

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Highlights:

- Analysis of the energy performance at an urban scale by the generation of a spatial system with individual records for each building obtained from the big data stored in the cadastre
- Developement of a precision tool to assess the potential for improving energy efficiency in the urban fabric
- The change of scale involved helps bridge the gap between the analysis of individual buildings (bottom-up) and city-wide statistics (top-down approach)

Use of cadastral data to assess urban scale building energy loss. Application to a deprived quarter in Madrid

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Abstract

European directives and the objectives of the continent's 2020 strategy identify an urgent need to rehabilitate inefficient urban environments and bring them in line with a twenty-first century social market economy based on low carbon emissions and the harnessing of existing resources. An overarching approach informed by environmental, social and economic integration should be adopted to recover the built heritage and the cities that house it. Urban potential should be accurately assessed to ensure full advantage is taken of existing resources without generating false expectations and the concomitant perverse effects on the objectives of integrated urban regeneration.

The development of precision tools to assess the potential for improving energy efficiency in the urban fabric is a priority. This study proposes a method for calculating energy loss across building envelopes based on the exploitation of cadastral data with open source IT tools. The output includes neighbourhood-scale information on the thermal performance of building envelopes and energy dispersion relative to a city's climate based on energy loss calculations. More generally, it establishes energy efficiency of the existing urban fabric from precise energy indicators developed with pooled geometric data collected building by building from the cadastre.

The method is verified by analysing the findings for a case study in an area on the outskirts of Madrid characterised by inefficient construction and listed as a deprived neighbourhood, with a population very likely to be subject to energy poverty. The methodology described can be extrapolated to other European cities with cadastres similar to Spain's and in particular to those in temperate Mediterranean climates with cold winters and warm summers.

Keywords: integrated urban regeneration, energy efficiency, urban data science, cadastre.

1 Introduction

Models based on samples of existing representative buildings constitute a tool widely used today to estimate the energy performance of the building stock [1]–[5]. The detailed information provided by these methods is generalised to draw overall conclusions. The problem with that approach is its small scale, which prevents it from delivering a sufficient number of statistically representative cases to reproduce all the complex reality of cities.

Earlier studies [6] estimated the energy vulnerability associated with urban-scale construction based on statistical models and pooled data drawn from Spain's Population and Housing Census [7], [8]. The findings identified the urban areas with inefficient residential buildings based on the period of construction. City neighbourhoods can be classified and energy poverty indicators obtained for each census division by including income data in the analysis.

By generating a spatial system from the big data stored in the cadastre, the breadth of the study can be expanded beyond the built unit and whole urban areas can be analysed to a satisfactory level of accuracy. With the inclusion of data on the thermal performance of existing buildings in this system, much more comprehensive energy models than obtained to date can be developed for the building stock. That in turn yields a more accurate diagnosis of the current state of whole neighbourhoods and an appraisal of the impact of energy improvement measures. The change of scale involved helps bridge the gap between the analysis of individual buildings and city-wide statistics.

The Permanent Committee on Cadastre in the European Union is attempting to harmonise European cadastres with a view to information compatibility, exchange and transparency [9]. The digitisation, systematisation and publication of cadastral data favour research. Where urban spatial data are accessible and interoperable, the geographic information in data corpora can be integrated or inter-related, providing a sound basis for decision-making. Studies such as the one described here smooth

the ground for developing European-scale environmental management tools that can be applied to the INSPIRE (Infrastructure for Spatial Information in Europe) project [10].

2 Objectives

The primary objective of this study was to develop tools for including energy efficiency criteria in integrated urban regeneration measures [11] with a view to meeting the objectives of European building energy efficiency directives [12], [13]. More specifically, the aim is to facilitate the design of strategies for rehabilitating urban areas with inefficient buildings to comply with the provisions of Article 4 of Directive 2012/27/EU [14] requiring Member States to establish a long-term strategy for mobilising investment to regenerate their residential and commercial building stock. Designing such strategies calls for a quantitative assessment of the status quo to accurately estimate the potential for improvement.

Issues associated with the mitigation of fossil fuel depletion and climate change, such as the reduction of energy consumption and dependency, CO₂ emissions abatement and urban air pollution, were also broached. The aim was to improve the conditions prevailing in indoor space, which affect occupants' health. Improving energy efficiency in deprived quarters would also alleviate energy poverty [15].

2.1 Limiting energy loss

In the passive solar approach to the rehabilitation of existing neighbourhoods, wintertime heating demand is reduced by limiting losses and encouraging solar gain, whereas gain must be limited and energy losses furthered to reduce summertime cooling demand [16].

In Madrid, Spain, which has a continental Mediterranean climate and is characterised by multi-occupancy, high-rise housing, the primary source of residential energy consumption is heating, which accounts for approximately 55,3 % of the total [17]. The rest of the demand is generated by household appliances (17.6 %), domestic hot water (17.4 %), cooking (6.5 %), lighting (2.6 %) and cooling (0.7 %). Energy losses have been identified in a number of studies as determining factors in domestic heating demand [18]. The situation is particularly sensitive in deprived, low-income neighbourhoods

characterised by inefficient buildings in which poor, obsolete envelopes deliver low thermal performance [19]. Limiting such losses is presently regarded as the most urgent strategy to reduce urban energy consumption.

This study aimed to develop a Model for Analysing Spatial Data (Spanish initials, MADE) to estimate the potential for reducing losses by comparing current conditions to the possible results of implementing energy efficiency improvements. The vehicle proposed was the characterisation of the thermal performance of urban areas.

2.2 Areas studied

The area studied covered residential neighbourhoods characterised by inefficient multi-family housing built between the nineteen forties and the nineteen eighties [20]–[22]. In keeping with the literature, particular attention was paid to supplementing the existing information on neighbourhoods listed as deprived urban areas [23] to attempt to mitigate the difficulty of furthering rehabilitation in quarters with a paucity of resources [24].

The findings were validated by applying the method to ‘Poblado de Canillas’, a neighbourhood in Canillas quarter, Hortaleza District, Madrid, Spain. Most of this neighbourhood, which is listed in the country’s Atlas of Deprived Neighbourhoods [25], has the lowest heating energy efficiency rating possible (letter G). Moreover, several building complexes are listed in the Iberian DOCOMOMO registry of heritage structures [26], making their conservation a priority.

3 Methods

The Method for Evaluating Energy Losses (Spanish initials, MEPEC) uses cadastral databases as a source of information. The cadastre is the administrative registry of rural, urban and special property values kept by the Ministry of the Treasury and Public Service. Entry in the cadastre is mandatory and cost-free and the unprotected data are public. First, last and corporate names, tax ID number and address of property owners constitute protected data, as well as the cadastral value of the terrain and, as appropriate, of any property units on it.

Fig. 1.Descriptive and graphic output files for a cadastral query (Sede Electrónica de Catastro, 2011)

This study generated information for rehabilitation research addressing improvements by estimating energy efficiency indicators for urban environments. That involved supplementing the existing elements of building energy analysis with non-protected cadastral data (Figure 1), which were exploited to conduct a detailed urban-scale analysis for each property unit (identified with the reference code, REFCAT). That procedure entailed parametrising the features of urban morphology that affect the energy performance of whole neighbourhoods [27]–[29] and cross-referencing those elements with the data required for energy assessment. The procedure consisted in the following steps:

- generation of three-dimensional neighbourhood models based on vectorial (SHP) cadastral data
- computation of the built area by usage and the area of the thermal envelope of each building associated with the respective use as specified in the cadastre, based on the entry of unprotected alphanumeric data (CAT) into the vectorial (SHP) model

- calculation of the thermal performance indicator for the envelope: the overall heat transmission coefficient ($KG_{urb}, W/m^2 K$), by entering information on building thermal characteristics into the model (see section 4.1).
- estimate of energy dispersion in the city based on the calculation of energy loss (H_t , kWh year) in each building and building group, using the degree-day method [30] and entering site climate data into the model
- estimate of the energy efficiency indicator for the urban fabric based on the normalisation of loss per built volume, H_t/V (kW/m^3 year).

3.1 Cadastral data downloading and processing

Citizens can download Directorate General of the Cadastre (DGC) data through a number of services. The ones used for this study are listed in Table 1, showing the type of data received, the source, a brief description of the service offered on the cadastre's website and the respective heading.

Table 1. Mass data download services (Sede Electrónica de Catastro, 2011a)

<https://www.sedecatastro.gob.es>

Service	Type of data	Source	Description
Vectorial cartography	Alphanumerical Vectorial	Cadastral	Vectorial cartography, with information by town/city and layer of the cadastral cartography
Website	Alphanumerical	Cadastral	Unprotected cadastral information. SOAP (simple object access protocol)

Vectorial cartography

As noted earlier, cadastral cartography is provided in vector format (shapefile) by town/city, with separate shapefiles for each layer. The layers/tables available include:

- CONSTRU: urban sub-lots showing the built volume within the plot
- MASA: plot groups (city blocks and rural polygons)
- PARCELA: cadastral plots
- SUBPARCE: cultivated subplots.

The cadastral plot schedule comprises the layers MASA, PARCELA, SUBPARCE and CONSTRU.

CONSTRU includes urban sub-plots, which show the built volumes on a plot. The fields relevant to the method proposed here are defined in Table 2.

Table 2. CONSTRU layer attributes used (Sede Electrónica de Catastro, 2011b)

FIELD NAME	TYPE OF DATA	LENGTH	DESCRIPTION
REFCAT	VARCHAR2	14	Cadastral reference for the plot
CONSTRU	VARCHAR2	16	Built heights
NUMSYMBOL	NUMBER	2	Sub-plots with buildings: identified with the number 11
AREA	NUMBER	10	Element area in square metres

REFCAT14 and REFCAT20 are the plot and property unit identifiers defined in the cadastre.

- REFCAT14 / REFCAT: cadastral plot reference, 14 unique characters for each cadastral plot. More than one property unit may lie on a given plot.
- REFCAT20: cadastral reference for buildings, 20 characters, the first 14 of which identify the respective cartographic plot and the other six the property unit on the plot.

Website services (WS)

The website service furnishes unprotected cadastral data (all except ownership and value) on a property unit as identified by its cadastral reference, including:

- CADASTRAL PLOT: location, area and share in tenure
- PROPERTY UNITDESCRIPTION: cadastral reference, location, classification (rural/urban), main usage, built area (m²) and year of construction
- CONSTRUCTION: main usage, staircase, storey, dwelling and area (m²).

Data downloads and processing

This section addresses the manner in which software and information were integrated to download, process and exploit the spatial data [31]. Figure 2 shows the flowchart for the program used to obtain façade length per built storey and the property unit data described in the preceding section.

The Python language modules used were:

- Pandas (<http://pandas.pydata.org>), a data analysis module
- Geopandas (<http://geopandas.org/>), for readier handling of geospatial data, a function that extends the data types used by Pandas to perform spatial operations on geometric types.

Fig. 2. Spatial data model flowchart

The field CONSTRU in the CONSTRU.SHP layer/table (1) described under the heading ‘Vectorial cartography’ gives sub-plot height codes. That information was used to build the height adjacency

matrix (2-3) from which, via spatial analysis (4), façade length and orientation data were obtained for each property unit recorded (5).

The REFCAT field, also in the CONSTRU.SHP layer/table (1) described under ‘Vectorial cartography’, lists the cadastral references for each plot. The data described under ‘Website services (SW)’ (8-9) were found for the property units on each plot using the respective cadastral references (6-7).

3.2 Geometric characterisation

The vectorial and alphanumerical cadastral data downloaded were processed with Spatial Data Analysis Model (MADE) software to characterise the neighbourhood geometrically. Model output, a data sheet for each cadastral reference, showed the built volumes on each plot. In the MEPEC method, the geometric variables affecting buildings’ energy performance were also included in the model.

Heated/cooled area

The cadastral built area was found for each property unit (*REFCAT 20*) sited on each cadastral plot (*REFCAT 14*) with buildings (*numsymbol 11*). The data available sufficed to associate each property unit with a detailed usage. Spaces which, further to the existing legislation [32], require heating/cooling were selected for energy assessment purposes, whilst communal areas such as garages, warehouses and similar were excluded. Information on the year of construction recorded in the cadastre was also collected. With a view to determining the cadastral value of property units, the Directorate General of the Cadastre periodically updates these data, taking account of the improvements made in buildings over the years by applying a remodel rating.

MADE data output can be converted into a matrix tabling area data against the variables usage and period [33]. Urban complexity can be estimated by entering usage information into the MADE [34]. Entering building usage profiles (residential, academic, commercial...) also yields information relevant to energy demand studies of whole neighbourhoods by time of day and season [35]. That fairly recent time-based approach to models for estimating energy demand [36] acquires particular importance

when estimating demand peaks for modelling HVAC systems and supply grids by district. The aim is to apply it to future rough pre-dimensioning for neighbourhood solar energy installation and distribution grid layout.

The application of this method to the case study of the Canillas neighbourhood showed that the area is predominantly residential and nearly all building services were installed in the period 1940-1980, with no thermal insulation (table and figure 3).

Table 3. Heated/cooled area (m²) in the Canillas neighbourhood by use and period

Use/Period	pre-1940	1940-1979	1980-2006	post-2006	TOTAL
HOUSING	392	104327	28795	1237	134751
RETAIL		4987	684		5671
EDUCATION		6708			6708
HEALTH		1644			1644
LEISURE-HOSTEL.		255			255
OFFICE		147			147
SPORTS		1610	27		1637
WORSHIP		895			895
INDUSTRIAL		29			29
OTHER		676			676
TOTAL	392	121278	29506	1237	152413

Fig. 3. Classification of other than residential uses in Canillas (m²)

Building height and volume

Although methods are currently in place to predict building height from 2D models [37], the volume of building elements can be more precisely deduced from cadastral CONSTRU data and SHP 2D geometry. Python software (CONSTRU_ALTURAS.ipynb) was developed to transfer each CONSTRU height code to a matrix (an extract of which is reproduced in Table 4) giving the number of storeys, from H01 to H60 (maximum in the city of Madrid). The value 1 in a cell indicates that the property units on the level specified contained information on built area, usage details and year of construction. The total height of each building was found by computing the number of value 1 storeys. Although cadastral coding also describes below-grade storeys and their usage, this study was simplified by including above-grade areas only, on the assumption that below-grade space is not inhabitable and not heated or cooled. Neighbourhood mean building height was weighted to footprint area.

Table 4: Model output data on heights calculated from built volume

REFCAT	Year of construction	H01	H02	H03	H04		H60	Number of storeys	TOTAL HEIGHT (m)
4994542VK4749F	1957	1	0	0	0		0	1	3
4994538VK4749F	1959	1	1	0	0		0	2	6
4994539VK4749F	1962	1	1	1	0		0	3	9
4994541VK4749F	1959	0	1	0	0		0	1	3
5094206VK4759C		1	1	0	0		0	2	6
4994540VK4749F	1959	1	1	1	1		0	4	12
....									

The approximate heated/cooled volume of buildings was found from the area and number of storeys. As the cadastre lists the number of storeys but not the height of each, a standard 3 metre height per storey (30 cm for the structural floor and 2.70 m for indoor clearance) was adopted in all cases to assess the potential of the method. Although this simplified value was adopted, the model could be adjusted more precisely if the specific storey height for each urban area were entered, given the significance of the impact of that parameter on heated/cooled volumes.

Envelope area

The vectorial model values for perimeter, area and height in the cadastre's SHP cartography were the input data for the MADE. Façade orientation and length were deduced from the geometric data. Python ADP software (*Fachadas_shp_polylines.ipynb*) was used to store the information in the downloaded cadastral plot records.

Gross façade area was computed from the perimeter of the polygons containing buildings and the respective height. The 2D lines for height were defined via line element centroids to detect and subtract party walls: if two lines had the same centroid and a different cadastral reference, they were identified as party walls and not computed. That procedure ensured that the relationship between adjacent built volumes could be analysed precisely for each storey.

The angle perpendicular to the line objects defining polygon perimeters was found with the *AZIMUTH* function and translated into façade orientation (N, SE, S, SW, W, NW) with the *ORIENTACION* function (Table 5). The output data consisted in one line *Shapefile* for each story in the neighbourhood analysed (Figure 4). Although façade orientation was irrelevant to the energy loss estimate *sensu stricto*, this information was entered into the MADE because the intention was to use the same model in future to determine solar gain.

Fig. 4. Computation of case study façade areas by orientation (ground storey)

A fixed 16 % of openings for all façades, irrespective of orientation, was assumed to find the transparent area and, by subtraction from the total, the net opaque area. The aforementioned percentage was adopted on the grounds of samples of multi-family housing developments constructed on the outskirts of Madrid between 1940 and 1980 [38].

Table 5. Façade dimensions in the Canillas neighbourhood, total by orientation

Orientation/Dimension	E	N	NE	NW	W	S	SE	SW	Total
Length (m)	8547	13201	745	1477	8533	13157	1495	7678	47926
Area (m ²)	25642	39604	2237	4433	25600	39472	4486	2304	143778
% openings	16 %	16 %	16 %	16 %	16 %	16 %	16 %	16 %	16 %
Tnspt area (m ²)	4103	6337	358	709	4096	6315	717,83	369	23004
Opq area (m ²)	21539	33267	1879	3724	21504	33156	3769	1935	120773

Total roof area for the neighbourhood was assumed to be the same as the sum of the building footprint areas. The cadastral configuration codes for the buildings were used to identify porticoes, porches and structural floor overhangs in contact with the outdoor air to distinguish them from the grade level floors for subtraction from the total.

Table 6. Envelope areas in the Canillas neighbourhood by period of construction

Element	Pre 1940	1940-1979	1980-2006	2007-2013	TOTAL
Façade (gross)	827	119314	22375	1262	143778
% openings	16 %	16 %	16 %	16 %	16 %
Façade (trnspt)	132	19090	3580	202	23005
Façade (opaque)	694	100224	18795	1060	120774
Roof	526	36037	12142	411	49116
Floors in contact w/ air	0	497	432	0	930
All other floors	526	35539	11710	411	48186
TOTAL	1878	191387	46660	2085	242010

Here the MADE output data consisted in a summary of the neighbourhood-wide thermal envelope (Table 6), obtained by pooling the data associated with each REFCAT code, grouped by the construction periods defined in section 3.3 (Table 8).

Other urban geometric indicators: compact structure, density...

Useful indicators for relating urban layout to energy performance can be obtained with a number of simple operations and data pooled for all the existing buildings (Table 7). Compactness was found as the ratio between heated/cooled volume and the area of the thermal envelope. Its inverse is the urban form factor.

$$C = V_{\text{acond}} / S_{\text{env}}$$

where:

C = Compactness (m^3/m^2)

V_{acond} = volume of air associated with heated/cooled usages (m^3)

S_{env} = total area of the thermal envelope (m^2)

Table 7. Summary of geometric indicators for the neighbourhood and three specific buildings (tower, high-rise and single family dwelling)

Reference	Env. area (m ²)	Footprint (m ²)	No. storeys (units)	Mean height (m)	Volume (m ³)	Compactness (m ³ /m ²)
Total Canillas neighbourhood	243317	49769	3.22	9.65	480253	1.97
Tower REFCAT 4994547VK4749F	5380	346	13	39	13647	2.21
High-rise REFCAT 4992543VK4749D	706	155	4	12	2200	2.50
Sng fam REFCAT 5292448VK4759C	170	35	2	6	208	1.22

The values of the following indicators, useful for characterising the energy performance of the Canillas neighbourhood (total area = 198 218 m²), were calculated as follows:

D	2.42	Density	(built volume/total neighbourhood area)
RSD	0.68	Residential surface density	(housing use area/total neighbourhood area)
FAR	0.77	Floor area ratio	(Inhabitable area/ total neighbourhood area)
BCR	0.25	Building coverage ratio	(area occupied/total neighbourhood area)

3.3 Thermal envelope characterisation

The thermal characteristics of the building envelopes in the neighbourhood were entered into the MADE to estimate urban-scale energy losses. Estimated envelope thermal performance values were allocated to each period [39]. The data used were linked to the variable *year of construction* in each building's cadastral reference.

A number of studies have been conducted in Europe on building stock thermal performance [1], [40]. In Spain the requirement to include thermal insulation in building envelopes was not enacted until 1979 [41]. Construction solutions for building envelopes in several Spanish cities dating from different periods have also been analysed [42]–[45]. The division of the building stock into the periods proposed here (pre-1940, 1940-1979, 1980-2006, post-2007) is fairly constant across all those studies.

The classification of envelopes by construction period is consistent with the criterion adopted by the Spanish Government [46], [47] in its long-term strategy for the energy regeneration of obsolete buildings, designed in keeping with European requirements [14]. That strategy identifies urban areas built prior to 1979 as inefficient clusters. In Madrid, buildings constructed prior to the entry into effect of the first energy efficiency legislation are known to account for 56 % of the total housing stock [20].

If known, the real values of envelope thermal transmittance can be entered in the model. The data sheets available for some of the developments built in Canillas, a neighbourhood designed in the nineteen fifties were used to attribute values to the case study parameters (Figure 5).

36

UTM: 40.462116, -3.647760.
P.D.Canillas
Distrito: Hortaleza-Canillas

DATOS DEL CONJUNTO

Año: 1959 N° viviendas: 1424 (791)
Superficie construida: 59695 m²
Superficie ocupada: 29304 m² (13541 m²)

DATOS CONSTRUCTIVOS

Fachada	1/2 pie+ ca 5cm+THS+ enlucido	F7
Cubierta	Plana. Asfáltica.	C6
Carpintería	Madera	H2
Vidrio		
P. solar	Persiana	P1

Fig. 5. Sample data sheet for the Canillas neighbourhood (Oteiza et al., 2016)

Original	Translation
DATOS DEL CONJUNTO	DATA FOR WHOLE NEIGHBOURHOOD
Año	Year
N° viviendas	No. of dwellings
Superficie construida	Built area
Superficie ocupada	Area occupied
DATOS CONSTRUCTIVOS	CONSTRUCTION DATA
Fachada	Façade
½ pie+ca 5cm-THS-enlucido	½ foot+5 cm air space-face brick partition-plaster
Cubierta	Roof
Plana. Asfáltica	Flat. Asphalt
Carpintería	Joinery
Madera	Timber
Vidrio	Glazing
P. solar	Solar protection
Persiana	Blind

The period prior to 1979 was characterised with values drawn from studies based on samples of the building stock in place at the time [38], [48], [49]. To render the data more generally applicable, functional town planning models for developments built on the outskirts of Spanish cities in the period 1940-80 were assumed to be similar. The studies reviewed appeared to indicate scant variation in the construction systems used. Intense housing construction that began after the Spanish Civil War (1936-1939) to accommodate mass domestic migration induced urban uniformity [50]. The enactment of specific legislation for social housing [51], [52] and the consistent application of the same construction processes based on labour-intensive brick masonry during the dictatorship led to such uniformity. These conditioning factors determined the morphology of outlying neighbourhoods, driven by the premises governing State-fostered developments, and had a bearing on private developments. Some authors have concluded that the difference between social and wholly private housing are insignificant in many respects [53].

Beginning in 1979 legislation specifically addressing building heating/cooling and energy efficiency was gradually enacted in Spain [32], [41], [54], resulting in progressively stricter construction demands as regulations and industry experience improved residential thermal performance. The legal requisites in place in each building's cadastral year of construction were used to characterize the enclosures by periods.

For neighbourhoods where the construction solutions were unknown, the values listed in Table 8 were used. A simplified approach, consisting in applying thermal transmittance values (U-value, W/m^2K) to each building based on its (cadastral) year of construction, was adopted to characterise façades (including opaque and transparent elements), roofs and floors.

Table 8. Envelope thermal transmittance values by period and construction element

Period/Element	Façade	Openings	Roof	Outdoor floors	All other floors
Pre-1940	2.00	3.70	2.67	2.50	1.00
1940-1979	1.55	3.70	2.40	2.50	1.00
1980-2006	1.20	3.50	1.00	1.20	1.00
Post-2007	0.66	3.38	0.38	0.49	0.49

4 Results

$KG_{urb}(W/m^2K)$, a thermal envelope quality indicator, was determined and energy loss, H_t (kW), assessed for the entire neighbourhood by relating envelope data (Table 6) to construction characteristics (Table 8) for all the buildings, grouped by period. An overall urban morphology energy efficiency indicator, $IEE_{urb}(kW/m^3)$, was defined to take account of the total energy loss calculated for the neighbourhood, per its total built volume.

4.1 KG_{urb} , urban overall heat transmission coefficient

KG (overall heat transmission coefficient) is the mean of the thermal transmission coefficients (U) of the various envelope elements in a building, weighted by the area of each element. Neighbourhood envelope quality was determined based on a simplification involving the overall heat transmission coefficient, KG_{urb} , the result of summing the thermal transmittance, U (W/m^2K), of each building's envelope elements weighted by their area. It can be used to characterize urban clusters.

$$KG_{urb} = \sum U \times A / \sum A$$

where:

KG_{urb} = urban overall heat transmission coefficient (W/m^2K)

U = thermal transmittance of exposed surface (W/m^2K)

A = area of exposed surface (m^2)

That operation was performed for the (transparent and opaque parts of) façades, roofs and floors by matching the thermal characteristics of each envelope element to the year of construction specified in the cadastral reference (REFCAT14) for each building.

Fig. 6. Overall loss coefficient KG (W/m²K) for each building in the neighbourhood

Figure 6 shows the overall heat transmission coefficient, KG, estimated for each building in the case study, based on the weighted mean of the UxA values for each envelope element. Building thermal characteristics differed from one period to another. The lowest thermal quality was found in the original urban fabric built between the nineteen fifties and eighties, with even lower values found for scantily compact arrangements (corner buildings, towers...). Buildings in the west end of the neighbourhood, constructed in 1990-2006, performed better than the rest and had a different potential for improvement.

4.2 Energy losses due to conduction across the envelope

Energy losses are estimated as the sum of losses due to conduction across the envelope and convection-related losses induced by air infiltration. This study characterised the former. Characterising undesired infiltration-induced losses would call for studying envelope air-tightness [55].

$$H_t = KG_{urb} \times A_{tot} \times (T_{int} - T_{out})$$

where:

H_t = transmission heat loss (kW)

KG_{urb} = urban overall heat transmission coefficient (W/m²K)

A_{tot} = Total neighbourhood envelope area (m²)

T_{int} = indoor air temperature (°C)

T_{out} = outdoor air temperature (°C)

Climate information must be entered in the MADE to estimate total yearly energy losses (Rodríguez-Soria et al., 2015). A simplified estimate of the difference between indoor and outdoor temperature can be found with the degree-days (GD) method: i.e., by summing wintertime temperature differences between a base value, a , and the mean daily temperature when lower than a second value, b . In Spain the value used is 15 °C for a and b both [41]. This method was applied to take the effects of global warming into consideration by computing degree-days from updated climate data [56].

Table 8. Mean yearly degree-days (base=15/15) in NBE CT 79 and updated for 1981-2010

	Code NBE CT 79 mean yearly degree-days and climate class (base= 15 °C)		Updated mean yearly degree-days and climate class for 1981-2010 (base = 15 °C)	
Madrid	1 404.9	D	1 281.3	C

According to the model results for Canillas, the yearly energy losses for the neighbourhood as a whole amounted to 13 967 635 kWh (Table 9) which has a direct impact on heating demand. The analysis suggested that global warming prompted an 8.80 % abatement in energy loss.

Fig. 7. Yearly energy losses (kWh) in Canillas neighbourhood buildings

Table 9. Yearly energy losses (kWh/year) delivered by the model for the Canillas neighbourhood, tower, 4994547VK4749F, high-rise 4992543VK4749D and single family dwelling 5292448VK4759C

	Volume (m ³)	Env. area (m ²)	KG (W/m ² K)	UxAtot (W/K)	Losses (kWh)	IEE (kWh/m ³)	GW scenario losses (kWh)
Total Canillas neighbourhood	480253	243317	1.70	414254	13967635	30.55	12738793
Tower 4994547VK4749F	13647	5381	1.87	10056	181418	28.55	309231
High-rise 4992543VK4749D	2200	707	1.81	1278	23831	24.4	39314
Sng fam 5292448VK4759C	208	170	1.81	308	5725	49.94	9473

GW = global warming

Losses were greatest for housing in very high towers, followed by high-rises, which varied depending on whether the buildings were compact or otherwise (Figure 7). The largest losses were logically observed for the largest scale buildings. Non-housing also exhibited high energy losses, denoting a need for energy improvements in the respective envelopes and inclusion of such buildings in residential area rehabilitation plans.

4.3 Urban energy efficiency indicator

The effect of urban morphology on energy dispersion in a city can be summarised by means of an indicator of the losses (H_t) per unit of building volume.

Losses per heated/cooled volume:

$$IEE_{urb} = H_t / V_{acond}$$

where:

IEE_{urb} = urban energy efficiency indicator (kWh/m³)

H_t = transmission heat loss (kWh)

V_{acond} = volume of air to be heated/cooled (m³)

This is an ideal indicator to characterise the effect of urban morphology on energy efficiency. It covers architectural features (size, volume, compact configuration) and includes both quantitative (exchange areas) and qualitative (construction characteristics) envelope data as well as the climate-induced demands at a given site. Its inclusion in city planning quality standards is consequently recommended to ensure that they take energy efficiency into consideration [57].

The IEE_{urb} value found for the Canillas neighbourhood was 30.55 kWh/m³. Loss per unit of habitable area (kWh/m²) constitutes another useful indicator for comparing energy loss data to the energy demand ceilings laid down in the existing legislation [32]. The value found for Canillas was 91.65 kWh/m² of conduction-induced loss across the envelope per unit of inhabited area. The values of both parameters were consistent with the heating energy demand estimates set out in energy certification procedures for existing buildings [58].

Fig. 8. IEEurb and KGurb of Canillas (in red) and Ht/V indicator for the buildings in the sample analysed

The Ht/V value for each building in the Canillas neighbourhood is plotted against its overall heat transmission coefficient (KG) in Figure 8. This indicator provides a measure of passive building energy performance, including morphological aspects in addition to envelope quality. Some buildings with poor quality envelopes but in compact configurations were found to deliver higher efficiency than others with better quality façades. The energy required per volume of air to be heated varied substantially in the three buildings analysed, all with old, poor quality envelopes: the highest value was recorded for the single family dwelling and the lowest for the apartment block, the most compact structure.

Energy needs were observed to depend not only on the thermal quality of building enclosures, but also on geometric factors. The findings showed that, as building KG declined with envelope improvements in successive construction periods, thermal transmission and with it losses also tended to decline.

Nonetheless, good quality buildings (low KG values) were found to have higher losses per unit of heated volume than others of even better quality.

5 Discussion

The drastic reduction of energy demand to optimal cost-effectiveness levels is the primary objective of strategies enhance building energy-efficiency [13]. The design of tools to monitor factors that affect demand is crucial to appropriately dimensioning plans to regenerate inefficient building stocks in keeping with Article 4 of Directive 2012/27/EU on energy efficiency [14], which is binding on all EU Member States. The method described here aims to explore these issues in depth by deepening the understanding of energy loss that has a direct impact on demand, while also locating and characterizing the most inefficient urban clusters.

To estimate total energy demand, information on solar gain as well as a model for air exchange and an estimate of internal loads must be entered into the MADE [30]. The possibility or otherwise of capturing solar energy is found by analysing façade orientation. The method proposed cannot accommodate accurate calculation of passive solar energy (solar gain) because it is not yet able to account for obstacles in the path of sunlight. Studies are nonetheless underway to assess the shadows projected by nearby buildings on vertical and horizontal surfaces, including public spaces, hour by hour in a typical year.

Final energy consumption estimated from demand calculated as per standard ISO 13790:2008 E can be predicted by entering HVAC system information in the model. That estimate poses uncertainties when cross-referenced with real energy consumption data, however, with deviations of up to 100 % [59]. Such deviations may be the result of a number of circumstances, such as a climatologically atypical year, the application of use patterns that fail to reflect building occupant practice or unsatisfied demand in comfort-deprived or energy-poor households. In parallel with these studies, comfort and real consumption monitoring campaigns are being conducted in situ to calibrate the models with real data to deliver much more accurate predictions of post-energy rehabilitation consumption.

Energy consumption for cooling accounts for a very low percentage of the total in Spain's residential sector. That may be because the use of passive measures to lower cooling demand is fairly widespread in Spanish households. Nonetheless, the upward trend observed with the popularisation of air conditioning systems will foreseeably continue to climb with climate change-induced temperature rises.

Not all the geometric properties that affect buildings' energy efficiency assessment are available in the cadastre: parameters such as height, required to calculate the volume of air to be heated/cooled, and the area of glazed openings, are missing. In this case study these data were extracted from reports of research based on samples of existing housing. More generally, the depth of analytical detail on a given urban fabric to be entered into the model depends on the degree of accuracy required for the study at issue.

Characterising thermal performance on the grounds of the year of construction may yield erroneous results in neighbourhoods where comprehensive urban reform has improved energy efficiency. More reliable findings entail verifying assessments by analysing large quantities of data collected in field campaigns. In Madrid, field work has revealed cases (such as large housing developments in the Gran San Blas and Caño Roto districts), where exterior thermal insulation was installed in façades on the occasion of urban regeneration operations conducted in the nineteen eighties [60]. The absence of cadastral records (such as in San Blas) on the date of reforms detracts from the precision of the method described hereunder. Nonetheless, with the use of new technologies, the formulation of cadastral information is becoming more and more rigorous.

In another vein, basing building characterisation on the legislation in effect in a given period is tantamount to assuming compliance with its provisions, despite the non-verifiability of that premise. Post-1979 envelopes were all assumed to be fitted with thermal insulation, further to the legislation in force at the time. Particularly in the early years, however, workmanship may not have been to standard. Thermal insulation technology and durability of the materials used have improved since the nineteen seventies' energy crisis. Nonetheless, some of the materials installed earlier may have

deteriorated in the interim. Furthermore, in urban areas built in regulatory transition periods (1979, 2006), inconsistencies may arise between the date of construction recorded in the cadastre and the date of the design, which determines the legislation applicable [61].

Given the stark energy situation prevailing in much of Spain's residential fabric (and in all likelihood in that of many other Mediterranean regions) the primary target tends to be clusters of inefficiency where the buildings have no thermal insulation whatsoever [42]. Other pockets of low efficiency housing can be found, however, which, while built to the requirements of the earliest building energy efficiency standards, are far from compliant with the European directives presently in effect. Such neighbourhoods were excluded from the present study, along with those where urban-scale rehabilitation was performed to improve the envelope, albeit minimally, for they are not regarded as the most vulnerable from an energy efficiency standpoint. Nonetheless, once the most urgent objectives are met, the obsolescence of urban areas built in the nineteen eighties and nineties, prior to the entry into effect of Spain's current technical building code, is likely to attract considerable interest.

6 Conclusions

The availability of IT tools to process big data and determine the energy efficiency of whole neighbourhoods with no need for building-by-building analyses or simplifications based on representative structures will spur research in urban data science and encourage the collection of more accurate information on building energy efficiency. Cadastral database processing brings new levels of detail to urban studies that were impossible until such data were made publicly available. The work of the Permanent Committee on Cadastre in the European Union has contributed positively to the transparency of the data in public records.

Cadastral data have been applied here to develop a tool usable in energy rehabilitation strategy design for quantifying heat transfer across a building envelope. The passive energy efficiency indicator defined for neighbourhoods encompasses urbanistic and architectural factors (dimensions, orientation and shape of buildings and site characteristics) as well as construction features (quality of envelope elements). This indicator is useful for detecting priority areas of inefficient construction and defining

the buildings most severely affected. The findings show that in addition to construction features, which are normally spotlighted, geometric factors have a significant impact on energy loss.

The potential for reducing the demand associated with energy loss can be estimated by comparing model-computed present losses to improved scenarios. The model accommodates thermal transmittance information on different solutions for each envelope element (opaque façade, windows, roofs and floors). A rough estimate of the total investment needed to improve envelopes in neighbourhood energy rehabilitation operations can be calculated from the unit costs of improvements. Given that all European countries' definition of NZEB is based on optimal cost methodology, the present study is useful for defining energy demand factors included in the definition of 'nearly zero energy neighbourhoods (NZEN)'. It may also furnish information useful for the design of energy supply infrastructures and district-wide heating systems.

The volume of data proves to be effective to diagnose neighbourhood-scale needs. Big data processing power anticipates the possibility of municipal-scale applications and, by summing municipalities, estimates of nationwide needs.

In this study estimative indicators were used to characterise urban scale energy efficiency. More specifically, the method proposed delivered detailed building-specific as well as pooled data for whole neighbourhoods on at least the following parameters:

- area heated/cooled, by use (m^2)
- area of envelope elements (m^2)
- building height (m) and volume (m^3)
- compactness (m^3/m^2) and form factor (m^2/m^3)
- density
 - gross
 - RSD, residential surface density
 - FAR floor/area ratio
 - BCR building coverage ratio
- KG_{urb} overall heat transmission coefficient
- H_t , total energy loss by building, neighbourhood, usage (kW)
- IEE_{urb} , urban energy efficiency indicator (kW/m^3)

Some of these parameters should be included in European urban quality standards to ensure that energy efficiency is addressed in such rules.

In the present case study, façades were identified as the element accounting for the largest energy losses in buildings. Whilst roofs were observed to be the weakest element in the neighbourhood analysed, they exhibited lesser losses than façades in absolute terms, for as most of the buildings are high-rises, the area involved was smaller. In contrast, in the standard single family dwelling, absolute loss was greatest across the roof. Losses were lowest in floors: in the case study, the value was just half that observed for roofs. Although the gross area of the two elements was approximately equal, heat transmission across the latter was much less intense. The floors in contact with the outdoor air, while weaker than the rest, accounted for scanty 2 % of the total floor area. Moreover, as they were generally found in more recent buildings, their heat performance was better than in earlier construction. Energy rehabilitation plans should include measures to improve tertiary use buildings as well as housing. The huge energy losses recorded in the former constitute a matter of particular concern in buildings in use around the clock. The conclusions drawn for the present case study can be extrapolated to similar neighbourhoods on the outskirts of Madrid built between 1940 and 1980.

Indicators for other types of urban fabric are being developed at the present by this method.

Façade openings must be characterised more fully to enhance model precision, for windows have too short a service life for the scale of construction studied to be characterised by the year built. Rather, intense field work is required to obtain detailed information on the present condition of façade openings in the areas to be rehabilitated.

By applying pooled population and housing census statistics, this study added a dimension not previously addressed, thereby raising the resolution of the urban analysis conducted with respect to earlier studies. When cadastral information is deployed, the unit of analysis is the individual building, while energy data sheets are available for each cadastral reference. Moreover, data corpora can be compared if cadastral information is pooled on the census division scale. For instance, entering

population statistics broken down by census division into the model yields information relevant to socio-economic analyses of energy needs by person, age group, level of schooling or others.

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