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Long-term changes in 3D urban form in four Spanish cities

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HIGHLIGHTS

- We characterize the horizontal and vertical patterns of urban development between 1965 and 2015 in four Spanish urban areas.
- We find that urban expansion with lower densities has significantly changed the height of new buildings.
- Urbanized volume has noticeable increased by roughly 350% during five decades.
- A clear trend towards expansion is observed in city outskirts while city-cores have followed incremental steps towards densification over time.

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ABSTRACT

Three-dimensional urban form has a considerable influence on urban sustainability, being the reason spatial planning regulate it. Yet, we know very little about the development of building density and building height over time. In this study, we characterize the horizontal and vertical patterns of urban development in Barcelona, Madrid, Valencia, and Zaragoza between 1965 and 2015. Our analysis is based on a unique combination of cadastral data and LiDAR point clouds, which we use to characterize building footprint, height, and volume, at decadal intervals. Subsequently, we characterize urban expansion and densification processes using building volume and Urban Form Types. We find that height of new buildings shows a significant downward trend during the 70′s for the four urban areas and a decreasing trend after the 2008 real estate bubble for the cases of Barcelona and Valencia. Over the analyzed period a decrease of 116, 313, 217 and 157 cm in average building height was observed for Barcelona, Madrid, Valencia, and Zaragoza, respectively. Urbanized volume of all cities together has expanded by roughly 350% between 1950 and 2015. Sparse built-up form showed the largest absolute increase, although it contains only a low fraction of new built-up volume. A clear trend towards expansion is observed in city outskirts and the development of new urban clusters in municipalities closer to the main city. At the same time, settlements have followed incremental steps towards densification of the city-cores over time. This study provides a first step towards comprehensive understanding of long-term changes in 3D urban form, which can inform the development of policies that target the third dimension in urban form to steer sustainable urban growth.

1. Introduction

In recent decades urban areas worldwide have rapidly expanded (Li, Verburg, & van Vliet, 2022), and changed in terms of urban form (Ren, Cai, Li, Shi, & See, 2020). In Europe, the settlement pattern of traditionally dense urban centres has been transformed by the growth of settlements outside metropolitan areas and in rural areas (Kasanko et al., 2006; Tombolini et al., 2015). In the Mediterranean region in particular, urban areas have grown beyond population needs in successive waves of compact and, more recently, increasingly dispersed urbanisation (Tombolini et al., 2015; Zambon, Serra, Sauri, Carlucci, & Salvati, 2017). Even though demographic changes show a transition towards zero growth and ageing (Gálvez Ruiz, Diaz Cuevas, Braçe, & Garrido-Cumbrera, 2018), built-up areas are expected to continue growing as a result of socioeconomic developments.

The current trend towards low-density urban areas requires an

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increasing amount of land for urban functions (Glaeser, 2011), which competes with other land demands (van Vliet, 2019), and constitutes a challenge for sustainable development (Bakker, Verburg, & van Vliet, 2021). The need for rational use of land to avoid urban sprawl and the revitalization of existing urban areas are two main objectives from European and Global agendas adopted in the 2030 Spanish Urban Agenda for Sustainability. To achieve sustainable urban development, a shift towards compact urban forms has to be pursued (Dieleman & Wegener, 2004). This will save travel kilometres, reduce land consumption (Bibri, Krogstie, & Kärrholm, 2020), and minimize urban heat island effects and air pollution (Liang and Gong, 2020) as urban morphology affects and is affected by climatic, environmental, efficiency and socio-economic factors (Bonczak & Kontokosta, 2019; Ren et al., 2020; Wong et al., 2011; Zhao, Jensen, Weng, Currit, & Weaver, 2019).

The recording and monitoring of urban morphology is therefore an important prerequisite for all attempts to steer sustainable urbanisation. For a long time, many large-scale studies on urban morphology worked in two dimensions (Lemoine-Rodríguez, Inostroza, & Zepp, 2020; Wu, Zhao, Zhu, & Jiang, 2015). Today, new data allow the analysis of changes in 3D urban form over longer periods of time. While urban morphology as a scientific discipline studies urban forms and the actors and processes responsible for their change over time (Oliveira et al., 2020), the term is also often used to refer to the configuration of the main physical elements that structure the city, such as buildings, streets and squares (Kropf, 2017). The International Seminar on Urban Form (ISUF) in 1994, integrating ideas from the American, British and French urban morphology schools, reached an initial agreement to conceptualize it with form, resolution and time (Moudon, 1997). Several interpretations have been developed since then as for example Levy (1999), who established that urban form is characterized by forms of buildings, streets and plots or Lowry and Lowry (2014) that broadly defined it as the spatial patterns of the built environment. Urban form thus refers to a multi-faceted phenomenon that is often analysed in particular by means of building heights, footprints and volumes as well as urban morphological types.

Most land-use or zoning plans aim to regulate aspects of urban form, for example with stipulating minimal and/or maximal building heights, footprints, building volumes, setbacks and floor-area ratios (Walczak, 2021). If these regulations are enforced, over time the built environment reflects them. Characterizations of horizontal and vertical dimensions of the built environment can thus support effective urban monitoring. In particular, the data on the long-term evolution of the built environment can be used to analyse the achievement of spatial planning objectives on settlement form. For planning and managing urban areas, plausible methods for measuring 3D urban form thus are paramount (Bruyns, Higgins, & Nel, 2020).

The measurement of 3D urban form characteristics has been carried out for years using field surveys, which are costly and labour intensive (Bonczak & Kontokosta, 2019; Ren et al., 2020). Recent development in remote sensing image interpretation have created alternative opportunities for extracting 3D urban form properties. Optical imagery has been used to map horizontal urban form and its changes at large spatial scales (Huang, Lu, & Sellers, 2007; Lemoine-Rodríguez et al., 2020; Wu et al., 2015). The estimation of fine-scale 3D building properties is generally carried out using high-spatial-resolution satellite imagery, synthetic aperture radar (SAR) or Light Detection and Ranging (LiDAR) (Kedron, Zhao, & Frazier, 2019; Frantz et al., 2021; Li, Koks, Taubenböck, & van Vliet, 2020). High resolution single images were used to retrieve building height based on adjacent shadows (Liasis & Stavrou, 2016) for buildings with a height up to 20 m. Multi-view and single high resolution images have been used to estimate digital surface models by stereo matching (Tian, Cui, & Reinartz, 2014) or deep learning (Amirkolaee & Arefi, 2019; Cao & Huang, 2021). SAR data has been also used to derive building properties using side-looking, interferometric or tomographic sensors (Esch et al., 2020; Sun, Hua, Mou, & Zhu, 2019; Sun et al., 2022). Furthermore, LiDAR have been widely applied, due to its accuracy and resolution, to model individual 3D building properties gaining in detail with higher point densities (Priestnall, Jaafar, & Duncan, 2000; Labetski, Vitalis, Biljecki, Arroyo Ohori, & Stoter, 2022; Peters, Dukai, Vitalis, van Liempt, & Stoter, 2022) and characterize urban form (Bonczak & Kontokosta, 2019; Zhao et al., 2019). A current trend in the extraction of 3D urban form consists on combining remote sensing datasets with ancillary data to improve feature extraction (Esch et al., 2020; Li et al., 2019). Yet, the technology for measuring building height is relatively new, as a result of which there is virtually no data on changes in building height over time.

Few studies also employed these methods to map changes in 3D urban form over time, but these studies are generally constrained by the availability of appropriate data. For example, Chen et al. (2020) mapped the horizontal and vertical densification in Denmark cities using deep learning and Landsat time-series. Yet, the relatively coarse input data only allowed the identification of 'high' and 'low' buildings, respectively, without further estimation of their height. Zhao, Weng, and Hersperger (2020) benefitted from three available LiDAR datasets and land-use maps to depict 3D form changes in Austin, Texas from 2006 to 2016. The relative novelty of LiDAR data only allowed a characterization of urban growth for recent periods. Liu, Chen, Li, and Chen (2020) followed another approach as they characterized the 3D form of residential buildings of different ages using historical images and administrative data from 1990 to 2018 in Xiamen city, China, though, the unavailability of demolished buildings data did not allow to analyse temporal changes overtime. These examples illustrate the current challenges of datasets towards mapping changes in 3D physical building structure over long-term periods of time. Physical urban form is not the only aspect of urban morphology, which has a complex conception that varies between authors including distinct aspects such as physical form, land use and activities or function, between others (Kropf, 2017). Physical built form, hereinafter referred as urban form, can be expressed using different indicators (Moudon, 1997; Peters et al., 2022), and with different levels of detail (Chen et al., 2020; Labetski et al., 2022). In this manuscript, we analyse the changes in urban form based on two main simple indicators (i.e. footprint and height) as: i) these characteristics are often regulated with planning; and ii) considering the characteristics of Spanish cadastral dataset, the low point density of LiDAR data, and due to data availability (e.g. historic land-use maps) to derive further urban form metrics.

In this paper we leverage a time series of cadastral data for four Spanish cities in combination with LiDAR for the same cities to analyse both horizontal and vertical change in urban fabric between 1965 and 2015. We analyse the changes in building footprint, height, and volume for Barcelona, Madrid, Valencia, and Zaragoza in order to increase our understanding of urban development. Although Mediterranean cities have for a long time conformed with a compact city model, we expect that these cities follow the global trend of low-density urban sprawl linked to a decrease in building height. To test this hypothesis, we identified the following research questions: (1) What is the long-term trend over time in the height of new buildings? (2) What contribution do changes in building height and changes in building footprint make to volumetric changes over time? (3) How do changes in 3D urban form translate in changes in urban form types?

2. Materials and methods

In this study we analyze the urban form and their changes of four cities in Spain, using a combination of LiDAR and Cadastral data (Fig. 1). Sub-section 2.1 describes the study area which consists of four Spanish Functional Urban Areas (FUAs), and sub-section 2.2. depict the computation of building properties (footprint, height and volume) based on cadastral and LiDAR data sources. Subsequently, sub-sections 2.3 to 2.5 provide the analyses used to answer the three main research questions based on the computed building properties, including height changes over time, the decomposition of the volumetric component into

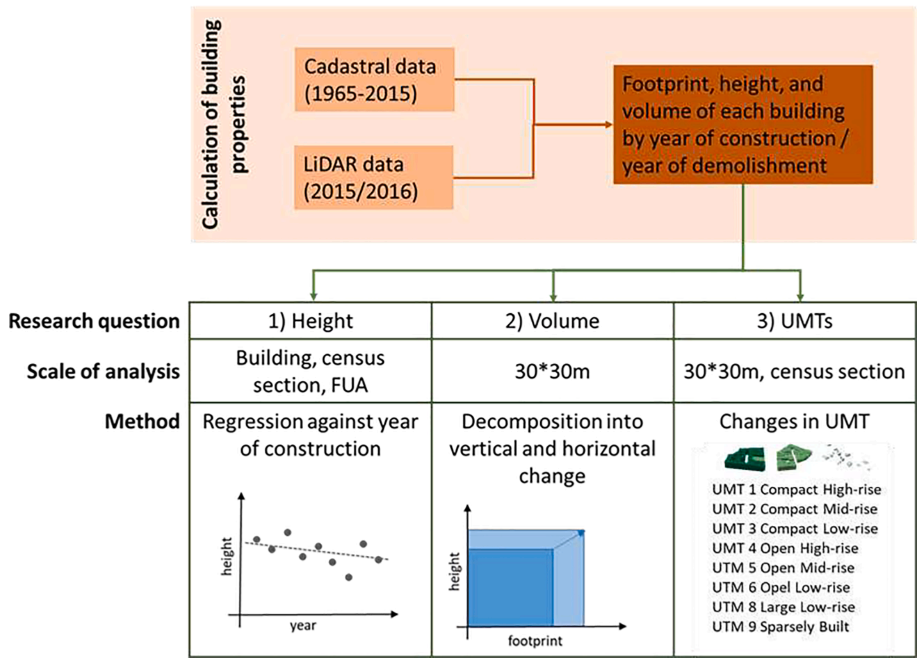


Fig. 1. Methodological overview of the study.

vertical (building height) and horizontal (building footprint) changes, and mapping urban form types, respectively.

2.1. Study area

Our study area consists of the FUAs of Barcelona, Madrid, Valencia, and Zaragoza. From here on we refer to them by the name of the respective cities (Fig. 2). These functional urban areas were selected based on the fact they include a large share of all urban expansion (Tombolini et al., 2015; Díaz-Pacheco & García-Palomares, 2014) and they are large enough to analyse urban form patterns overtime. Larger cities tent to be affected by higher travel distances, land consumption or heat island effects, in which planning instruments are widely developed.

The FUAs are defined by the Digital Spanish Urban Atlas and include the city-core and its commuting zone, based on municipal boundaries. Municipal boundaries have changed over time, and in this study we consistently use the most recent delineation for all periods, for reasons of consistency. Barcelona is located in the north-east coast of Spain and integrates 165 municipalities with a combined area of 3,285 km^2. The metropolitan system is characterized by a compact city-core, two metropolitan rings and 7 sub-centers (Catalán, Saurí, & Serra, 2008, and Tombolini et al., 2015). The rings are defined as the municipalities located in concentric bands around the main city (Vinci, Egidi, López Gay, & Salvati, 2021; Zambon et al., 2018). The population has changed from 2.53 Million to 5.03 Million between 1960 and 2015, and urban areas have grown predominantly in the outer part of the metropolitan region (Tombolini et al., 2015). Madrid is the capital of Spain, includes 52 municipalities with a total area of 2,887 km^2. The Madrid urban core is located in the center of the FUA and suburban municipalities form six rings around this centre (Díaz-Pacheco & García-Palomares, 2014). The population growth is higher than in any other analysed urban area, increasing from 2.35 Million to 5.99 Million between 1960 and 2015, and the urban growth is characterized by a dispersion pattern (Moliní & Salgado, 2012). Valencia is the third most populated FUA in Spain with 1,55 Million inhabitants in 2015 (Digital Spanish Urban Atlas, 2015) located on the centre-east coast of Spain. The FUA integrates 45 municipalities with a total area of 634 km^2. From 1960 to 2015 the population has increased by 0.78 Million and urban growth is mainly linked with the expansion of Valencia city, and the coastal and interior municipalities. Zaragoza is located in the north-east of Spain and the FUA includes 15 municipalities with a total area of 2,205 km^2. Zaragoza city includes roughly 90 % of the population in 2015, and the FUA has increased from 0.33 Million to 0.74 Million since between 1960 and 2015.

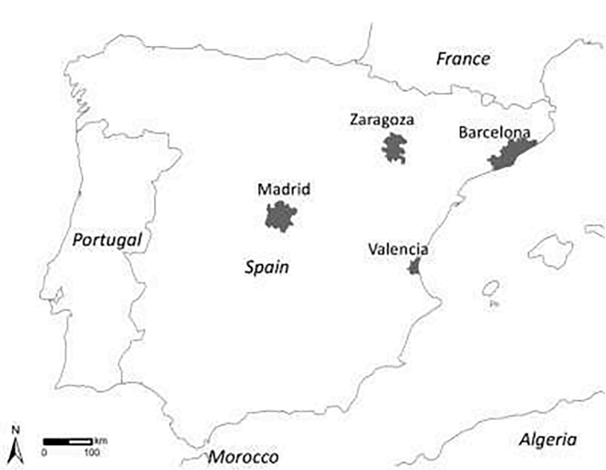


Fig. 2. Spatial extent of selected FUAs of Spain.

2.2. Computation of building properties

The Spanish cadastral datasets and the LiDAR point clouds from the Spanish National Plan for Aerial Orthophotography constitute the two main data sources to compute building properties (Fig. 1). The cadastral data is provided by the Spanish Ministry of Finance (Spanish cadastre, 2021) and includes current and historical information about building footprints, year of construction, building status (e.g. functional, ruin), gross floor area, and floor number, among others. The LiDAR data was gathered from the PNOA second coverage collected between 2015 and 2016 for the selected urban areas. Table S1 in the Supplementary Material shows the flight acquisition parameters and accuracies. The classified point clouds, with up to four return signals per pulse, were provided in 2 × 2 km tiles in LAS format in European Terrestrial

Reference System (ETRS) 1989 Universal Transverse Mercator (UTM). Overall 7,290 tiles were processed, including 4,566 for Madrid, 1,230 for Barcelona, 404 for Valencia, and 1,494 for Zaragoza. Cadastral and LiDAR datasets were used to compute building properties for each building and, subsequently, aggregated at three scales: a pixel of 30 × 30 m, census section and FUA scale. The 30 × 30 m pixel was selected as a medium-resolution size matching commonly maps derived from satellites (Zhao et al., 2020) to capture the heterogeneity within the following levels of aggregation. The census section was selected as it is the base unit for urban management and planning in Spanish cities. The FUA scale was selected to provide an overall summary, specifically used for the analysis of building height (see 2.3). Using the cadastral data, we calculated the building surface fraction (BSF) for the entire study period using ten-year time intervals (1965, 1975, 1985, 1995, 2005, and 2015). Specifically, for each point in time we combined previously existing buildings with newly added buildings, and we subtracted the demolished buildings. For example, the buildings for 1995 are calculated as the buildings existing in 1985 plus the new buildings developed between 1986 and 1995 minus the demolished buildings between 1986 and 1995. The BSF was calculated as the ratio of building footprints to overall area for two scales of analysis: a pixel of 30 × 30 m, and census section (see section 2.5). The calculations for ≈ 1.05 million buildings, including 367,213 in Madrid, 485,963 in Barcelona, 136,545 in Valencia, and 57,004 in Zaragoza were implemented in R.

Building heights were calculated based on cadastral data in combination with LiDAR data. Specifically, using the LiDAR data, we constructed both digital terrain models (DTMs) without built-up elements, and digital surface models (DSMs) including all elements above terrain, using the point-triangulated Irregular Network-Raster interpolation method (Renslow, 2013) at a 1 m resolution. The average height of buildings was subsequently computed by subtracting the DTMs from the DSMs models within each building footprint, resulting in a normalized digital built-up model (nDBM). An internal buffer of 1 m to the building footprints was applied previous to the normalization, to ensure point cloud returns were completely within buildings footprints. Furthermore, nDBM values bellow 1.5 m were disregarded, because the Spanish cadastral datasets only include buildings with heights over 1.5 m. These calculations were done in ArcGIS 10.5. For buildings that are demolished, replaced, or otherwise no longer existing, building heights were estimated from the number of floors, as this information is recorded in the cadastre (as opposed to the actual height itself). For this calculation, we assumed an average height per floor of 3 m. This value may lead to potential error in total height as it neglects the height of the roof, and because floor height can vary between buildings (Liu et al., 2020). Consistent with the calculation of BSF, we calculated average building heights for 30 × 30 m pixels (see sections 2.4 and 2.5), for census sections (see section 2.5) and for FUA scale (see section 2.3).

2.3. Analysis of height changes over time

We conducted a regression of the height of new buildings against the time they were built to characterize the vertical trends over the five analysed decades. Specifically, we compared the performance of an ordinary least square linear regression (OLS) with respect to generalized additive model (GAM) models to analyze the relationship between height and time. Particularly we tested generalized additive model cubic regression (GAM cr), generalized additive model P-splines (GAM ps) and generalized additive model gaussian process (GAM gp) using "mgcv" package in R environment. Furthermore, we computed the first derivative of GAM models to identify statistically downward significant periods of change in time series. A regression was fitted for each FUA using the average height per FUA and year of new buildings. The goodness of fit of the models was summarized, for those models that the dependent variable was significant, using the R^2 statistic and p-value. The selection of the best-fit model for the FUAs was based on goodness of fit model statistics.

2.4. Decomposition of volume changes into horizontal and vertical changes

Using building footprints and building heights we calculate the change in building volume for each ten-year period at 30 × 30 m pixel resolution, and subsequently attribute these changes to changes in footprints and changes in height, respectively according to equations (1) and (2).

$$\textit{Volume change due to vertical change} = F(t0) * \Delta H \quad (1)$$

$$\textit{Volume change due to horizontal change} = \Delta F * H(t1) \quad (2)$$

Where F is built footprint, H refers to build height, t0 and t1 refer to the start and end of a period (e.g. 1965 and 1975), while ΔH and ΔF refer to the absolute change in height and footprint in this period, respectively.

To discuss the patterns of vertical and horizontal changes we define the concepts urban expansion, densification, and volumetric densification as follows: Urban expansion is defined as the development of new built-up in places that were not urbanized previously. Densification refers to the increase of built-up area in already urbanized places. Volumetric densification is attributed to the increase of built-up height in already urbanized places. Urbanized, in all three processes, refers to the presence of built-up land within a spatial unit.

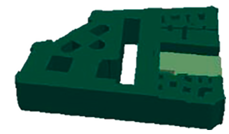
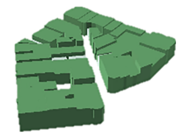
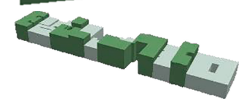
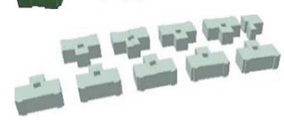
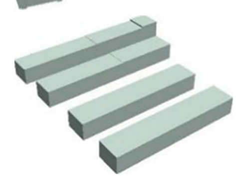
2.5. Delineation and mapping of urban form types

We used building height and building surface fraction (BSF) to delineate Urban Form Types (UFTs). This approach builds on a classification originating from Local Climate Zones (Stewart & Oke, 2012) and recently further developed for purposes of planning evaluation (Zhao et al., 2020; Liu et al., 2020). Stewart and Oke (2012) defined 17 standard Local Climate Zones classes with 10 relating to urban environments, while excluding other areas such as bare soil or water landscape zones. Zhao et al., 2020 built on this typology and presented nine types that are especially suitable for spatial-planning evaluation.

Following closely the work by Zhao et al., 2020, this study precedes as follows. UFTs are delineated based on threshold values of BSF and building height. Standard values have been proposed, but these are often adjusted to specific study areas (e.g. Zhao et al., 2020; Liu et al., 2020). We adjusted, when needed, the standard values using a semi-automatic k-means clustering analysis, as proposed by Hidalgo et al. (2019), which applied this method in France with accurate results. Though k-means is a classic method it's well suited to easily adapts to new sets of data, it is relatively simple to implement and scales to large data sets being transferable for the four analysed FUAs. Adjusted threshold values shown in Table 1 were used to characterize urban areas as 'high-rise' (UFT 1 and 4), 'mid-rise' (UFT 2 and 5), and 'low-rise' (UFT 3, 6, 8 and 9). Similarly, we used BSF to determine the form groups according to the surface fraction as 'compact' (UFT 1, 2, and 3), 'open' (UFT 4, 5, and 6), 'large' (UFT 8) or 'sparse' (UFT 9). Additional built-up properties were disregarded to perform the delineation (e.g. sky view factor) for having low importance (Hidalgo et al., 2019; Zhao et al., 2020) or due to data availability (i.e. historic land-use maps to define imperviousness) in accordance with Liu et al. (2020).

UFT were mapped at ten-year time intervals from 1965 to 2015 at 30 × 30 m pixels and census section scale for Barcelona, Madrid, Valencia and Zaragoza. The urban expansion processes were measured considering the relative UFT extent in respect to the total functional urban area. UFT transitions were analysed by computing change matrices in accordance with Li, van Vliet, Ke, and Verburg (2019), for five periods 1965–1975, 1975–1985, 1985–1995, 1995–2005, and 2005–2015, respectively. The densification processes were defined according to Zhao et al. (2020) as the transformation of low-ranking UFTs, characterized by low-density urban forms, to high-ranking UFTs with high degree of compactness and height (e.g. UFT 9 to UFT 3).

Table 1
Urban form types (UFTs). Names and threshold values of building surface fraction and height properties for mapping at census section and 30 m pixel scales. BSF stands for building surface fraction, Height refers to height of constructed elements.

UFT	Description Stewart and Oke (2012)	BSF	Height	3D illustrations
UFT 1 Compact High-rise	Dense mix of tall buildings. Land cover mostly paved.	(>40)	>25	
UFT 2 Compact Mid-rise	Dense mix of mid-rise buildings. Land cover mostly paved.	(>40)	>10–25	
UFT 3 Compact Low-rise	Dense mix of low-rise buildings. Land cover mostly paved.	(>50)	3–10	
UFT 4 Open High-rise	Open arrangement of tall buildings. Abundance of pervious surfaces.	(<40)	>25	
UFT 5 Open Mid-rise	Open arrangement of midrise buildings. Abundance of pervious surfaces.	(<40)	>10–25	
UFT 6 Open low-rise	Open arrangement of low-rise buildings. Abundance of pervious surfaces.	(20–30)	3–10	
UFT 8 Large low-rise	Open arrangement of large low-rise buildings. Land cover mostly paved.	>30–50	3–10	
UFT 9 Sparsely built	Sparse arrangement of small or medium-sized buildings. Abundance of pervious surfaces.	(<20)	3–10	

Subsequently, alluvial graphs were derived from change matrices to depict the flows between periods and the UFT distributions for each node (i.e. decade). The graphs were used to identify UFT urban expansion and densification trajectories, relying on the relative occurrence of changes from one UFT to another.

Adjusted threshold values compared with the standard defined Local

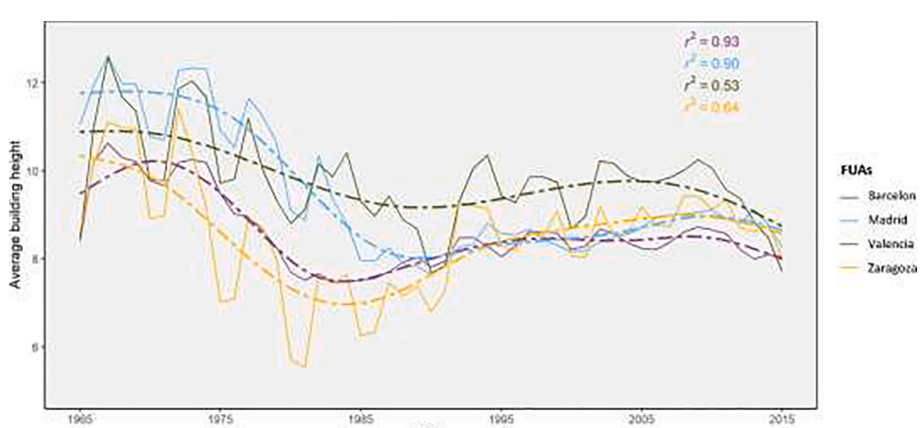


Fig. 3. Average FUA building height vs time. The trends in building height, derived from GAM P-splines models, are shown for Barcelona, Madrid, Valencia, and Zaragoza with dashed lines.

Climate Zone thresholds (e.g., Tables 2 and 3 in Stewart and Oke (2012) are indicated in parentheses. Stewart and Oke (2012) standard LCZ 7 and 10, including 'Lightweight low-rise' and 'Heavy industry' were not observed in the study areas and these two types were merged into the other eight UFTs by modifying the thresholds.

3. Results

3.1. Heights of new buildings

Average building height shows a significant and decreasing trend during the 70′s for the four analyzed FUAs and a decreasing trend after the 2008 real estate bubble, this last only statistically significant for Barcelona and Valencia (Fig. 3). Barcelona shows a statistically significant downward trend from 1969 to 1982 and a secondary downward trend from 2010 to 2012 with a decrease of −19 cm per year and −4 cm per year during these periods, respectively. Madrid present a statistically significant building height decrease of −19 cm per year during the period 1973 to 1987. Valencia shows a statistically significant downward trend from 1973 to 1977 and a secondary downward trend from 2008 to 2015 with a decrease of −9 cm per year and –23 cm per year during these periods, respectively. Zaragoza present a statistically significant building height decrease of −28 cm per year during the period 1972 to 1980. For the overall period (1965 to 2015), the change in height was of −116 cm, −313 cm, −217 cm and −157 cm for Barcelona, Madrid, Valencia and Zaragoza, respectively (Fig. 3) according to GAM P-splines fitted values. The number of constructed buildings between 1965 and 2015 equals 764,059, representing 68.77 % of the total number of buildings of the four FUAs combined. The temporal series trend in building height over time explains 93 %, 90 %, 53 % and 64 % of all variation in building heights over time, for Barcelona, Madrid, Valencia, and Zaragoza respectively. These trends were estimated using GAM P-splines models, which showed the highest performance within the compared algorithms (see Supplementary Materials). Even though there is still a considerable variation in building height in specific years or periods that might be explained by other factors, such as policies. Specifically, the first decade and the period 1995–2005 represent periods with higher newer buildings, and these represent 47 % of all buildings constructed in the study period.

3.2. Horizontal and vertical changes in building structure over time

Decomposing the characteristics of built-up volume allows to categorize the contribution of horizontal and vertical growth in urban expansion, densification, and volumetric densification processes. The horizontal growth contributes 2.89 km^3, which represents 95.37 % to the total increase in built-up volume in the four urban areas together between 1965 and 2015, denoting a clear increase in urban expansion (Table 2). Vertical growth, volumetric densification, is only of minor importance (0.14 km3). It contributes slightly more in Barcelona (7.73 %) and Valencia (5.34 %), and presents the lowest contribution in Madrid (2.25 %).

Fig. 4 and Fig. 5 show the spatial patterns of built-up volume related to horizontal and vertical growth. Four typical combinations of volume change due to horizontal and vertical changes were found. The increase of volume change due to medium horizontal increases reflects the appearance of new urban clusters mainly located between built-up areas with low density, while a medium horizontal and vertical increase reflects densification of existing urban areas and a consolidation of the urban core as for example in Barcelona during the period 1975–1995 or in Madrid during the period 1995–2005 (Fig. 4). These two combinations represent on average around 65 % of the total changes, which accounts for 3.02 km3, in the four FUAs. Another prominent combination refers to high horizontal increases, which indicate the appearance of new neighbourhoods generally located in the outskirts of the city with a high built-up density, or high vertical increases with medium horizontal increase, reflecting a consolidation of urban city cores with more compact forms. These last two combinations represent on average roughly 28 % of the changes in the four FUAs.

Analysis of volume changes due to horizontal and vertical growth reveals some general patterns. The number of pixels with a high horizontal increase or a high vertical with medium horizontal increase at the start of the analysed period is predominantly concentrated in the urban cores. Conversely, at the end of the period these changes are mainly located in the outskirts of the cities and in new urban areas not linked with the main urban core. This indicates a consolidation and

Table 2
Built up changes in footprint, height, volume, volume as horizontal or vertical change for the analysed FUAs from 1965 to 2015 in ten-year periods.

City	Year	Building footprint (km^2)	Average building height (m)	Building volume (km^3)	Change in building footprint (km^2)	Change in average building height (m)	Change in building volume (km^3)	Building volume as horizontal change (km^3)	Building volume as vertical change (km^3)
Barcelona	1965	38.15	8.42	0.36	–	–	–	–	–
	1975	64.15	8.98	0.66	26.01	0.56	0.30	0.27	0.031
	1985	83.07	8.70	0.84	18.92	−0.28	0.19	0.17	0.021
	1995	103.79	8.57	1.04	20.72	−0.13	0.19	0.18	0.015
	2005	129.13	8.54	1.30	25.34	−0.03	0.26	0.25	0.011
	2015	140.63	8.53	1.42	11.50	−0.01	0.13	0.12	0.006
Madrid	1965	23.63	11.06	0.31	–	–	–	–	–
	1975	47.69	11.14	0.59	24.06	0.08	0.28	0.28	0.006
	1985	67.46	10.67	0.81	19.76	−0.47	0.22	0.22	0.005
	1995	91.66	9.95	1.05	24.20	−0.72	0.24	0.23	0.006
	2005	122.61	9.56	1.39	30.95	−0.39	0.34	0.33	0.007
	2015	139.85	9.51	1.60	17.24	−0.05	0.21	0.21	0.005
Valencia	1965	13.47	8.48	0.13	–	–	–	–	–
	1975	22.95	9.06	0.24	9.48	0.58	0.11	0.10	0.005
	1985	30.37	9.17	0.33	7.42	0.11	0.09	0.08	0.005
	1995	37.11	9.14	0.40	6.74	−0.03	0.07	0.07	0.004
	2005	46.12	9.20	0.50	9.01	0.07	0.10	0.10	0.005
	2015	50.34	9.24	0.55	4.22	0.03	0.05	0.05	0.003
Zaragoza	1965	6.31	8.61	0.06	–	–	–	–	–
	1975	11.51	8.95	0.12	5.20	0.34	0.06	0.05	0.002
	1985	15.59	8.44	0.16	4.08	−0.50	0.04	0.04	0.002
	1995	19.35	8.36	0.20	3.76	−0.08	0.04	0.04	0.001
	2005	24.14	8.40	0.25	4.79	0.04	0.05	0.05	0.002
	2015	28.57	8.44	0.30	4.43	0.04	0.05	0.05	0.001
Total change					277.83		3.02	2.89	0.143

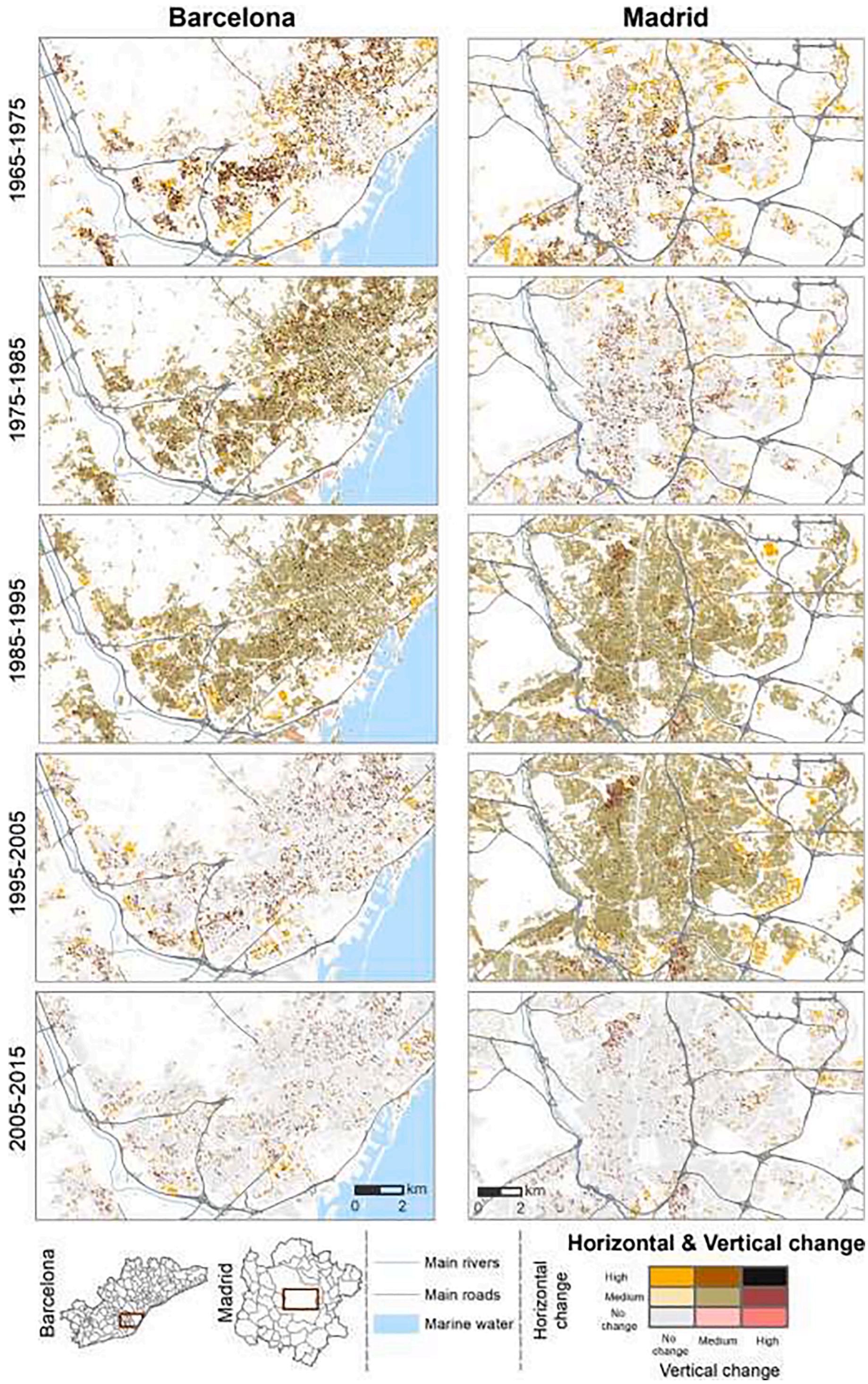


Fig. 4. Volume changes due to horizontal (building footprint) and vertical growth (building height) between 1965 and 2015 for Barcelona and Madrid. For horizontal change, the following thresholds are applied per 30 × 30 m pixel: No change is 0; Medium refers to above 0 up to 2500 m^3; High include values above 2500 m^3. For vertical change, the following thresholds are applied per 30 × 30 m pixel: No change is 0; Medium refers to above 0 up to 125 m^3; High include values above 125 m^3.

densification process of main urban areas in the FUAs. In this sense, the built-up volume of the main municipality of the FUAs represented 53 % of the total building volume of the FUAs between 1965 and 1975, which accounts for 3.87 km3. Afterwards, the non-central municipalities grew faster, leading to a smaller share of building volume in the main city (e.g. 36 % in the period 2005–2015). Particularly, the largest relative increase in building volume outside city centres was observed in Madrid and Valencia, changing roughly from 50 % to 70 % of total building volume between 1960 and 2015, while Zaragoza presents a smaller change from 14 % to 24 % of total building volume between 1960 and 2015.

3.3. Spatial pattern of UFTs and their changes over time in Spanish FUAs

In order to disentangle how changes in 3D urban form translate in changes in urban form types by addressing research question 3, we

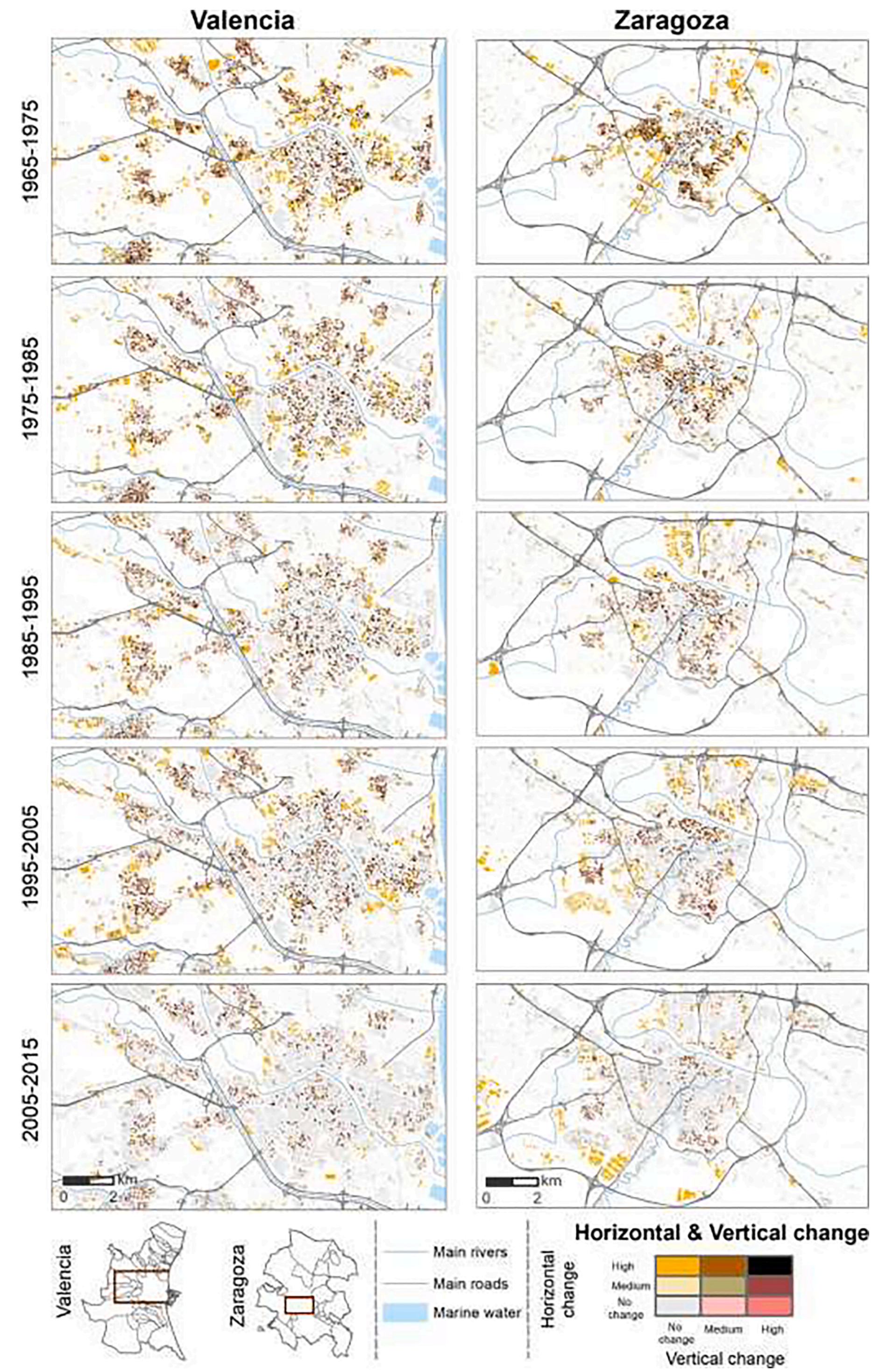


Fig. 5. Volume changes due to horizontal (building footprint) and vertical growth (building height) between 1965 and 2015 for Valencia and Zaragoza. For horizontal change, the following thresholds are applied per 30 × 30 m pixel: No change is 0; Medium refers to above 0 up to 2500 m^3; High include values above 2500 m^3. For vertical change, the following thresholds are applied per 30 × 30 m pixel: No change is 0; Medium refers to above 0 up to 125 m^3; High include values above 125 m^3.

present results on (1) the spatial distribution of UFT for the four FUAs individually for three points in time and two spatial scales, (2) the share of area and building volume included in each UFT and (3) transitions between the UFT's over time to analyse the expansion and densification trajectories.

Sparsely built-up form predominates, in terms of area, in each of the five decades in all FUAs (Figs. 6, 7 and 8). It is the UFT with the largest increase in space over time, although it comprises only a low proportion of the building volume. Urban expansion has increased the continuous area of urban fabric, thus reducing the available non-urban land at the urban fringes. At the same time, the urbanized areas located in the city-core have become denser over time and low-density UFTs are increasingly located around the main transport networks and in surrounding new urban developments. The densification was not linked with a large development of high-rise forms, which is still rare in all four cities. Despite these general trends, the rate of change and the spatial patterns

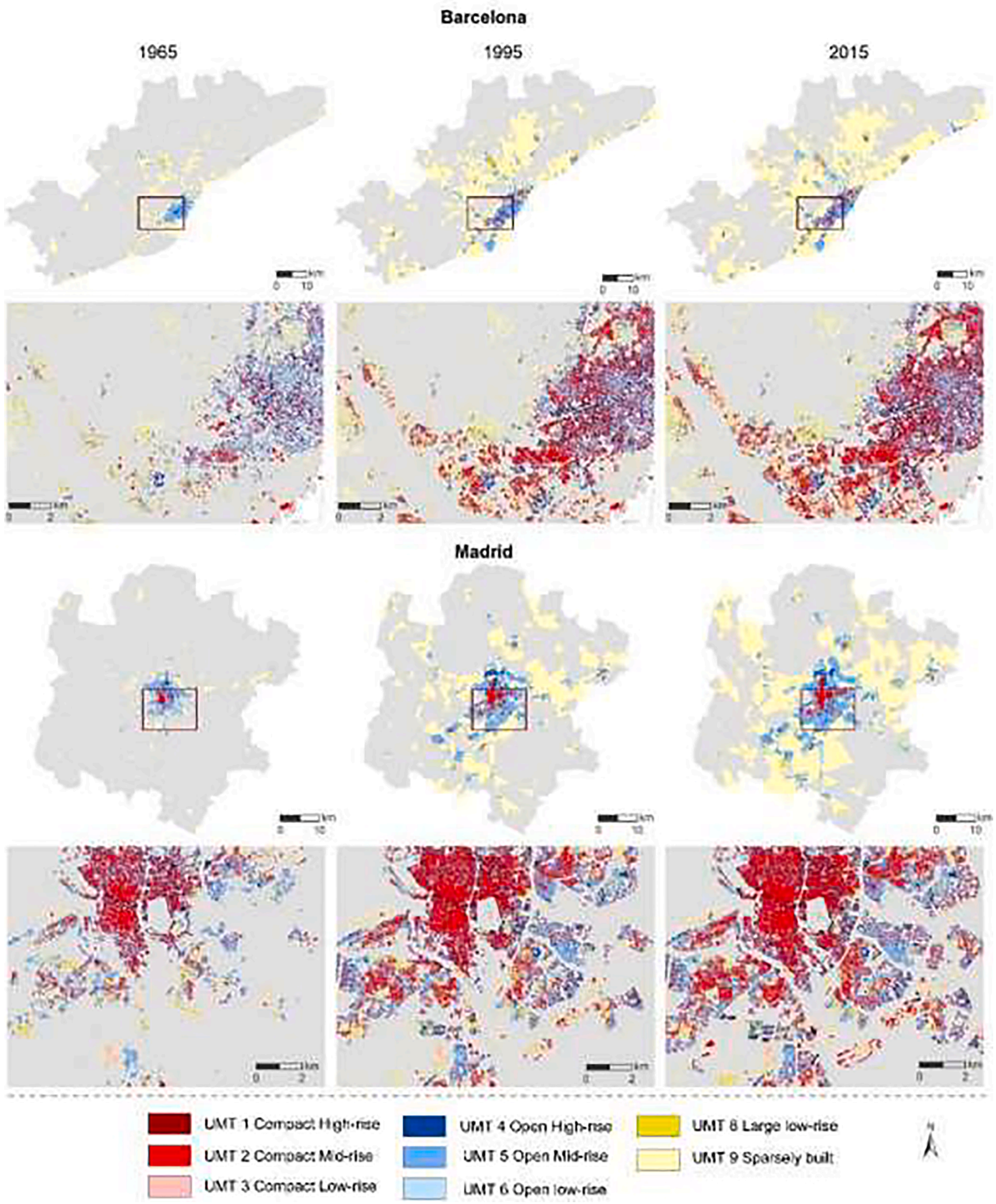


Fig. 6. Urban form type (UFT) distributions for Barcelona and Madrid in 1965 (left), 1995 (center), and 2015 (right) at census section and pixel level (red subsets). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

varies within the analysed cities, which are described in the following paragraphs. UFT distribution for year 1965, 1995 and 2015 at census section and 30 × 30 m pixel level are presented in Fig. 6 and Fig. 7.

In 1965, Barcelona was predominantly characterized by sparsely built-up forms (UFT 9) linked to villages located in the outskirts and close to the coastline, while open mid-rise (UFT 5) was predominant in Barcelona city, Terrassa and Vilanova i la Geltrú. This UFT 5 contains 15.40 % of the urbanized area and 12.71 % of the total built-up volume in 1965 (Fig. 8). While UFT 9 and UFT 5 are still the predominant types in 1995, we observed a change towards the development of denser and more compact urbanized areas in 2015. Particularly, compact mid-rise forms (UFT 2) slightly surpassed open mid-rise (UFT 5) in 2015, covering 1.76 % and 1.75 % of all urban land, respectively. Compact mid-rise areas contain 12.32 % of all building footprint and 36.72 % of all building volume in 2015, values that nearly double the ones in 1965. UFT 2 forms are currently located in the western borders of Barcelona city, including municipalities such as L' Hospitalet de Llobregat and Santa Coloma de Gramenet. On the other hand, UFT5 is still prominent in Barcelona city-core linked with Cerdá urban blocks design. The majority of the urban area is still classified as sparsely built in 2015, but the location has drastically change over time. Currently UFT 9 is located between the main sub-centers and the coastline in Barcelona generating a higher degree of urban continuity. The sub-centers, like Rubí, which were classified as UFT 9 in 1965 has considerably gain in density allocating now the new low-density urban developments in their outskirts (Fig. 6).

Sparsely urbanized areas are the most common urban form in Madrid along the five analysed decades. In 1965, these sparsely built-areas are mainly distributed in the outskirts of Getafe, the western outskirts of Madrid city, and in the surrounding villages. Conversely, the eastern and

Fig. 7. Urban form type (UFT) distributions for Valencia and Zaragoza in 1965, 1995, and 2015 at census section and pixel level (red subsets). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

southern outskirts of the city were mainly characterized by the presence of UFT 5 in 1965, comprising 18.96 % of total built-up volume (Fig. 8). Since 1995, the pattern of UFTs has not changed much. Changes in UFTs between 1965 and 1995, as well as between 1995 and 2015 show both expansion and the development of denser and more compact urbanized areas over time. UFT 9 is distributed in 2015 at the outside rings, especially in the western and northern municipalities of the FUA (Fig. 6). Densification processes have increased the presence of compact mid-rise forms over time, especially in Madrid city-core, representing 15.85 % of the urbanized area and 38.34 % of the building volume in 2015. On the other hand, UFT 5 is predominant in the newer developments close to Madrid city and main cities such as Leganés, Getafe, Alcorcón or Alcalá de Henares, among others.

Valencia has a higher presence of low-rise forms than mid-rise urban forms (Fig. 8). Low-rise forms were in 1965 within the surrounding villages in the northern and southern areas of Valencia city, as well as in interior municipalities such as Torrent, Paterna or Burjassot. Even though municipalities from the interior, the north, and the south of Valencia city have expanded and densified over time, low-rise forms are still cover the majority of all urban land in 2015, representing 47.41 % of the urbanized area and 31.88 % of the building volume. Furthermore, as for the rest of the analysed FUAs, sparsely urbanized areas dominate over time. In 1965 these were mostly found at the outskirts of Valencia city, and close to villages in the north and the south of Valencia city, as well as in interior municipalities. In 2015 we observe sparsely urbanized areas in almost the entire FUA (Fig. 7).

In Zaragoza we observe a trend towards densification over time, characterized by a decrease in the share of urban land with open forms, and an increase in the share of urban land with compact forms. Throughout the entire study period, compact forms have contained the majority of the building volume in the city (Fig. 8). Open forms are characteristic for newer urban developments, while compact areas are

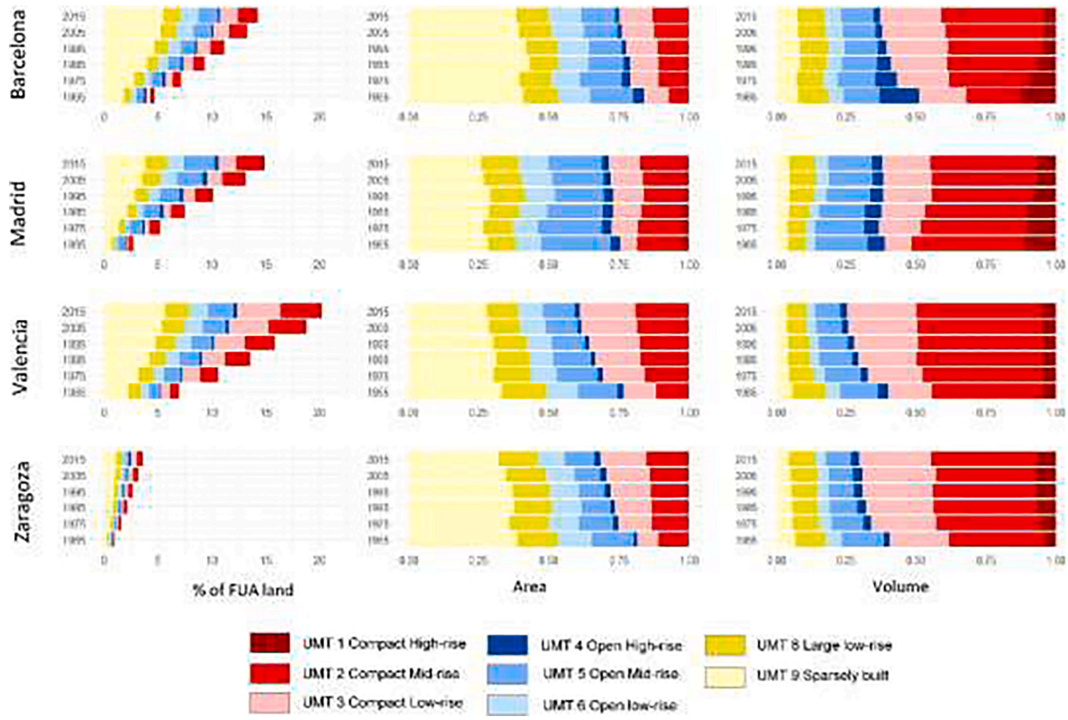


Fig. 8. Left) percentage of functional urban area occupied by each UFT, computed at pixel level, for decadal periods from 1965 to 2015; center) Share of urbanized area (30 × 30 m pixels classified with a specific UFT) in each UFT. Right) Share of building volume included in each UFT.

representative of the Zaragoza city-core and its consolidated neighbourhoods. Consistently, the height of the buildings is higher in the city-core (e.g. compact and open mid-rise) than along the axes of development in the direction of the Ebro, Gallego, and Huerva rivers (Fig. 7) (e.g. compact low-rise forms and lower density forms). The presence of sparsely urbanized areas has increased over time, moving from the city outskirts to the development axes.

The expansion of urbanized area has been considerable with 278 km^2 between 1965 and 2015, in the four FUAs combined. Madrid represents the largest expansion from 4.67 % to 14.87 % of the total land of the

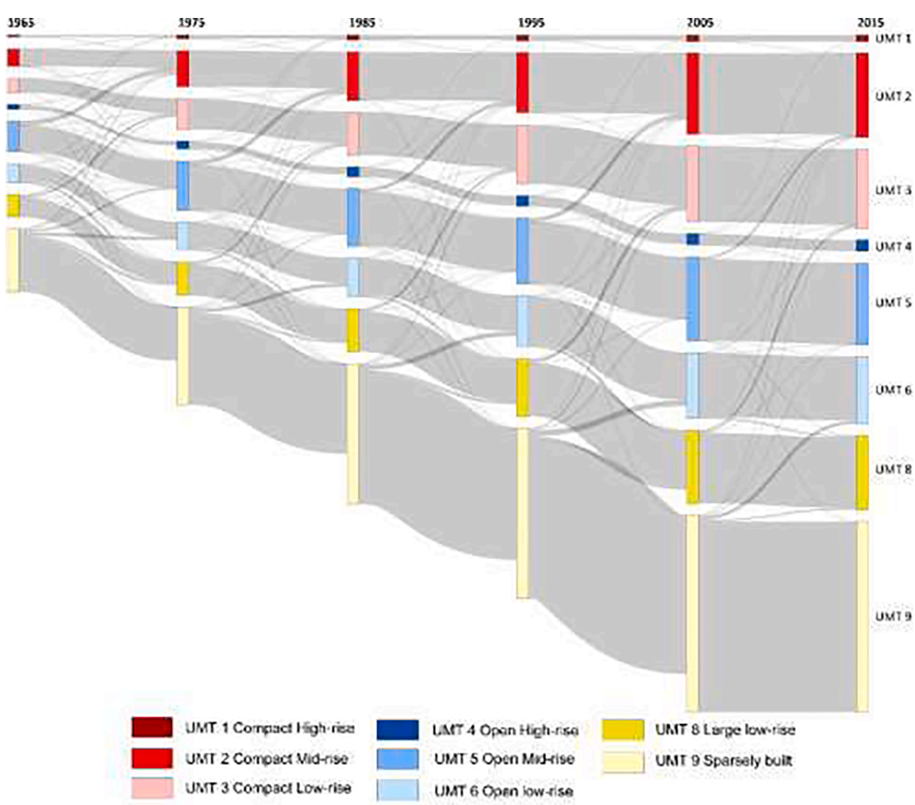


Fig. 9. Urban expansion and densification processes, expressed in transitions between UFTs for all four functional urban areas combined between 1965 and 2015. Depicted transitions are selected to show all observed changes higher than 5 ha (~11 30 × 30 m pixels) in steps of 10 years. The width of the alluvial graph links is proportional to the land area of the corresponding UFT change. Separate figures for Barcelona, Madrid, Valencia, and Zaragoza functional urban areas are provided in the supplementary material (Figure S1 to Figure S4).

FUA, with 116 km2 growth (Fig. 8, left). On the other hand, Zaragoza represents the smallest expansion from 1.00 % to 3.60 % of the total land of the FUA, with only 22 km2 of new building footprint since 1965. The most prominent expansion period in terms of urbanized area was from 1995 to 2005, related to the Spanish real estate bubble, followed by the period 1965–1975. Contrarily, the period 2005–2015 shows the lowest urban expansion, which can be related to the aftermath of the 2008 economic crisis. In terms of area, sparsely built-up form predominates, though the relative contribution to the total urbanized area has slightly decreased, on average for the four FUAs combined, in 4.28 % from 1965 to 1995 (Fig. 8 center). At the same time, compact forms have increased, on average for the four FUAs, 10.40 % in area from 1965 to 1995, denoting a trend towards densification. Throughout the entire study period, the urbanized area increase of compact forms was linked to an increase of volume, being the form type that contains most of the building volume (Fig. 8 right). Contrarily, sparsely built forms represent on average 33 % of the total urbanized area and roughly 5 % of total building volume, denoting how 3D urban form translates in disperse urban form types.

Fig. 9 shows the urban expansion and densification transitions between UFTs observed in the four functional urban area between 1965 and 2015. The most notable transition in terms of urban expansion was the transition from non-urban areas to UFTs overall (Fig. 9). Urban densification accounts for 18.92 % of the total urbanized area between 1965 and 2015 for the four FUAs (Fig. 9, all upward bend connections from low-intensity urban forms to high-rates). Densification processes were more relevant in Valencia (29.37 %) and Barcelona (24.57 %), while it accounts for only 11.74 % in Madrid (Figure S1 to Figure S4 in the Supplementary Material). The densification from open mid-rise (UFT5) to compact mid-rise (UFT2) was the most pronounced change between 1965 and 1985 accounting for 23.60 % of the densified areas. Another prominent change trajectory, between 1965 and 2015, is from sparsely built areas (UFT9) into open low-rise (UFT6) areas, accounting for 23.82 % of the densification changes. Between 1985 and 2015, the densification from UFT9 to UFT6 accounts for 27.52 % of the changes, exceeding the transition from UFT5 to UFT2 that represents 19.38 % of the densification changes. At the same time, a large share of large low rise (UFT8) to compact low-rise (UFT3) during the period 1965–2015 has consistently reinforced the densification of urban areas. The diversity of observed densification processes indicates that built up form changes are not only taking place in the main cities, but also in small villages and more rural areas that started with a little presence of urbanized area and has been transformed into compact build-up environments.

4. Discussion

4.1. Long-term changes in urban form in Spain

This study shows a downward trend of new buildings height during the 70′s for the four analyzed FUAs and a decreasing trend after the 2008 real estate bubble for the cases of Barcelona and Valencia. The overall period (1965 to 2015) showed a change in height of −116 cm, −313 cm, −217 cm and −157 cm for Barcelona, Madrid, Valencia and Zaragoza, respectively. The global trend of urban expansion with lower densities, reported also for Mediterranean environments in recent decades (Tombolini et al., 2015), does produce a decrease in average building height in Spanish functional urban areas accepting our prior hypothesis. Even though the long-term trend in larger FUAs shows a decrease, considerable variation of building height is observed between periods and specific years. The decrease of building height starting $\approx$ 1970 may be related to a reduction in building policies and political instability during the transition period. The development of public building, predominant in previous decades linked to land law of 1956, was limited but the provision of industrial land had some exceptions, which may explain the development of buildings with lower height (Díaz, 2016). The start of the democracy changed the power from a central government to regional or municipal scales. The downward trend after the construction bubble may be explained by a reduction of new neighbourhoods within the main cities, generally characterized by higher heights and open spaces, counterbalanced by the still building of detached or industrial buildings. Further analysis should focus on analysing height variability for shorter periods of time and its explanatory factors such as population density (Frantz et al., 2021) or planning strictness (Liu et al., 2014). Currently, land-use planning instruments are developed and implemented at a municipal scale in Spain, which have provided local authorities a great power to steer urban development's generating heterogeneous outcomes in terms of urban form within a FUA. The development of stricter planning goals in Spain was proposed only in 2015 with the Land and Urban Rehabilitation law, which is not within our study period. Logically, building heights vary more within cities than across cities, as these generally include higher buildings in the centre and lower buildings in the outskirts.

Horizontal growth contributed roughly 95 % of the total increase in building volume in the five decades analysed, which indicates that urban expansion processes predominate in Mediterranean cities (Zambon et al., 2017; Ren et al., 2020). Our results resemble those found elsewhere in Europe (Kasanko et al., 2006), which reveal a change in urban development models towards urban dispersion into rural landscapes. Our long-term analysis shows that in 1965 vol increase was concentrated in urban cores, while it was observed in the outskirts of the cities and in rural environments in more recent decades. The speed of volume increased differed, with the highest increases in the decades 1965–1975 (0.74 km3 in all FUAs combined) and 1995–2005 (0.75 km3 in the four FUAs combined). The spikes in urban development in the period 1965–1975 are related to a drastic liberalization of the Spanish economy after the ending of the autarky period (Alvarez-Palau, Martí-Henneberg, & Solanas-Jiménez, 2019). The Spanish economy experienced an intense economic growth, supported by favourable European and international economic conditions. This lead to a large increase in buildings, both in terms of area and volume, due to rise in family income, tourism, second-houses and rural exodus (Carbajal, 2003). The National dwelling plan of 1961–1976 further promoted social housing, designed to accommodate rural exodus and to support the construction sector by subsidies.

The highest urban growth rates in the period 1995–2005 were heavily reliant on low interest rates of the loans for the construction sector, deregulation measures that allowed Spanish municipalities to increase their income by creating new buildable land, and the overall world economic situation. Together, these conditions yielded unprecedented urban development in Spain (Díaz-Pacheco & García-Palomares, 2014; Serra, Vera, Tulla, & Salvati, 2014; Varela-Candamio, Rubiera Morollón, & Sedrakyan, 2019), consistent with our observations in changes in building volume in this period. The subsequent crash of the real estate bubble was the major cause of a reduction in urban growth during the period 2005–2015, which showed the lowest increase in built-up volume in the entire study period. The evolution of urban areas entails multiple factors from the increase of population to economic, investments and policies regulations. In this sense, recent reorient in planning regulations to restrict urban development, control urban dispersion and revitalize existing urban areas, which follows the 2030 Urban Agenda aims, are key to make a rational use of soil and steer sustainable urban development.

The urban form of Mediterranean cities have been traditionally characterized by compactness and dense urban cores (Ondoño, Abellán, & Garcia-Gonzalez, 2021), while a trend towards expansion with lower densities have been witnessed during recent decades (Tombolini et al., 2015). Our results are in accordance with this trend as the increase of sparsely built-up forms showed the highest expansion in terms of area suggesting a trend of *peri*-urbanization and suburbanization processes. These developments occupy a relatively larger area of land, while they represent only a small proportion of all built-up volume. Our findings resemble those found in China (Li et al., 2019) and Europe (van Vliet, Verburg, Grădinaru, & Hersperger, 2019), which show that village landscapes with low densities were the main destination of new built-up land. Yet, while it is the largest urban form type in terms of land area, the share of urban land characterized by sparsely built land (UFT 9) decreased over time. This paradox illustrates the challenge in sustainable urban development.

Urban expansion has reduced the availability of non-urban land within vicinity of urban areas, increasing the pressure on land previously found in other countries like China (Li et al., 2019). Overall, the changes have created a hybrid model, or new urban–rural relationships model (Serra et al., 2014), with presence of compact big and intermediate cities and dispersion within the outskirts and between cities (Catalán et al., 2008; Díaz-Pacheco & García-Palomares, 2014). In this context, Barcelona has been described by a polycentric growth model, with seven relevant sub-centres (Catalán et al., 2008; Tombolini et al., 2015). Madrid also presents elements of polycentrism, with the consolidation of sub-centres in outer rings (Díaz-Pacheco & García-Palomares, 2014) and an emergent polycentric pattern is observed in Valencia with additional subcenters in the outskirts of the main city. At the same time, a trend towards densification has developed over time. Changes from low-intensity urban forms to high-rates accounts for 19 % of the overall form changes. These modifications have been characterized by gradual changes towards more compact UFTs, following similar trajectories as transformations in Austin (USA) (Zhao et al., 2020) and changes from rural to urban in China (Li et al., 2019). However, densification processes were not linked to a large development of high-rise buildings, which are still rare in the FUAs studied.

4.2. Characterizing 3D urban form for long term analyses

Urban form transformations are often analysed based on two-dimensional information, without further integration of both horizontal and vertical components (Li et al., 2020). The increasing availability of 3D data sources now allows to analyse these urban growth processes (Liu et al., 2020; Zhao et al., 2020). Specifically, LiDAR data has the resolutions and accuracy to accurately characterize building footprints and heights (Bonczak & Kontokosta, 2019; Ren et al., 2020). Yet, LiDAR cannot be used to study long-term changes, due to novelty of this technique, though the future acquisition of data could provide opportunities for such analysis in the medium to long-term. This study integrates LiDAR and cadastral datasets to characterize at long-term the volumetric component providing building footprints and heights along a continuous scale as well as urban form types representing discrete classes. The analysis of urban form parameters by means of building heights, footprints, and volumes and how these are translated to categorial UFTs could contribute to a more in deep understanding of urban growth and may offer insights on the impacts of spatial planning in urban form, which could be of interest for the development of sustainable areas in the future (Bonczak & Kontokosta, 2019; Walczak, 2021). While development trajectories of different cities are inherently unique, we speculate that other cities in Mediterranean Europe and potentially even in the rest of Europe have similar long-term trends, because of the shared cultural background and comparable long term economic and social developments. Yet, on shorter time periods and for individual cities, specific political or other conditions are likely to differ.

The mapping of UFTs trajectories in selected Spanish FUAs shows that urban growth occurs at different paces over time and space (Díaz-Pacheco & García-Palomares, 2014). Even though urban areas are subject to continuous changes, long-term analysis allows a better understanding of the historical and socio-economic context that shape urban form (Catalán et al., 2008; Moudon, 1997). The use of the Local Climate Zones framework (Stewart & Oke, 2012) for long-term 3D UFTs mapping as an extension proposed by Zhao et al. (2020) and also applied by Liu et al. (2020) constitutes a suitable approach to go beyond the urban form horizontal dimension and analyse the volumetric spatial dynamics. The UFTs framework is flexible as it relies on two basic parameters only (i.e. building height and footprint), disregarding variables as sky view factor, canyon aspect ratio and roughness, which have been recently considered with lower importance (Hidalgo et al., 2019; Zhao et al., 2020). Thus, makes it interpretable and connected to practical context of planning and design (Wang, Georganos, Kuffer, Abascal, & Vanhuysse, 2022), and suitable for long-term characterization (Liu et al., 2020). Furthermore, the selected basic parameters are also important factors affecting the trapping of air pollution, generation of urban heat islands, and soil sealing (Tobias et al., 2018; Wong, Nichol, To, & Wang, 2010). Yet, one limitation of the current research is the lack of integration of roads and streets and other non-building impervious surfaces, based on the unavailable land-use from historical records. Recent authors have proposed simplified methodologies to determine street properties (i.e. street width) assuming that buildings are square shaped and evenly distributed in grid cells (Li et al., 2022), yet we have not included as the traditional city-centre form of Spanish cities present a higher heterogeneity.

Future research could focus on combining the 3D urban form characterization with socio-economic information or availability of green infrastructure to further understand the urban environment imprint in society, climate, and liveability at different scales (e.g.: from the urban area as a hole to the neighbourhood level). Furthermore, the links between 3D dimensions' urban form and multi-functionality of urban areas could reveal additional insights in drivers behind urban form changes. In this sense, the cadastral datasets might constitute not only a suitable dataset for understanding urban growth trajectories (Ondoño et al., 2021), but also to further understand 3D functional spatial patterns of urban environments. Form types could also provide a starting point for a more nuanced representation of urban densities that could be integrated in land-use change models, which are essential to envision sustainable urban development (Domingo, Palka, & Hersperger, 2021; Wang, van Vliet, Debonne, Pu, & Verburg, 2021). Hence, a transferrable approach to map 3D form of urban areas is essential to explore solutions for sustainable urban growth, especially in areas where urbanization exceeds beyond population growth.

5. Conclusions

Urban forms exist in a wide variety ranging from sparsely distributed buildings to compact urban city-cores. This study analyses long-term changes in height, volume, and 3D urban form types (UFTs) by integrating cadastral and LiDAR datasets from 1965 to 2015 in Barcelona, Madrid, Valencia, and Zaragoza FUAs. We show a downward trend of average height of new buildings during the 70′s for the four analyzed FUAs and a decreasing trend after the 2008 real estate bubble for the cases of Barcelona and Valencia. Over the analyzed period the average height of new buildings in Barcelona, Madrid, Valencia, and Zaragoza decreased 116, 313, 217 and 157 cm, respectively. This changes in building height results predominately from urban expansion at the fringes with small- and medium sized buildings. These urban form patterns are against the Spanish Urban Agenda goals that favors compact developments and the revitalization of existing urban areas. Built volume has increased by around 350 % over the period, with the highest rates in 1975–1985 and 1995–2005, slowing after the 2008 housing bubble. The breakdown of the volumetric component of urban development shows a tendency towards urban expansion. Furthermore, we were able to show that around 95 % of the increase in built volume comes from horizontal growth. Over the five decades, developments with a relatively low proportion of building volume per area have predominated. At the same time, however, the central city centres became denser over time.

This study is one of the first attempts to analyze 3D urban form changes over half a century. It takes advantage of newly available data for Spanish cities and develops novel methods to document changes in in height, volume, and density within existing urban fabric and at the edge.

The ability to characterise the built environment presented in this study can support effective urban monitoring. In particular, the data can be used to analyse the achievement of spatial planning objectives on density and settlement form. In this sense, the methods developed for this three-dimensional analysis are interesting tools to better plan and manage urbanisation processes in cities around the world, thus supporting cities in creating a more sustainable urban environment.

Declaration of Competing Interest

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Data availability

The cadastral data and LiDAR data used for the study is publically available for download (https://www.sedecatastro.gob.es/; https://centrodedescargas.cnig.es/CentroDescargas/index.jsp).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2022.104624.

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