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Research Article

A quantitative spatial methodology for delimiting historical centers – an application in Guarda, Portugal

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Abstract: A historical center can be defined as the oldest part of a city where a significant part of the building stock dates back to the early stages of urban growth. Historical centers often contain special urban fabrics with unique, historic, social and cultural identity. Owing to this, they have been subject to special urban planning interventions in order not only to protect the existing urban fabric and its originality, but also to revert depopulation and built deterioration processes aiming to make these old centers attractive and functional again. However, in the inter-urban domain, there is a deficit of spatial planning research, and the delimitation of historical centers is a topic that has been under explored. This paper describes a morphological approach for delimiting the historical center of Guarda, Portugal. Methodologically, the work uses building stock-age data from eight periods between <1919 to 2011 and is supported by both statistical and spatial analysis. Statistically, the urban evolution of the city was analyzed through threshold values and five novel building indexes. Spatially, the work involved disaggregated GIS analysis to map the evolution of built-up areas and to identify the consolidated urban areas. A sensitivity analysis was also performed to assess the influence of some parameters on the obtained boundary. Results indicated that the historical center of Guarda was consolidated in the 1960s and, since then, has been relatively unchanged. The obtained boundary shows a suitable spatial adjustment considering the consolidated urban area and the official boundary included in the Urban Rehabilitation Area.

Keywords: historical center, building data, urban boundaries, urban evolution, consolidated urban areas, geospatial statistical analysis

1 Introduction

Historical centers play a major role in enhancing place identity, memory and belonging [9]. They are defined by many different aspects, including building characteristics, which reflect the evolution of the urban expansion, as well as the historical and cultural development of the city [37]. Besides their central position relative to the surrounding urban areas and hinterlands, historical centers started to decline when they gradually lost their functions as urban hubs of gathering, transport, and commerce [58].

A historical center in Portugal is defined as the oldest central part of an urban settlement where a significant part of their building stock dates back to the early stages of the urban growth process [29]. In Portugal until the 1970s, policies were mostly focused on demolishing buildings, widening streets, and in constructing new buildings, streets and public areas to adapt the city centers to the new needs in terms of mobility and comfort [26]. In the 1970s, policies gained a new focus on the preservation and rehabilitation of these areas. The aim was to preserve the collective memory of historical centers and to reverse their abandonment and deterioration. Rehabilitation was supported in several governmental programs, such as RECRIA, REHABITA, SOLARH and PROHABITA, which provided incentives and funding for the operations. Recently, the topic gained new ground in the context of Urban Rehabilitation Areas (URA), which provide fiscal incentives to rehabilitate deprived and obsolete urban areas, including those located in historical centers.

In the planning domain, the delimitation of urban areas is still considered a difficult task [5,71]. Urban areas, defined too narrowly or too broadly, could be inefficient in detecting specific problems such as sprawl and building deterioration. Besides the urban specificities of historical centers (heritage vulnerability, complex and compact urban fabric), the delimitation of these spaces has been scarcely analyzed [20]. The literature indicates that delimitations have been supported in different quantitative and qualitative methods and data, providing different and sometimes vague, unsuitable and unrealistic limits [12,42,65]. This is the case of Portugal, where the delimitation of these areas has been supported in municipal decisions by adopting different methods and criteria [56].

This paper describes a methodology using building age disaggregated data to delimit a historical center, understood as the oldest central part of a city [29, 47]. The method is applied in Guarda, a medium-sized Portuguese city, and is supported by both statistical and spatial analysis. Statistically, the method estimates a threshold value to identify the oldest cores and uses five novel building indexes to understand the urban evolution and to identify the consolidated urban areas. Statistical operations are based on building data from eight periods between <1919 (the oldest period available) and 2011. Spatially, the method uses the Census block units (statistical tracts), which contain the building stock data for each period. Various Geographic Information Systems (GIS) operations are proposed to understand how construction evolved, map the different urban areas and delimit the historical center. Finally, a sensitivity analysis is conducted to assess the accuracy of the proposed method and to understand the extent to which the method is sensitive to changes in some statistical parameters used to delimit the historical center of Guarda.

By providing an objective and reproducible method for delimiting historical centers, this study could be useful for planners and policymakers in understanding the existing urban structure and, therefore, in supporting planning policies for historical centers' preservation and rehabilitation, urban resilience, building energy renovation, traffic circulation, among others. The study is also useful for researchers as it contributes to fulfilling the deficit of empirical analysis in delimiting historical centers.

The paper is organized as follows. Section 2 describes the existing literature review, as well as the approaches and methods used for delimiting urban areas and historical centers. Section 3 introduces the study area, and describes the data and method used in this study. Section 4 presents the results, while Section 5 discusses the main findings obtained. Finally, Section 6 concludes and offers some insights for future work.

2 Related work

The delimitation of historical centers can be analyzed within the broader field of delimiting city centers, which may include many different concepts, such as central business districts, downtown areas, inner cities, and point zero, among others [32, 80]. While city centers may have identical physical and morphological features, they are not consistent or uniform across cities [67], which complicates the task of delimiting these areas and has inspired the use of various delineation methods and tools. Furthermore, city centers have been described as classic examples of vague regions with indeterminate boundaries [1, 32, 69]. Besides the lack of consensus about the best way of delimiting urban areas [66, 74], city centers have been mostly delimited by using qualitative or quantitative methods.

Qualitative methods are based on mental constructions and subjective interpretations of the urban space [67]. Research carried out by Lynch [41] was influential in the use of cognitive perceptions to delineate urban spaces, including city center boundaries. Within these methods, urban delimitations can be obtained by performing questionnaires, surveys and interviews. For example, Montello et al. [45] conducted a behavioral study, where participants were invited to draw a line on a base map to obtain an empirical delimitation of downtown Santa Barbara, California. Similarly, Nieśioruk [48] also conducted a survey to delimit the city center of Lublin, Poland. In this case, a group of students was invited to draw mental maps of the city center to test their spatial cognition. In a different approach, Hollenstein and Purves [32] used georeferenced and tagged metadata associated with Flickr images to describe the concept of downtown across the USA and to understand the borders of city center neighborhoods at the level of individual cities. Moreover, qualitative methodological approaches have been also conducted to collect perceptions of city centers [2] and perceptions about the urban quality of city centers [83]. However, urban delimitations and studies based on individual perceptions are often considered vague and changeable [45,74].

Quantitative methods, supported by functional and morphological approaches, are the most common in urban delimitations. Functional approaches usually rely on the aggregation of economic activities, resulting in areas with different land uses and functions [12,68]. Accordingly, city centers have been delimited through several variables, including the concentration of specific activities such as commerce [63] and services [12], the distribution of land uses [40], the relocation of uses and activities [22], the type of employment [28, 36], and the distribution of tourist attractions, accommodation and facilities, which are particularly relevant in historical centers [30, 38].These variables have been analyzed through indexes showing the concentration of specific activities/uses [8, 81], kernel density estimations representing continuous surface of specific indicators [77], cluster analysis indicating proximity relationships [36, 81] and by applying fuzzy-set models to address geographic vagueness [1]. Some other authors, such as Jiang and Liu [34], used street network data to delineate urban boundaries. Their method was able to capture the underlying structure of the geographic space and to detect the city center. Urban travel flows have also been used to make functional delimitations. For example, Cats et al. [14] classified city centers by using public transport flow data, while Sun et al. [65] adopted human travel flows generated from social networking data to identify city centers. However, delimitations based on travel flows have some limitations as they do not reflect the mobility of non-commuters [23].

In turn, morphological approaches are based on the principle that city centers have different physical characteristics when compared to the surrounding urban structures [67]. These approaches often rely on using population and building data. Urbanization has been regarded as the concentration of people in a space [36,71]. Alone or combined with other variables, population densities have been widely adopted to delimit urban areas and city centers [60, 71, 74]. In the case of European historical centers, recent studies show that many of them are still characterized by lower population densities due to gentrification and touristification [30,38,44]. On the other hand, urbanization is also described by built environment variables such as the concentration of buildings in an area [5,60]. Therefore, city centers can be delineated by using different building parameters, including: the floor area ratio [74], building height, volume, and size [64,67] and building density [5,15,60]. In the specific case of historical centers, the building age can be used to isolate the older from the surrounding newer areas. Besides being adopted in some broader urban studies [4,47], only a few authors attempted to use the building age to delineate city centers [11].

In the morphological approaches, building data is preferable to population data since residential population only shows where people sleep at night. Thus, delimitations supported on population data may fail to classify city centers devoid of residents [5], which is particularly the case of many historical centers in Portugal. Building morphological approaches are based on objective and easily comparable data [66], but some building data, namely age, is often unavailable at the intra-urban scale [82], which may restrict its use in the delimitation of city centers.

3 Study area, data and method

3.1 Study area

Guarda is a municipality and a city located in the Eastern part of Portugal in the NUTS 2 Região Centro (Figure 1). According to the 2011 Census [61], the municipality has an area of 712 km^2 and a population of 42,541 inhabitants living in 43 *freguesias*, a municipal administrative subdivision. Having a population density of 59.7 inhabitants/km^2, Guarda is a paradigmatic example of a rural peripheral region. The city is the main urban center, containing about 62% of the whole municipal population.

The city was founded in the 12th century by the second Portuguese King, D. Sancho I to encourage people to settle there and provide defense from the Spanish threat. Thus, the city was originally established due to military reasons and had an important role in maintaining national sovereignty. Guarda was chosen as a location by several kings to ratify treaties and establish diplomatic agreements. This legacy is still visible in Guarda's built environment, such as the walls and castle remains, the Cathedral and the Monastery of Saint Francis among others. Nowadays, the city is characterized by contrasts and a wide range of uses and land occupation with a strong functional diversity.

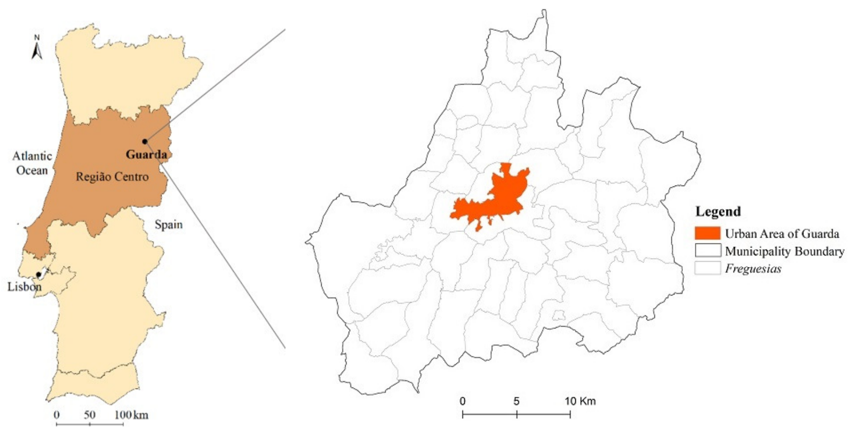


Figure 1: Location of Guarda [18].

In 2011, the municipality of Guarda had a total of 19,376 buildings, while the city had a total number of 6,129 buildings, from which 5,287 were exclusively for residential use [61]. The spatial distribution of building age is shown in Figure 2.

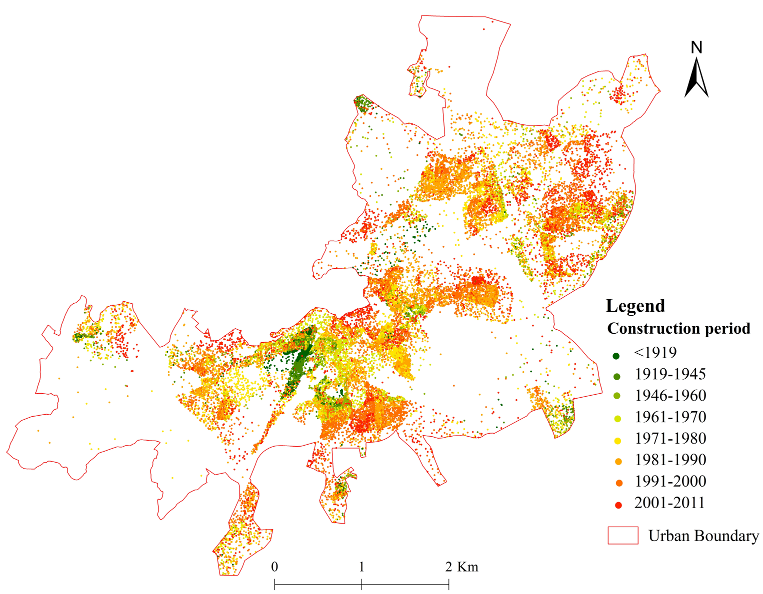


Figure 2: Building age in the actual urban boundary [61].

According to Figure 2, the oldest buildings (green dots) are mostly concentrated, while the buildings constructed in the last decades (orange and red dots) are spread by the entire urban boundary. This distribution suggests that the urban growth process started in some settlements (oldest buildings) and spread towards adjacent and more distant areas. The low-density building areas shown in Figure 2 are mainly due to topographic reasons and to building restrictions associated with protected areas. In 2011, a total of 180 buildings previous to 1919 were located in the urban boundary [61].

3.2 Method and data

It has been argued that any delimitation of urban areas should be consistent with a description of their internal geography [5]. This paper uses building Census data to identify and delimit the historical center of Guarda. Censuses are a relatively common source of statistical data to describe building stock [82]. In Portugal, Census tracts are small and homogeneous geographic units representing urban or rural spaces. In the case of urban spaces, these tracts correspond to urban blocks usually with similar morphological and functional characteristics [62]. Thus, the use of Census tracts may ensure delimitations respecting the internal geography of the spaces.

The method is based on both statistical and spatial analysis. Statistically, the method is supported in the data provided by the Census 2011 [61] at the level of statistical tract. For each tract, the Census provides building data for the following eight periods: buildings constructed before 1919 (hereinafter referred to as <1919, which is the oldest building data available), between 1919-1945, 1946-1960, 1961-1970, 1971-1980, 1981-1990, 1991-2000 and 2001-2011. Having such disaggregated building data, the oldest urban areas can be identified and it can be analyzed how urbanization evolved in the city during the last 100 years.

Spatially, the method is supported on Census block units, which contains the building stock data. Through GIS operations, it is possible to understand how construction evolved, map the respective urban areas and delimit the historical center. GIS tools have been widely used for delimiting urban areas, including city and historical centers [59, 79, 80]. In this paper, ArcGIS 10.5 was the software used to perform spatial analysis. Figure 3 shows the distribution of the statistical tracts within the urban area. The current boundary of the city is an area of 1,837.71 ha and comprises 530 statistical tracts.

One of the problems resulting from using building stock data to delimit a historical center is the age and the number of buildings from specific periods that should be used to classify an area as "historical" [26]. In the literature and depending on the subject area, the concept of "historical" or "old" building varies in definition. The concept has also been differently understood among urban planners. For example, Economidou [21] and Mazzarella [43] argued that buildings that were 50 years old or more could be considered "'old" or "historical". Lucchi et al. [39] classified the buildings constructed before 1945 in Calavino, Italy, as historical constructions. Also in Italy, Fabbri et al. [24] showed that 30% of the buildings of Ferrara date back to before 1945, which confirm the highest importance of the city in the past. In the case of Visby, Sweden, a UNESCO World Heritage Site, Broström et al. [10] also classified the buildings built before 1945 as traditional constructions. In Vermont, USA, Hoesen and Letendre [31] considered the building construction over the years 1885-1940 as historical buildings. Inversely, some authors, such as Rosser et al. [51] classified the modern buildings of Nottingham, UK, as those post-1980. Therefore, and for planning purposes, the use of building data from a period <1919 could be considered old enough to delimit the oldest part of a city.

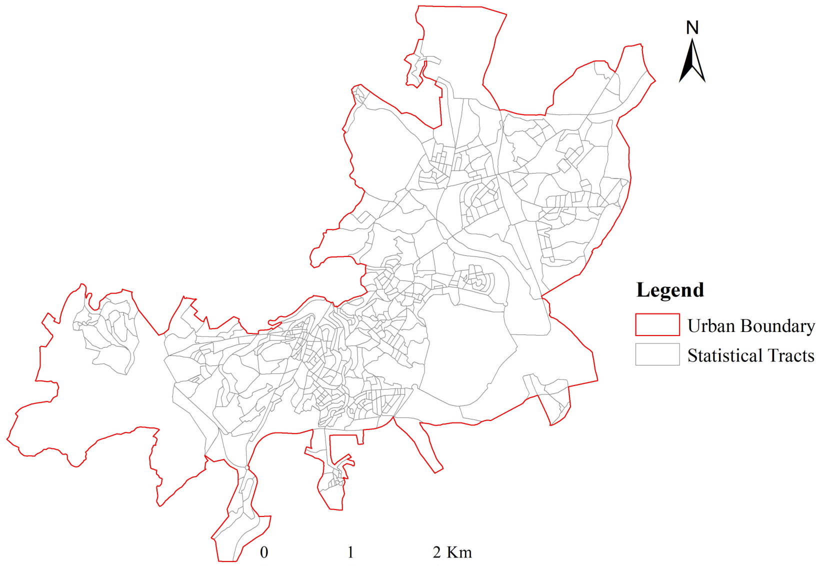


Figure 3: Urban boundary of Guarda and its statistical tracts [59, 62].

A second problem consists of how to use building stock data to delimit historical centers and how to isolate them from newer urban areas. To solve this problem, the method proposes a three-step approach by: i) identifying the areas containing the oldest cores; ii) identifying the consolidated urban areas; and iii) dissolving the oldest cores with the adjacent consolidated urban areas. In this study, the oldest cores were defined by tracts containing the oldest buildings, while consolidated urban areas were understood as tracts with continuous urban fabric having no or few space available for new constructions [13, 55].

The work was therefore developed according to the following steps. The first step consists of identifying the areas containing the oldest cores. Statistically, the oldest cores can be identified by using a threshold value regarding the number of buildings constructed <1919 in each tract. Threshold values supported by building density rates have been adopted to decide whenever a statistical tract can be classified as consolidated or not [50]. In this paper, the threshold value was estimated through the normal distribution of the buildings constructed <1919 and the respective density curve (Figure 4). The mean value (μ) of the buildings constructed <1919 in the city was 3.21 and the standard deviation (σ) was 3.62.

The probable distribution also shows all the possible values and likelihoods regarding the number of buildings constructed <1919. In the case of Guarda, as shown in Table 1, the highest probability corresponds to X≥3 buildings/tract, while the lowest probability corresponds to X ≥10 buildings/tract. As the range X≥6 buildings/tract corresponds to an intermediate probability (22%) and represents 63% of the buildings constructed <1919, this is the most appropriate threshold value to define the oldest cores in the city. Furthermore, the density curve (Figure 4) shows that 34% of buildings/tract are within a range of $\mu + \sigma$ = 6.83.

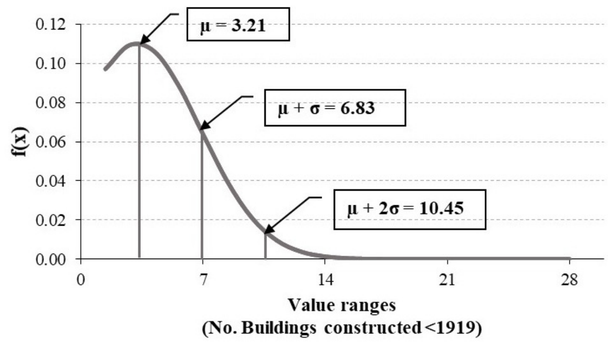


Figure 4: Probability density function for buildings constructed before 1919 [61].

f(x)	$\phi(z)$	Probability (P)	Percentage
P(X $\geq \mu$)	P(Z $\geq$ 0)	0.5	50.0%
P($\mu \leq$ X $\leq \mu + \sigma$)	P(0 $\leq$ Z $\leq$ 1)	0.3413	34.1%
P(X $\geq \mu + \sigma$)	P(Z $\geq$ 1)	0.1587	15.9%
P(X $\geq$ 3)	P(Z $\geq$ -0.06)	0.5239	52.4%
P(X $\geq$ 6)	P(Z $\geq$ 0.77)	0.2206	22.1%
P(X $\geq$ 10)	P(Z $\geq$ 1.88)	0.0301	3.0%

Table 1: Probable distribution of the buildings constructed before 1919 [61].

Identifying the oldest areas can be done by performing GIS spatial operations, namely by dissolving continuous tracts containing a certain number of buildings constructed <1919 above the threshold value. This spatial operation will show the location of the urban cores containing the oldest building densities (buildings/tract).

The second step of the work consists of identifying the consolidated urban areas in the city. To identify these areas, this study proposes using five novel building indexes: the Accumulated Building Index (AccBuIndex), the Building Consolidation Index (BConsIndex), the Building Consolidation 2011 Index (BCons2011Index), the Building Intensity Index (BIntIndex) and the Urban Sprawl Index (USpIndex). Indexes have been widely used in morphological approaches to delimit urban areas by aggregating areas with identical characteristics [5, 60] and to analyse the evolution of urban areas [57, 64]. Few indicators have been developed, however, to quantify and examine spatial-temporal urban growth [3]. The AccBuIndex shows how construction has grown over the last 100 years in all urban area by considering the accumulated number of buildings constructed in each statistical tract and in each one of the eight periods analyzed (<1919, <1919–1945, <1919–1960 and so on). This index aims to identify the continuous urban fabric area (CUFA) in each period *i* and is calculated according to equation 1.

$$AccBuIndex = \sum_{i=1}^{n} (NBuild)_i \quad (1)$$

where $(NBuild)_i$ is the number of buildings in the statistical tracts for period *i* and *i* corresponds to the periods <1919, <1919–1945, ..., <1919–2011, ... and *n* is the number of periods in analysis.

The BConsIndex and the BCons2011Index are proposed to analyze the process of urban consolidation in the city. These two indexes can detect when the CUFA became more consolidated: the higher the value, the greater the consolidation of the CUFA. More specifically, the BConsIndex measures the density of buildings constructed in CUFA until each period *i*. This index is calculated according to equation 2.

$$BConsIndex = \frac{(Build)_i}{(Area_{Cont})_i} \tag{2}$$

where $(Build)_i$ is the total number of buildings identified in CUFA for period *i*, $(Area_{Cont})_i$ is the area of the CUFA identified for period *i*, and *i* corresponds to the period in analysis.

In turn, the BCons2011Index measures the density of the buildings constructed up to 2011 (last period in analysis) in the CUFA for each period *i* analyzed (<1919, <1919–1945, <1919–1960 and so on). This index is calculated according to equation 3.

$$BCons2011Index = \frac{(Build)_{2011}}{(Area_{Cont})_i} \tag{3}$$

where $(Build)_{2011}$ is the number of buildings constructed until 2011 in the identified CUFA for *i*, $(Area_{Cont})_i$ is the area of the CUFA identified for period *i*, and *i* corresponds to the period in analysis.

These two urban consolidation indexes (BConsIndex and BCons2011Index) can be used to distinguish consolidated from remaining newer urban areas. The average of both indexes can be used as a threshold value to make such a distinction.

Finally, the BIntIndex and the USpIndex are proposed to analyze urban sprawl. Considering the CUFA identified for each period in relation to the total urban area (TUA), these indexes evaluate the building evolution and its expansion in the urban space taking into account the buildings constructed and their sprawl level. Results of BIntIndex and USpIndex can change between 0 and 1: values closer to 1 indicate high sprawl, while values near 0 indicate low sprawl.

Thus, the BIntIndex (equation 4) measures the building intensity in the CUFA for each period *i*:

$$BIntIndex = \frac{(Build)_i}{(Acum)_i} \tag{4}$$

where $(Build)_i$ is the total number of buildings identified in the CUFA for period *i*, $(Acum)_i$ is the cumulative number of buildings in all urban area until period *i*, and *i* corresponds to the period in analysis. In turn, the USpIndex (equation 5) measures the sprawl level in the CUFA for each period *i*:

$$USpIndex = \frac{(Trt)_i}{TotalTrt} \tag{5}$$

where $(Trt)_i$ is the total number of statistical tracts identified in the CUFA for period *i*, *TotalTrt* is the total number of statistical tracts in all urban area, and *i* corresponds to the period in analysis.

The five described indexes have the potential to make a detailed analysis of the urban evolution of a city by using building stock data. These indexes can be mapped to visualize and understand how urbanization evolved until each period *i*, namely in terms of urban consolidation and sprawl.

The third step of the work consists of delimiting the historical center by dissolving the oldest cores with the adjacent consolidated urban areas. This step of the work mainly involves GIS spatial analysis. First, the contiguous consolidated urban tracts are dissolved and then they are aggregated to the contiguous oldest cores previously identified. The obtained polygon may have interstitial non-urbanized areas, such as green spaces and non-urbanized areas resulting from restrictions to build around monuments and institutional facilities. When defining urban boundaries, these voids should be merged as they will not be changed in the future [71]. Thus, the final boundary should integrate not only the oldest and the consolidated urban areas, but also some spaces, such as clear and protection areas, to ensure a spatial continuity without voids.

Finally, a sensitivity analysis is developed to assess the accuracy of the described method. A sensitivity analysis is a process that aims to assess the response of a model to changes in input parameters, showing how a result changes when the input factors are modified [25]. If small changes in a specific input parameter result in a relatively large change in the result, then the outcome is said to depend on that factor. Thus, a sensitivity analysis quantifies the uncertainty of each parameter, contributing to a more accurate interpretation of the results [17]. Sensitivity analyses have been applied in a variety of urban planning studies usually by performing scenarios to simulate the impact that changes on statistical/spatial parameters may have on the results [17, 25, 75]. In the current study, as the size/configuration of the statistical tracts cannot be changed, the sensitivity analysis is performed by changing statistical parameters to understand whether one indicator is more influential than another and the impact of such changes on the delimitation of the historical center of Guarda. The two parameters that potentially may influence the results are the threshold value used to define the oldest cores and the building age. To avoid the problem of delineating urban boundaries based on arbitrarily threshold limits [33], the sensitivity analysis was performed in two scenarios. The rational of these scenarios are as follows:

Scenario 1 (S1): simulates the changes resulting from replacing the intermediate threshold value selected to define the oldest cores ($X \geq 6$ buildings/tract) by the threshold value that has the highest probability ($X \geq 3$ buildings/tract) and the lowest probability ($X \geq 10$ buildings/tract). This scenario is tested because building densities have been widely used in urban planning studies, including to delineate city centers [5] and to decide whenever a statistical tract can be classified as consolidated or not [50].

Scenario 2 (S2): simulates the changes resulting from replacing the oldest buildings as those constructed <1919 by those constructed <1945. This scenario is tested for three main reasons: i) because building data are time sensitive, having different temporal scales [35], which may limit the replication of this method in other cities/countries: ii) because buildings <1945 have been classified as old enough to be considered "historical" [10,31,39]; and iii) because buildings constructed in different periods have different styles and greatly influence the pattern of land used [49].

4 Results

4.1 Identifying the oldest urban cores

The first step of the work consisted of identifying the oldest urban cores. The range ($X \geq 6$) buildings <1919 was considered the most appropriate threshold value to identify these areas, as shown in Table 1. This range represents 63% of the buildings constructed <1919 and has a low spatial dispersion (σ=3.15). Figure 5 shows the result of dissolving the statistical tracts according to the threshold value of X≥6.

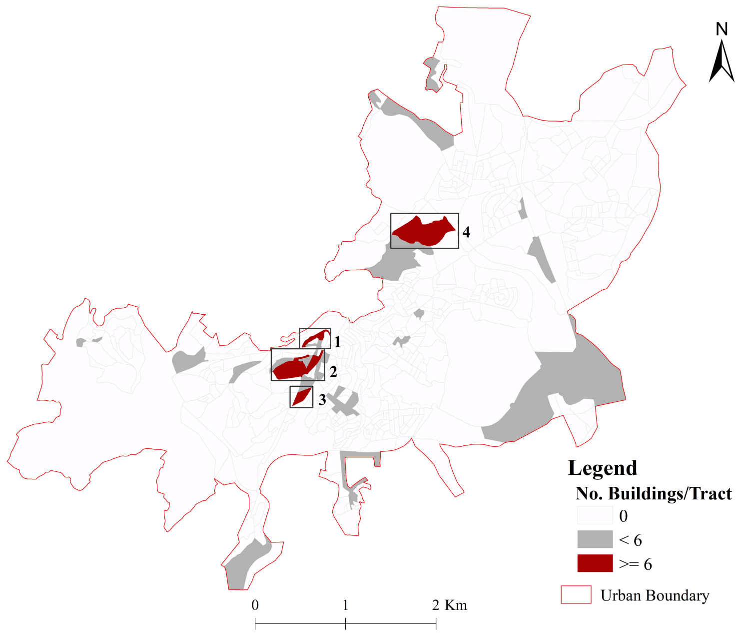


Figure 5: Buildings constructed before 1919 and the oldest cores identified [61].

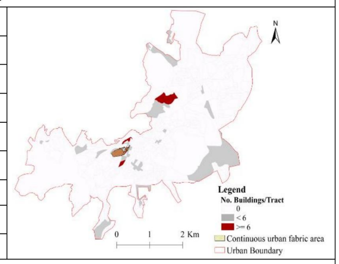
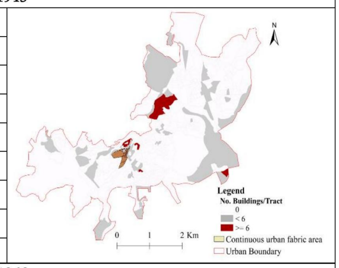
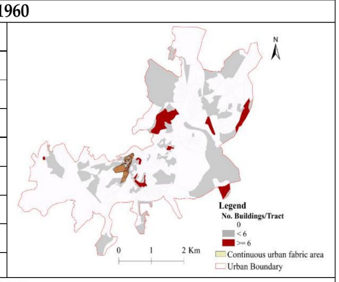
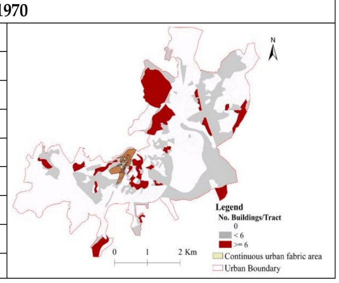
The results show that many tracts do not have any buildings constructed <1919 or have a density <6 building/tract (X<6). Regarding the densities ≥6 building/tract (X≥6), four main cores were identified, representing around 63% of these buildings. Three of them are located in the highest part of the city: core 1 contains 16 buildings, core 2 has 77 buildings and core 3 contains 14 buildings. In turn, core 4 is more distant and only has 6 buildings. Core 2 contains 43% of these buildings, as well as some historical and emblematic buildings, such as the castle tower, part of the Jewish quarter and the cathedral.

4.2 Identifying the consolidated urban areas

The second step of the work consisted of identifying the consolidated urban areas. As mentioned in Method and Data, the urban evolution was analyzed by calculating and mapping five novel building indexes: AccBuIndex, BConsIndex, BCons2011Index, BIntIndex, and USpIndex. The results of these statistical and spatial operations are presented in Table 2.

In addition, Table 2 also presents the Built Area Ratio (BAR) between the continuous urban fabric area (CUFA) and the total urban area (TUA) for each period *i*. The CUFA was delimited considering the contiguity of the statistical tracts and the value of AccBuIndex ≥6 buildings/tract.

The statistical and spatial analysis presented in Table 2 gives a detailed overview about the urban evolution of the city over the last 100 years. As shown in Figure 6, the two urban consolidation indexes (BConsIndex and BCons2011Index) grew continuously until 1960,

Parameters	CUFA	TUA	Spatial evolution
<1919			
BConsIndex (Build./ha)	**8.80**		
$Area_{Cont}$ (ha) ∣ Total Area (ha)	8.86	1837.71	
BCons2011Index (Build./ha)	**11.51**		
$(Build)_{2011}$	102	6129	
BIntIndex	**0.43**		
Build ∣ Acum	78	180	
USpIndex	**0.02**		
Trt ∣ TotalTrt	9	530	
BAR ($Area_{Cont}$/Total Area)	**0.005**		
<1919 - 1945			
BConsIndex (Build./ha)	**12.90**		
$Area_{Cont}$ (ha) ∣ Total Area (ha)	13.49	1837.71	
BCons2011Index (Build./ha)	**14.31**		
$(Build)_{2011}$	193	6129	
BIntIndex	**0.38**		
Build ∣ Acum	174	459	
USpIndex	**0.03**		
Trt ∣ TotalTrt	14	530	
BAR ($Area_{Cont}$/Total Area)	**0.007**		
<1919 - 1960			
BConsIndex (Build./ha)	**16.62**		
$Area_{Cont}$ (ha) ∣ Total Area (ha)	17.99	1837.71	
BCons2011Index (Build./ha)	**22.18**		
$(Build)_{2011}$	399	6129	
BIntIndex	**0.38**		
Build ∣ Acum	299	787	
USpIndex	**0.04**		
Trt ∣ TotalTrt	23	530	
BAR ($Area_{Cont}$/Total Area)	**0.01**		
<1919 - 1970			
BConsIndex (Build./ha)	**13.64**		
$Area_{Cont}$ (ha) ∣ Total Area (ha)	26.53	1837.71	
BCons2011Index (Build./ha)	**17.30**		
$(Build)_{2011}$	459	6129	
BIntIndex	**0.29**		
Build ∣ Acum	362	1269	
USpIndex	**0.05**		
Trt ∣ TotalTrt	27	530	
BAR ($Area_{Cont}$/Total Area)	**0.014**		

(to be continued)

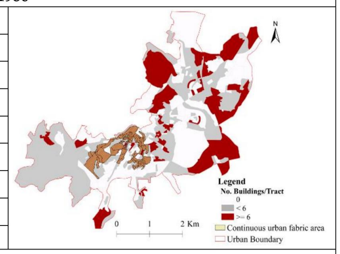
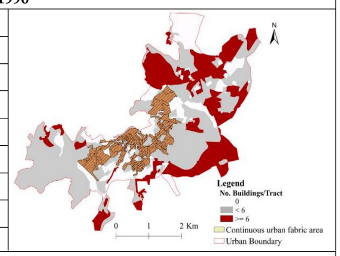
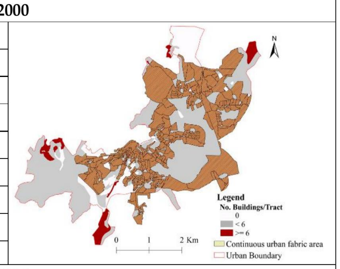
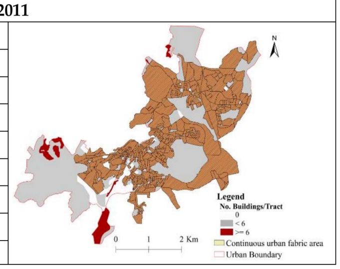
Parameters	CUFA	TUA	Spatial evolution
<1919 - 1980			
BConsIndex (Build./ha)	**8.57**		
$Area_{Cont}$ (ha) | Total Area (ha)	101.10	1837.71	
BCons2011Index (Build./ha)	**11.95**		
$(Build)_{2011}$	1208	6129	
BIntIndex	**0.39**		
Build | Acum	866	2212	
USpIndex	**0.13**		
Trt | TotalTrt	71	530	
BAR ($Area_{Cont}$/Total Area)	**0.055**		
<1919 - 1990			
BConsIndex (Build./ha)	**8.11**		
$Area_{Cont}$ (ha) | Total Area (ha)	234.04	1837.71	
BCons2011Index (Build./ha)	**9.90**		
$(Build)_{2011}$	2318	6129	
BIntIndex	**0.51**		
Build | Acum	1898	3692	
USpIndex	**0.28**		
Trt | TotalTrt	146	530	
BAR ($Area_{Cont}$/Total Area)	**0.13**		
<1919 - 2000			
BConsIndex (Build./ha)	**5.36**		
$Area_{Cont}$ (ha) | Total Area (ha)	849.46	1837.71	
BCons2011Index (Build./ha)	**5.91**		
$(Build)_{2011}$	5024	6129	
BIntIndex	**0.87**		
Build | Acum	4556	5256	
USpIndex	**0.63**		
Trt | TotalTrt	332	530	
BAR ($Area_{Cont}$/Total Area)	**0.46**		
<1919 - 2011			
BConsIndex (Build./ha)	**5.35**		
$Area_{Cont}$ (ha) | Total Area (ha)	1023.66	1837.71	
BCons2011Index (Build./ha)	**5.35**		
$(Build)_{2011}$	5479	6129	
BIntIndex	**0.89**		
Build | Acum	5479	6129	
USpIndex	**0.71**		
Trt | TotalTrt	378	530	
BAR ($Area_{Cont}$/Total Area)	**0.56**		

Table 2: Urban evolution in Guarda according to building construction [61].

where their highest values were obtained (16.62 and 22.18 buildings/ha, respectively). In the following periods, both indexes decreased continuously until 2011 when their lowest values were registered (5.35 buildings/ha for both indexes).

In turn, the two urban sprawl indexes (BIntIndex and USpIndex) showed a different evolution (Figure 6). Until 1970, urban growth was moderate and concentrated as shown by the low values of BIntIndex (0.29) and of USpIndex (0.05). After the 1970s, both indexes started a trend of continuous growth until 2011. The BIntIndex increased from 0.29 in 1970 to 0.89 in 2011, while the USpIndex increased from 0.05 to 0.71 in the same period. As shown in Figure 6, the construction of new buildings and the urban sprawl was particularly high during the 1990s.

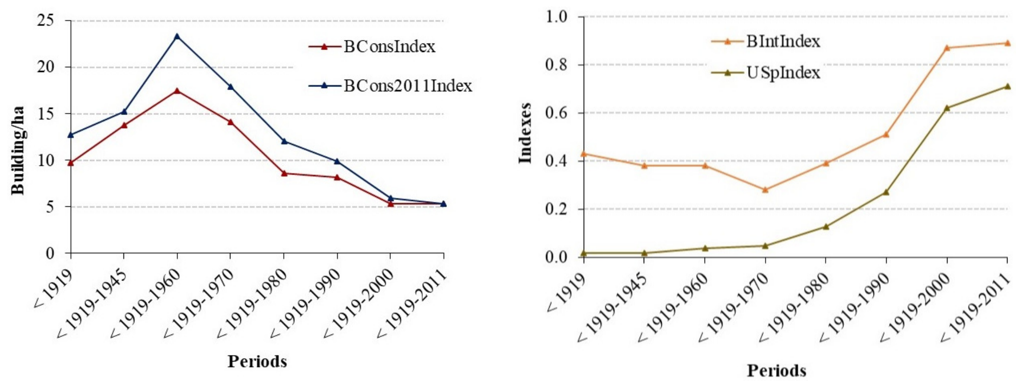


Figure 6: Evolution of BConsIndex, BCons2011Index, BIntIndex and USpIndex [61].

In sum, the indexes showed that the oldest areas, e.g., those with more buildings constructed <1919 and their adjacent tracts, were consolidated by the 1960s and that these tracts have been relatively stable since that period. Therefore, the statistical analysis suggests that by the 1960s (period <1919 - 1970), the oldest urban areas of the city were consolidated. From the 1970s and more notoriously after the 1980s, the city started a rapid and diffused process of urban growth with the construction of new buildings in areas increasingly distant from the oldest cores. In fact, the BAR (Table 2) shows a small dispersion in the period <1919 to 1970 (ranging from 0.005 to 0.014); but from 1970 to 2011 it shows an increasing urban dispersion, which is particularly noticeable in the period 1990 to 2011 (ranging from 0.13 to 0.56). The maps in Table 2, as well as Figure 2, indicate that building age decreases from the center to the periphery, suggesting that the growth started and spread from the oldest cores.

As described in the Method and Data, the consolidated urban areas can be distinguished from the newer urban areas by using the average between the BConsIndex and the BCons2011Index as a threshold value. Therefore, for the period <1919–1970, the consolidated urban areas were classified as those with densities greater than or equal to 15.47 buildings/ha (Figure 7).

As shown in Figure 7, the oldest cores 1 and 3, previously identified in Figure 5 are classified as consolidated areas. In core 2, all tracts have a density higher than 15.47 buildings/ha, except the two tracts where the cathedral and the castle tower are located. However, these areas will not be changed because they correspond to buffer zones around these monuments. Thus, core 2 is also a consolidated urban area. In turn, core 3 is consolidated but physically separated from cores 1 and 2. Regarding core 4, the building density is lower than 15.47 buildings/ha and (unconsolidated urban area). To sum up, cores 1, 2 and 3 are consolidated, but only cores 1 and 2 are spatially contiguous.

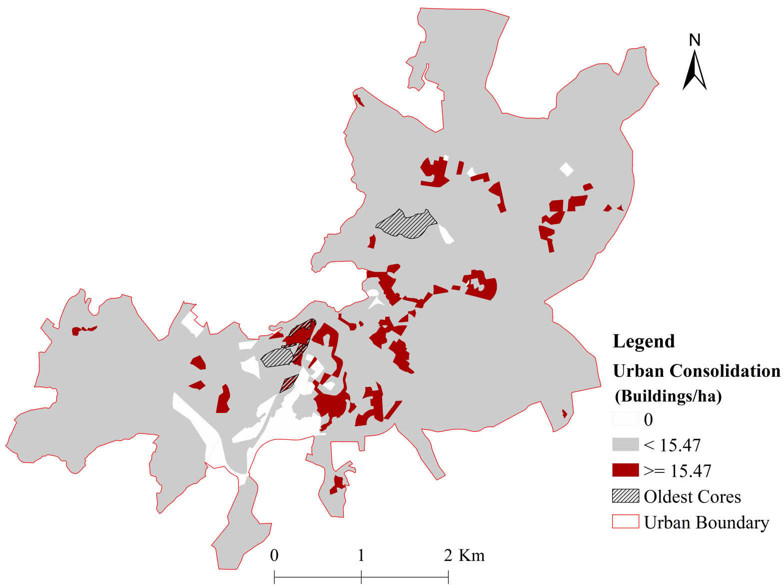


Figure 7: Consolidated urban areas [61].

4.3 Delimiting the historical center

The third step of the work was the delimitation of the historical center by performing GIS spatial operations. The contiguous consolidated tracts were dissolved and then aggregated to the contiguous tracts of cores 1 and 2. The obtained boundary is shown in Figure 8A.

The final boundary includes 30 statistical tracts, has an area of 15.94 ha and 415 buildings and has a density of 26.04 building/ha (Table 3). The number of buildings by tract ranges from 1 to 50 with an average of 13.83 buildings/tract. From the overall 415 buildings, 73% correspond to constructions <1970, 51% to constructions <1945 and 24% to constructions <1919 (Table 3 and Figure 8B).

The only official document providing a boundary of the historical center is the Guarda's Urban Rehabilitation Area (URA) [19]. The method used for delimiting the URA is not described in the respective document [19]. As shown in Figure 8A, the delimited boundary and the URA limit have a relatively similar size and shape, suggesting that the obtained boundary is consistent, and the official boundary includes the oldest buildings and the most consolidated urban areas. Nonetheless, the obtained boundary is larger (+3.9 ha) as it includes the buffer zones around the cathedral and the castle tower in the Southwest sector, as well as some old buildings such as Saint Peter's chapel located in the Southeast sector.

Statistical data	No. of buildings by period
Total area: 15.94ha	<1919: 99
Building density: 26.04 Build./ha	1919-1945: 114
Statistical tracts: 30	1946-1960: 64
Minimum No. of buildings/tract: 1	1961-1970: 25
Maximum No. of buildings/tract: 50	1971-1980: 25
Average building/tract: 13.83	1981-1990: 18
Standard deviation: 9.86	1991-2000: 35
Population: 487 inhabitants	2001-2011: 35

Table 3: Statistical data of the obtained limit [61].

For these reasons, it seems that the obtained boundary delimits the historical center more properly than the limit of URA.

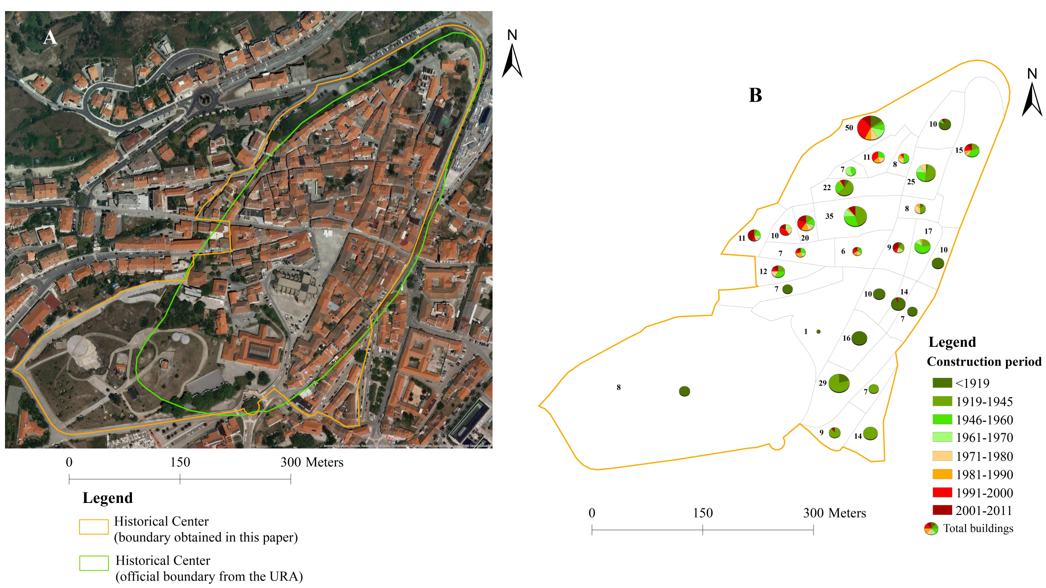


Figure 8: Boundary of the historical center and its comparison with the URA limit (A) and the building age by tract in the historical center (B) [19,61].

4.4 Sensitivity analysis

The final step of the work consists of developing a sensitivity analysis to test the accuracy of the results by conducting two scenarios.

The first scenario (S1) tests the impact of replacing the building density of X≥6 buildings <1919/tract by X≥3 buildings <1919/tract and by X≥10 buildings <1919/tract on the delimitation of the historical center. When X≥6 is replaced by X≥3, the number of the oldest cores rises from 4 to 6. As shown in Figure 9, except for core 6, the identified oldest cores have similar locations and, with the exception of core 1, they have different shapes as they contain more tracts. In this scenario, core 2 contains 53% of all buildings <1919. The calculation of the five indexes with X≥3 reveals a trend of urban consolidation and sprawl similar to that obtained with X≥6. As shown in Figure 10, the BConsIndex and BCons2011Index started to decrease after 1960, while the BIntIndex and USpIndex started to increase after that period. The threshold value to classify the consolidated urban areas rose from 15.47 buildings/ha to 17.00. From the six oldest cores identified with X≥3, only some tracts of two cores were classified as consolidated, e.g., having a building density ≥17.00 buildings/ha. After aggregating the continuous urban areas and dissolving the clearer areas, the obtained limit is shown in Figure 11. The new limit is very similar in terms of shape and area but differs from the initial boundary as it excludes one tract.

As shown in Figure 9, when X≥6 is replaced by X≥10, the number of oldest cores decreases (-2). The two cores identified fall in the areas of cores 2 and 3 of Figure 5, but they have different shapes and sizes. Core 1 contains 27% of all buildings <1919, while core 2 has 8%. In terms of urban consolidation, the BConsIndex and BCons2011Index also started to decrease after the 1960s (Figure 10), while the BIntIndex and USpIndex started to increase more consistently after the 1980s, but at a slower pace than with X≥6. The threshold value obtained with X≥10 (23.42 buildings/ha) was more restrictive and resulted in the exclusion of various tracts as it did not have the required density. The boundary obtained with X≥10 is smaller and has a different shape of that retrieved with X≥6 (Figure 11). Nonetheless, its tracts are located within the boundary delimited with the initial method.

To sum up, replacing the building density of X≥6 buildings/tract by X≥3 and by X≥10 causes changes in the oldest cores identified and in the building indexes statistics. However, the trend of urban consolidation and sprawl obtained with X≥3 and X≥10 is identical to that obtained with X≥6, as both indicated that the oldest urban areas were consolidated by the 1960s and the sprawl started to increase from the 1970s. Although the different limits were obtained with X≥3 and X≥10, they also fell within the same areas of the boundary retrieved with X≥6, which reinforces the notion that this area is the oldest and the most consolidated.

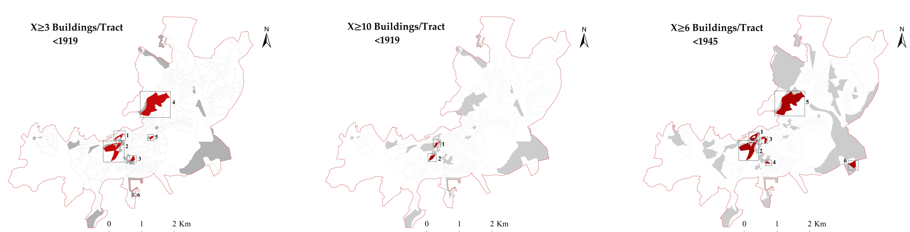


Figure 9: Oldest cores identified with the sensitivity scenarios [61].

The second scenario (S2) tests the impact of replacing the oldest buildings as those constructed <1919 by those constructed <1945. This change causes a direct impact on the number of buildings considered in the analysis (from 180 to 459), and as shown in Figure 9, on the number and shape of the oldest cores identified (+2 than with buildings <1919). The six oldest cores have a changeable number of buildings, ranging from 6 to 173. The most representative (core 2) is located in the area of cores 2 and 3 in Figure 5, which contains 38% of the buildings <1945. In terms of location, three of the six new cores fall in the areas of the

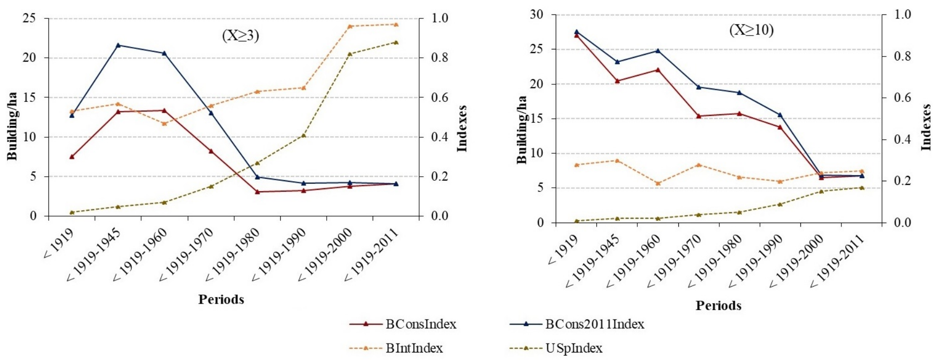


Figure 10: Performance of the building indexes in Scenario 1 (X≥3 and X≥10) [61].

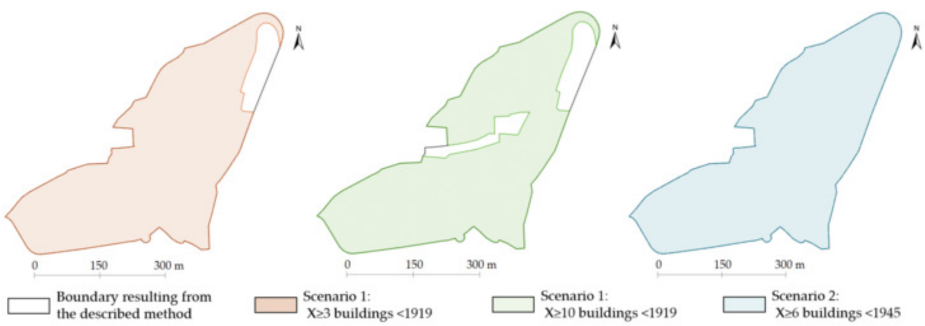


Figure 11: Comparison of the boundary obtained with the described method and those resulting from the Scenarios S1 and S2 [61].

cores represented in Figure 5. In terms of urban consolidation and sprawl, the calculation of the five indexes indicated that the results are exactly the same for <1919-1945 and subsequent periods. Accordingly, the threshold building density value (15.47 buildings/ha) and the limit after aggregating the continuous urban areas and dissolving the clearer areas is the same as that obtained with the initial method (Figures 8A and 11).

In sum, replacing the oldest buildings as those constructed <1919 by those constructed <1945 does not have practical implications in terms of understanding the urban evolution of the city, neither in the delimitation of the historical center of Guarda. This sensitivity scenario confirmed previous research indicating that, for urban planning purposes, buildings <1945 can been classified as old enough to be considered "historical" [10,31,39].

5 Discussion

Delimiting urban boundaries has been an enthralling challenge for planners due to the complex nature of urbanization and the multiple methods and approaches that have been used [33,46]. In this context, identifying and generating accurate urban center maps is considered a special difficult task [76]. Urban centers are not definite entities in the sense that they might not be located at the geometric or geographical center of a city and they might have fuzzy or indeterminate borders [16]. In the case of historical centers understood as the oldest central part of a city, they are the physical testimony of the history, development and occupation of a city and remain as one of the best sources of information about its origin and evolution [53]. To protect the historical and architectural values found in historical centers and to make these areas attractive, is fundamental to have a complete understanding of the genesis and evolution of these areas, which includes a proper identification of their boundaries. By delimiting historical centers, this method can help urban planners and decision-makers in adopting planning policies to preserve the built heritage and the overall urban fabric and to boost their capability of being attractive for contemporary urban functions. In addition, the delimitation of historical centers can be helpful in other fields: i) planning for urban resilience as historical centers are vulnerable to natural disasters and hazards, such as earthquakes and fires [7]; ii) planning for building energy renovation and efficiency, as old buildings generally have worst levels of insulation and energy efficiency than new constructions [24, 29, 43, 82]; and iii) planning for city logistics due to restrictions of freight vehicle circulation in these areas [72].

This paper describes a method to delimit the historical center of Guarda, Portugal, by using statistical and spatial data. Based on building stock-age data from eight periods between <1919 to 2011, statistically the method consists of estimating threshold building density and urban consolidation and sprawl values to identify the oldest cores, understand the urban evolution and delineate the consolidated urban areas. Spatially, the method involves various GIS operations using statistical tracts containing building stock data of each period to map the urban evolution and delineate the historical center.

The oldest cores, defined as those containing a prevalence of buildings <1919 above a threshold statistically value, were limited to a few areas. However, the cores containing the highest number of buildings <1919 and <1945 are located in the obtained boundary. From the 415 buildings found in the delimited boundary, 24% are <1919 and 51% are <1945. The sensitivity analysis also proved that this area contains the largest number of old buildings if other density threshold values are used. As highlighted in the Method and Data, the age to classify a building as "old" or "historical" is subjective and not consensual [26], but for urban planning purposes, buildings previous to 1945 have been classified as old enough to be considered "historical" [10, 31, 39]. Therefore, the method proved to be efficient in identifying and delimiting the oldest cores of the city.

In terms of urban consolidation, this study shows that the process of urban growth, which started in some settlements (oldest cores), spread towards adjacent areas and, more recently, towards more distant areas, which were previously rural spaces. From the urban point of view, the delimited boundary falls within an area that was consolidated by the 1960s. Since then, this area was relatively unchanged, which is also a characteristic associated with historical centers [43]. The sensitivity scenarios carried out produced similar results. They showed that the oldest urban areas were consolidated by the 1960s and the sprawl started to increase from the 1970s. Besides the somewhat different delimitations obtained when the statistical thresholds derived from the indexes are changed, they fall in the same area of the delimited boundary. Thus, the method also proved to be efficient in identifying and delimiting the consolidated urban areas of the city.

The boundary derived from spatial aggregation is consistent with the URA limit and seems to be more appropriate and rational as it includes clear areas around the cathedral and the castle tower and adjacent tracts containing old buildings. The different influence of criteria on the delimitation was explored through sensitivity analysis. As noted in the Results, not all parameters had the same influence in terms of identifying the oldest cores, the consolidated urban areas and, finally, delimiting the final boundary. We found that changing the threshold building densities exerts some influence, mainly when using X≥10 buildings <1919/tract but, as explained in Method and Data, this scenario has the lowest probability. The use of the highest probably (X≥3 buildings <1919/tract) produces less influence on the delimitation, while replacing the oldest buildings (<1919) by those built <1945 do not produce any effect. Thus, the sensitivity analysis also proved that the method adopted was the most accurate to delimit the historical center of Guarda.

Spatially, the findings presented in this paper have been organized from Census tract level data provided by SP [62]. The eight periods analyzed (<1919 to 2011) reflect those of the Portuguese Housing Survey (Census). The use of this type of data and time frames can be found in other studies focused on historical centers [24, 29, 51]. The size and number of buildings in each tract can vary greatly. In the case of Guarda, tracts range from 900 m^2 in the center to 694,000 m^2 in the suburb. The small size and compact structure of the Census blocks in the center allowed for capturing finer details and to have a delimitation that represents the ground accurately. Contrary to the findings of Soares et al. [60], where Census blocks were not found suitable to delimit potential urban expansion areas, this study indicates that these spatial units were suitable for delimiting the historical center of Guarda. In turn, statistical tracts are administrative divisions, which necessarily limits the shape and range of the delimited urban center [76]. A different organization of the tracts will result in different delimitations in terms of shape and size. The influence of this aspect on the final results was not simulated as we used the most disaggregated tract level.

The method described in this study is potentially replicable in other cities, particularly in small historical European cities, which generally present similar shaping characteristics [4]. Nonetheless, the replication of this method in other cities could be restricted by data availability, by some limitations of this method and by the specificities of the cities. First, it requires spatially located building age data. Building stock data are time sensitive, having past, present and future time scales and constants [35] that may constrain the replication of this method. This type of data could be difficult to access and be unavailable for specific periods of time [51, 82]. For example, to locate the current Victorian domestic stock, Roumpani et al. [52] reported that age building data were extremely difficult to access within the UK. Similarly, Lucchi et al. [39] noted that accurate historical building data are only available for the latest periods of the 19th century. Thus, the unavailability of building age data could be a major barrier to replicate this method in other cities.

Second, findings presented in this paper have been organized from Census-tract level data provided by SP [61]. Census are generally considered an accurate source for enriching urban models with some data about buildings [82]. However, as shown in the example of Guarda, Census tracts may vary widely in physical areas and may disregard topography and other physical features that are of major importance in urban design. Moreover, accurate Census data are not available in some countries [71] and may not include consistent and uniform data from the previous decades [82]. The lack of detailed spatial building age data can be determined by alternative sources and approaches. This includes the analysis of historical maps and data [4, 52], remote sensing LIDAR surveys [70], the use of building databases from public and private agencies [6, 70], among others. However, these sources also present some constraints. For example, historical maps are quite inaccurate regarding the location and the characteristics of the buildings [4, 39]. Private and public databases may only have data for some jurisdictions, they are usually expensive and tend to lack details [6,70]. Inventories of the temporal distribution of housing stock are often laborious, time consuming and require experts [31]. Thus, working with building age data may pose various challenges and restrictions, which may explain the frequent lack of historical information in the studies focused on urban growth [73]. Building age could also be combined with other morphological variables (building size, number of floors, etc.). For example, there is evidence that buildings in historical centers are usually smaller than those located in other urban spaces [51]. These attributes may be combined with age for delimiting historical centers.

Third, cities throughout the world are very diverse, ranging from small and compact cities with historical centers, to very large and more recent metropolis. The method proved to be efficient in delimiting the historical center of Guarda. As pointed out by Wurm et al. [74], in historical walled cities, the spatial delimitation of the city is a less complex task than in polycentric cities, which have undergone transformations in their spatial and functional structures. Thus, many more applications are needed to test the efficiency of this method, not only in cities with a size and morphology similar to Guarda, but also in larger and less compact cities with different morphologies. It will be particularly interesting to test how this method performs namely: i) in cities where the oldest buildings are more spread out within the urban area, such as in those reconstructed after the Second World War, such as in Poland and Germany, where many centers were partially or totally reconstructed [47,82], as well as in cities affected by severe natural hazards, such as earthquakes [7]; and ii) in cities with a diverse urban consolidation and sprawl patterns associated with specific regimes and political changes, as verified in Central and Eastern Europe with the transition from a socialist to a market-oriented society [54]. Even if the delimitation of a formal historical center may be difficult in these types of cities, the proposed urban indexes could give a detailed overview about the processes of urban evolution in these cities over time.

Finally, the described method consists of a purely morphological approach based on building data. We decided to adopt this approach because the criteria used are often easily comparable internationally [46]. However, this approach does not include the multiple functions that should be taken into consideration when designing policies for improving the urban functions and for fulfilling the diverse demands of the population living, working and visiting these areas.

6 Conclusion

Considering that many urban structures, such as buildings, streets and squares, are legacies from the past, it has been argued that, to a large extent, we live in yesterday's cities [78]. These legacies, including historic buildings and special urban fabrics with unique, historic, social and cultural identity, are often found in historical centers. However, these places have been experiencing a progressive decline and deterioration due to several interconnected factors related to their physical, functional and socioeconomic vulnerabilities [27]. Planning policies addressed for historical centers should be geared to face these vulnerabilities (physical deterioration, abandonment, tourism gentrification, urban resilience), while preserving the character of these places, the existing urban fabric and their originality. A proper delimitation of these areas is essential to help urban planners and decision-makers in adopting effective planning policies for historical centers.

This paper describes a statistical and spatial methodology for delimiting historical centers by using building stock age data. Statistically, the method estimates a threshold value to identify the oldest cores and is supported by five new building indexes to identify the oldest and the consolidated urban areas and to understand how urbanization evolved over time. Spatially, the method is supported on GIS and uses Census block units to analyze how construction evolved, to map the different urban areas and to delimit the historical center. The method, applied in Guarda, a medium-sized Portuguese city, proves to be useful in identifying and delimiting the historical center, understood as the oldest part of the city. Considering the specific features and vulnerabilities of historical centers, the described method has high potential for urban planning and design, especially to identify priority areas regarding urban rehabilitation. In the specific case of Portugal, the method can be useful for municipalities involved in revising their municipal master plans and in defining Urban Rehabilitation Areas. The revision of the municipal master plan represents an opportunity to delimit the historical center, which have specific needs and vulnerabilities when compared with the remaining newer urban spaces.

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