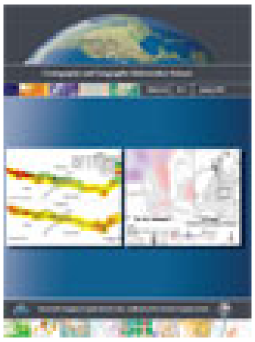

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Tracking a city's center of gravity over 500 years of growth from a time series of georectified historical maps

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ABSTRACT

It is surprising difficult to define where a city center lies, yet its location has a profound effect on a city's structure and function. We examine whether city center typicality points can be consistently located on historical maps such that their centroid identifies a meaningful central location over a 500-year period in Southampton, UK. We compare movements of this city center centroid against changes in the geographical center of the city as defined by its boundary. Southampton's historical maps were georectified with a mean accuracy of 21 m (range 9.9 to 47 m), and 18 to 102 typicality points were identified per map, enough to chart changes in the city center centroid through time. Over nearly 500 years, Southampton's center has moved just 343 m, often corresponding with the key retail attractants of the time, while its population has increased 80-fold, its administrative area 60-fold and its geographical center moved 1985 m. This inertia to change in the city center presents environmental challenges for the present-day, made worse by the geography of Southampton, bounded by the sea, rivers and major roads. Geographical context, coupled with planning decisions in the past that maintain a city center in its historical location, place limits on the current sustainability of a city.

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Georeferencing; city center; city evolution; spatial structure; typicality features; sustainable urban development

Introduction

Even in the present day, it is surprisingly difficult to define what is meant by a city or town center and precisely where it lies (Cheshire et al., 2018). There is no universal consensus on its definition and its spatial boundaries remain vague due to subjective judgment (Hollenstein & Purves, 2010; Lüscher & Weibel, 2013; Montello et al., 2003; Saraiva & Pinho, 2015; Thurstain-Goodwin & Unwin, 2000; Zhong et al., 2013). Attempts to find logical ways to define and measure the city center have led to the development of a wide range of analytical methods (Lüscher & Weibel, 2013). One of the first was proposed by Murphy and Vance (1954) that delineated central business districts (CBD) by taking into account the percentage of floor area of retail and commercial activity as an index of central business activity. Similarly, Thurstain-Goodwin and Unwin (2000) applied kernel density estimation (KDE) on four city center typicality indicators (employment type, density of built area, diversity of land use and visitor attractions) to create a continuous surface to identify peaks of density on the surface. Other methods use georeferenced and tagged metadata from https://flickr.com/ to identify clusters of uploaded photos whose tags are linked to the vernacular use of city core terms (Hollenstein & Purves, 2010). Montello et al. (2003) performed an experiment where randomly chosen people in streets were asked to outline on a map the "downtown" area, according to their own perceptions. Lüscher and Weibel (2013) conducted an online participant experiment using questionnaires, including a list of points of attraction, to develop a procedure for automatic delineation of city centers. Others have used public transportation smart card data (Roth et al., 2011; Zhong et al., 2013, 2014) and a centrality index (CI) based on the concept of central place theory (CPT) (Zhong et al., 2014) to identify the spatial structure of cities and human activity patterns (Roth et al., 2011). More recently, Cheshire et al. (2018) have shown that town centers may be defined systematically across the whole of Britain using multiple sources of micro-geographic data. Unfortunately, none of these approaches is applicable across a wide span of years because, clearly, no photographs, business data or public opinions are widely available for the early years. The challenge thus remains: how can the location of a city center be tracked over long periods of time?

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Supplemental data for this article can be accessed here.

Cities, in common with all landscapes transformed by human settlements, are continuously evolving, changing in both space and time. Although processes such as fire, agriculture and deforestation cause impacts on ecosystems, urbanization has undoubtedly been the most radical human-induced transformation of land in recent times (Clarke et al., 1997), necessitated by an expanding urban population. The pace has been rapid, for example, only 3% of the European population living in urban areas during the 1800 s (Goitia, 2003) whereas the figure is approximately 75% in recent years (EEA, 2011). This changing spatial-temporal dynamic is important because the spatial structure of a city has a pivotal role in influencing people's movements, and in determining the dimensions of sustainability and sustainable urban development, for example, in terms of economic growth and promotion of social and environmental equity (Anas et al., 1998; Zhong et al., 2014). As Cheshire et al. (2018) point out, urban policies are often aimed at ill-defined town centers in order to strengthen retail centers, to adjust shoppers' travel patterns and to reduce their carbon footprints. Yet as we emphasize here, the historical development of a city may constrain present-day options for change. The identification of changes in urban morphology and its structure are thus crucial for developing appropriate and efficient planning strategies to meet sustainability goals and for understanding constraints on change.

The obvious way to study the evolution and development of urban environments is by using historical maps (Brovelli & Minghini, 2012; Clarke et al., 1997; Forejt et al., 2018; Jenny & Hurni, 2011; Manzano-Agugliaro et al., 2013; Manzano-Agugliaro et al., 2014; Pindozzi et al., 2015; San-Antonio-Gómez et al., 2014). There are challenges in this, however, as historical maps have a degree of inaccuracy and uncertainty (Baiocchi et al., 2013; Brovelli & Minghini, 2012; Burt et al., 2020; Forejt et al., 2018; Manzano-Agugliaro et al., 2014; Qtaishat et al., 2006; Tucci & Giordano, 2011), often having been created before the introduction of standardized projections in the 19th century (Pindozzi et al., 2015; San-Antonio-Gómez et al., 2014). It is sometimes difficult to attribute a specific year to a historical map, since they often took several years to complete (Baiocchi et al., 2013; Brovelli & Minghini, 2012; EDINA, 2015; Hermosilla et al., 2014; Liu et al., 2018; San-Antonio-Gómez et al., 2014). For example, the map "Epoch 2 – County Series First Revision" used in this study and identified by Ordnance Survey (OS) as a map from 1890, was surveyed between 1888 and 1914 (EDINA, 2015). In order to compare historical data with modern cartography for qualitative and quantitative analysis, it is necessary to transform the unprojected historical data into the coordinate system of the contemporary maps (Baiocchi et al., 2013; Brovelli & Minghini, 2012; Liu et al., 2018; Pindozzi et al., 2015; San-Antonio-Gómez et al., 2014), often an error-prone and tedious process (Burt et al., 2020). This georeferencing inevitably leaves some error in the final result (Baiocchi et al., 2013; Brovelli & Minghini, 2012; Pindozzi et al., 2015; Qtaishat et al., 2006; San-Antonio-Gómez et al., 2014; Tucci & Giordano, 2011). The issue here is whether accuracy in georeferencing and the detail on historical maps is sufficient to identify the location of a city's center.

By using a case study city in southern England, UK, we address two main research questions:

(1) Can historical maps yield sufficient, consistent information to track changes in the location of the city center over time?
(2) Is there evidence that the location of the city center shows inertia to change?

We then consider whether the location of the historic center locks a city into a spatial pattern that may be unsuitable for modern transport and the needs of city users.

Materials and methods

Study site and map data sources

Southampton is located on the south coast of the United Kingdom approximately 120 km southwest of London. The city footprint is peninsula-shaped lying at the confluence of the rivers Itchen and Test. Its geographical location allows the city to benefit from a sheltered position, created by the presence of the Isle of Wight on the south of the Solent, that combined with the double high tide peaks of its waters, creates the right conditions for the transit of large ships (ABP, 2009; EDAW Limited, 2001; Neal, 2014). Archeological evidences suggest that some of the area of today's Southampton has been occupied by smaller settlements since the Stone Age (Neal, 2014). Although throughout its existence Southampton has been known as a port town/city, it has also experienced periods of glory as a spa and bathing destination (Brown, 2004; Neal, 2014). Alongside the expansion of its port, Southampton has recently been witnessing fast growth, that is expected to continue in the coming years. According to the latest UK census in 2011, the city has over 237,000 residents occupying an urban area of approximately 50 km^2 (David Lock Associates, 2013; EDAW Limited, 2001; ONS, 2014).

To undertake an analysis of the evolution of Southampton's urban form and its changes through time, a time series of 12 maps spanning nearly 500 years was used. These were sourced from the Elizabethan Times catalog (Welch, 1964), Southampton atlas catalog (The Southampton Record Society, n.d.), from Historic Ordnance Survey (OS) map data (EDINA, 2015) and from OS products for the present day (Table 1).

Map processing

Historical maps from Digimap (EDINA, 2015) were downloaded as TIFF files already projected to the British National Grid. Since the UK's County Series maps (Table 1) originally used the Cassini projection (the National Grid system only being implemented in the 1950 s), Ordnance Survey in partnership with RMSI India and Landmark Information Group, transformed the County Series' maps to the National Grid system prior to their distribution on Digimap (EDINA, 2015). It is therefore assumed here that the historical maps and vector data from Digimap are free from errors. The maps from the Elizabethan Times catalog (Welch, 1964) and Southampton Atlas (The Southampton Record Society, n.d.), only available as hard copies, were scanned as TIFF files at a resolution of 300 dpi and imported into ArcGIS 10.3 (ESRI, Redlands, CA) for georeferencing. The map used as the spatial data reference was an OS Vector Map, downloaded from Digimap (EDINA, 2016). Vector data is superior to raster data (e.g., an aerial photograph) for this purpose, as it is easier to match the smoothed edges or corners of vector objects on two maps as opposed to the stepped edges of rasterized objects. There is no specific rule to define the ideal number of control points to use in georeferencing, but studies on positional accuracy have recommended a minimum of 20 control points (San-Antonio-Gómez et al., 2014; USGS, 1999), and this was followed here.

Table 1. Historical and present-day cartography used (hereafter referred to by date). Ordnance Survey Digimap products are © Crown Copyright and Landmark Information Group Limited (2020). All rights reserved. (1890 - 2015).

Map Source	Map details
Southampton Atlas	1560 (Sheet II)
	1611 (Sheet III)
	1791 (Sheet IX)
	1862 (Sheet XII)
Elizabethan Times catalog	1835 (Map 19)
	1866 (Map 21)
Historic Ordnance Survey map data	1890, Epoch 2 (County Series 1st Revision)
	1910, Epoch 3 (County Series 2nd Revision)
	1930, Epoch 4 (County Series 3rd Revision)
	1960, Epoch i5 (National Grid Imperial ""6 inches to the mile" – First Editions)
	1990, Epoch m7 (National Grid 1:10,000 metric and 10,560 imperial – Latest editions)
Ordnance Survey	2015, MasterMap Topography

During the georeferencing process, the control points were placed strategically on locations that could easily be identified on both historical and vector maps. Such locations were mainly corners of historical buildings or building footprints, roads, street junctions and certain features of land morphology that remained constant through time. The number of control points used in the georeferencing process differed between the maps for a number of reasons. In the oldest maps, where the spatial extent of the urban area was smaller, the availability of potential locations to locate control points that would match the current vector map was more limited. As the date of the historical maps approached the time scale of the reference map, it was easier to identify a higher number of places to locate the control points. This is because the extent of the urban area was constantly increasing and also because the closer the date of the historical map to the present period, the easier it was to find potential places to anchor control points. To obtain the highest accuracy in the polynomial transformation of the historical maps, the control points corresponding to known features were widely scattered across the raster, including each corner.

As the intention of this study was to analyze changes in the urban form through time by overlapping maps from different time periods, the historical maps were transformed using polynomial models (of the category global, non-exact algorithms), that optimize fit across the entire map as opposed to locally (Boutoura & Livieratos, 2006; Brovelli & Minghini, 2012). Following the principle of parsimony, preference was given to Affine 1st order polynomial models when georeferencing the historical maps. Control points with large residual values were re-checked for digitizing accuracy (sometimes compromised by poor feature definition on the maps) and where doubtful were removed and others added in their place to maintain spatial coverage across the map. In cases where the root mean squared (RMS) error exceeded 20 m even after the removal of erroneous control points, 2nd order polynomial transformations were used in an attempt to reduce the residual error. Although 3rd order transformations reduced the RMS error still further, they were not used because they overfitted to the control points and caused distortion elsewhere, as well as adding more parameters, making the models more complex. The quality of the georeferencing process was visually assessed by overlapping the historical maps with the OS vector map since RMS error alone does not guarantee a good fit away from the control points. The RMS errors for the final georeferenced maps were cross-validated by jack-knifing using the qpcR library in R (Spiess, 2018) calculated and its geographical center (hereafter, the city boundary centroid) defined as the centroid of the polygon encompassing the city. This was used as a simple reference point for comparison with the location of the city center.

Delineating the city boundary

City boundaries were delineated in ArcGIS 10.3 (ESRI, Redlands, CA) as polygon feature classes on top of each georectified historical map. The digitizing process used a combination of map features and historical literature to identify the city boundaries at that time. In early maps, where the identification of the boundaries of the city was not clear either in the historical literature or explicitly on the map, a "500 m proximity rule" was applied. In other words, the city boundary was conceptually grown outwards until the next building or small group of buildings (e.g., fewer than five dwellings) was more than 500 m away, at which point growth stopped and the boundary was fixed. This combined approach was preferred in place of using a purely algorithmic one for all maps (e.g., by defining a polygon enclosing clusters of buildings and excluding buildings spaced more than a given distance apart). This is because it is clear in the literature that during some periods of history, certain features were regarded as being part of the city even though they were slightly displaced from the main concentration of activity. Once the boundaries were defined, the area of the city was

Defining the city center

Owing to constraints imposed by the quality of historical data, the methodology to define the city center had to be simple enough to be uniformly applicable across all historical and contemporary maps of the city. The approach consisted of identifying city center typicality points (Lüscher & Weibel, 2013) and calculating their weighted mean center. Based on the categories used by Lüscher & Weibel (Lüscher & Weibel, 2013), Table 2 shows the classes of typicalities that were found to be consistently identifiable across historical and contemporary maps used in this study (e.g., a particular religious building that could be tracked through time). Although Southampton presents a spatial pattern of polycentricity in common with many modern European cities (Ciommi et al., 2018), the analysis conducted here focused on the main center of the city or higher-order center as defined by Zhong et al. (2014). Southampton's higher-order center can be traced back to the original and only core of the medieval town. While Lüscher & Weibel (Lüscher & Weibel, 2013) did not consider physical or geographical barriers as

Table 2. Typicality features consistently identified on the maps to define city centers (adapted from Lüscher & Weibel, 2013).

Category	Typicality features	Rules applied
Accommodation, Eating and Drinking	Restaurant and Pub	
	Hotel or Guest House	
Attractions and Historical Landmarks	Museum	
	Cathedral	
	Castle and Medieval walls	A point was introduced on the main towers and main entrance Gates of the wall.
Commercial Services	Offices	
Entertainment	Theater	
	Nightclub	
	Cinema	
	Cultural Center	
Education and Health	Place of Higher Education or School	
	Hospital or Medical Services	
	Spa	
Public Infrastructure	Town Hall	
	Law Court	
	Library	
	Place of worship	
	Public Park	A point was placed on each of the corners of the park.
Retail	Department Store	
	Shopping Center	
	Shopping Street	A point was placed on the extremities and junctions of each of the identified commercial roads due to the impossibility of tracing back in history the exact number of shops.
	Market	
Transport	Main Railway Station	
	Coach Station	
	Ferry Terminal	

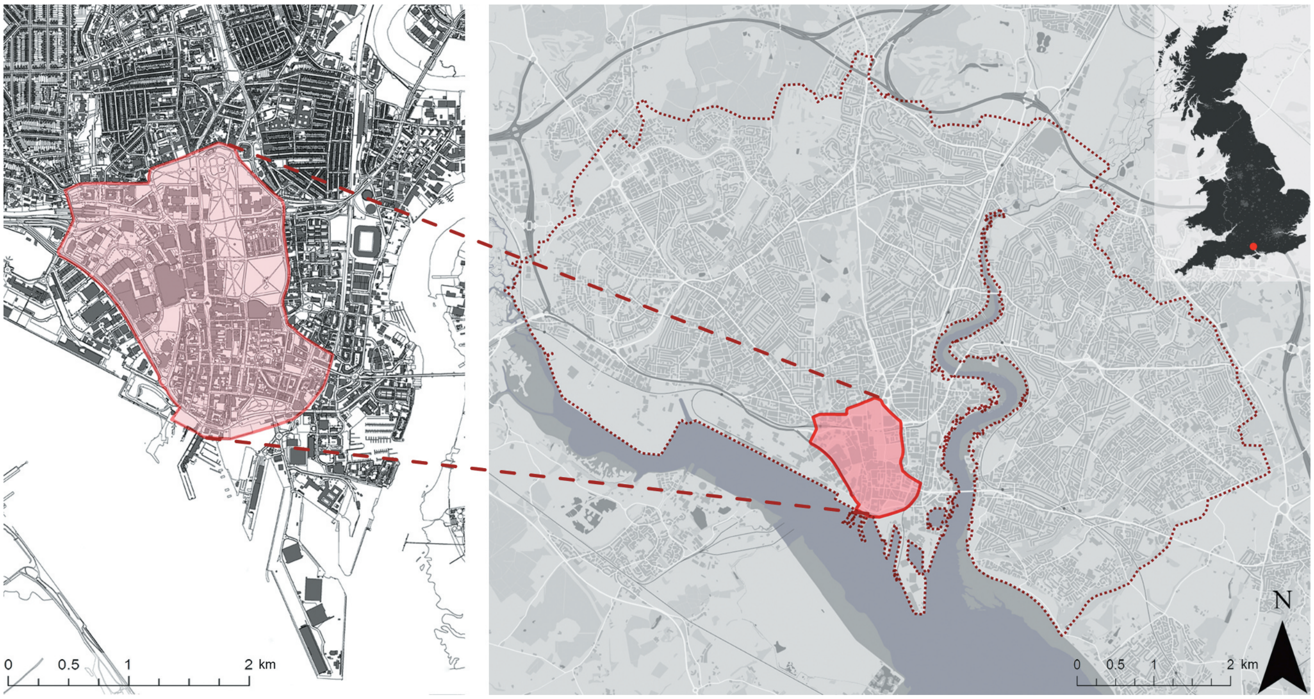

Figure 1. Location of Southampton and the area (masked) within which city center typicality points were identified on the time series of maps, delineated by major roads, railways and water bodies. Base map from 2015 (OS MasterMap Topography © Crown copyright and database rights (2020) Ordnance Survey (100025252)).

delimitators of the city center, these were taken into account in this analysis to restrict the typicality points to the higher-order center, using a mask delineated by major roads, railways and water bodies (Figure 1).

Results and interpretation

Accuracy of the georeferencing process

The number of control points needed to georeference the 1560 to 1866 maps varied between 28 and 123 (Table 3), the variation due to the level of detail and clarity of features, the spatial extent and the age of each historical map. Maps that were more recent tended to offer more features for georeferencing (43 to 123 control points after the 1830 s as opposed to 28 to 42 before) due to their cartography detail, but the 1862 map was an exception (Table 3). Four out of six maps were satisfactorily rectified using first order (Affine) transformations, the exceptions being the maps from 1560 and 1835, where a second order transformation was applied to approximate the value of the RMS error obtained for the other maps. For these two years, the largest residual of the control points (Table 3, column 4) remained around 80 m. Higher-order transformations were not used due to the deformations caused in the maps.

Comparison of RMS errors with and without cross-validation showed small differences of 1 to 2 m for all years except 1560, indicating that the models were well calibrated (Table 3). The difference of 14 m for 1560 reflects greater sensitivity to the control points used, possibly arising from the larger spatial extent of this early map. Non cross-validated RMS errors (reported here to facilitate comparison with the literature) ranged between 9.9 m for 1611 and 46.8 m for 1560 (Table 3). There was a steep increase in the accuracy of the maps as measured by RMS error between the 17th and 19th

Table 3. Georeferencing process used together with numbers of control points and residual errors. CV refers to jack-knife cross-validated residual and total RMS errors.

Map date	Order of polynomial used	No. of control points	Range of residual values (m)	Total RMS error (m)	CV range of residual values (m)	CV total RMS error (m)
1560	2nd	38	7.17–80.81	46.79	7.62–121.42	60.52
1611	1st	28	2.36–17.35	9.89	3.73–20.57	10.95
1791	1st	42	3.78–21.62	14.05	3.95–25.04	15.16
1835	2nd	123	1.37–79.36	17.54	1.39–93.26	19.30
1862	1st	43	4.59–33.64	16.94	4.78–37.64	18.48
1866	1st	110	0.82–38.68	18.61	0.84–42.04	19.23

centuries. Overall, the georeferencing process was considered successful since all RMS errors and the largest residuals (Table 3, column 5) were relatively small compared with the changes in the size of the city over time.

City growth through time

Figure 2 shows how the area of the city of Southampton changed in relation to its population growth. City area changed slowly from about 0.8 km^2 in the 16th century to 2.0 km^2 at the end of the 18th century (Figure 2). Expansion occurred on all sides of the former walled city but predominantly to the east and west (Figure 3 and Appendix). By 1835, however, the city had grown to 6.7 km^2 mainly by engulfing areas to the north (Figure 3) and remained more or less at this size throughout the 19th century (Figure 2). It was during the 20th century that the city expanded rapidly by absorbing adjacent areas to the east and west, increasing to nearly 50 km^2 by 1990, where it remains to the present day.

The growth of the city of Southampton followed a pattern that is typical of many cities. Masucci et al. (2015) describe a function whereby cities initially grow exponentially followed by condensation to a carrying capacity. In Southampton's case, the carrying capacity (or physical limit to growth) has always been defined by the coast to the south and in the present day is constrained to the west, north and east by its administrative boundaries marked by major roads and other towns and cities boundaries. The city reached this physical threshold by 1990, yet the population continued to grow exponentially to about 237,000 in the 2011 census (ONS, 2014; Figure 2). The growth of the city's area and its population means that the density is now at its highest and is still increasing.

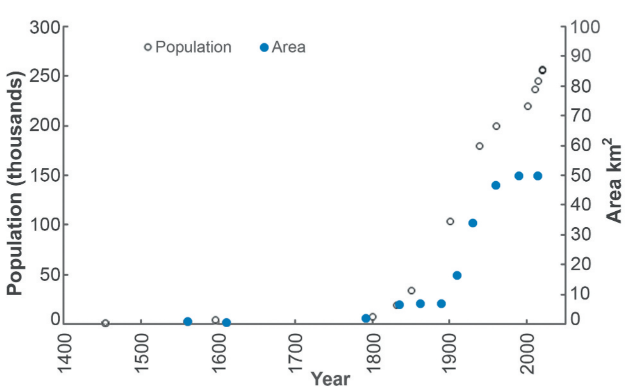

Figure 2. Growth in the surface area and population of Southampton from the 15th century onwards. Population data extracted from.Brown (2004), Neal (2014) and ONS (2014)

The physical limits of cities (and hence the existence of a condensation phase in their growth) are geographically defined by a sharp change from urban to rural areas (Masucci et al., 2015), and an associated drop in population over space. Of course, it matters whether a city is defined by its administrative boundaries (as here) or clusters of buildings or street intersections (Arcaute et al., 2016; Batty, 2013; Murcio et al., 2015; Pinho & Oliveira, 2009; Rozenfeld et al., 2011), or demographic and commuting data (Arcaute et al., 2015). In fact, although bounded by a motorway to the north, Southampton now effectively merges into the town of Eastleigh, with Southampton airport and Parkway railway station forming a link between the two urbanized areas. Using street networks and intersections to define the limits of a city, as proposed by Masucci et al. (2015), may incidentally include adjacent urban areas and therefore delineate an extended city boundary that does not correspond with the administrative one. While an analysis based on clustering may not have revealed the same condensation point as identified here based on the administrative boundary, growth in the city's area is highly likely to have followed a similar pattern (Figure 2). Although Masucci et al. (2015) argue that using administrative boundaries to analyze city growth does not allow consistent capture and measurement of dynamic aspects across the city, Rozenfeld et al. (2011) see it as an advantage as it can be used to study cities of all sizes. It may be added, based on the analysis here, that historical maps often lack the detail for reliable extraction of street networks and intersections, administrative boundaries offering a more consistent source of information on city size and shape.

Location of the city center through time

The number of identifiable typicality features as defined in Table 2 differed between maps with the general tendency for cartographers to map more detail over time (Table 4). All years contributed between 18 and 102 points to the calculation of the centroid and there was no visual impact of the difference in number on the city center's location.

During the 16th to 18th centuries, the city center as defined by the centroid maintained more or less the same position (Figure 4), the small apparent movements averaging 30 m each year. These early city center centroids were slightly above the geometric center of the town within the walls where most of the town center typicality features were located. However, shops to the north and particularly the east, acted as a magnet,

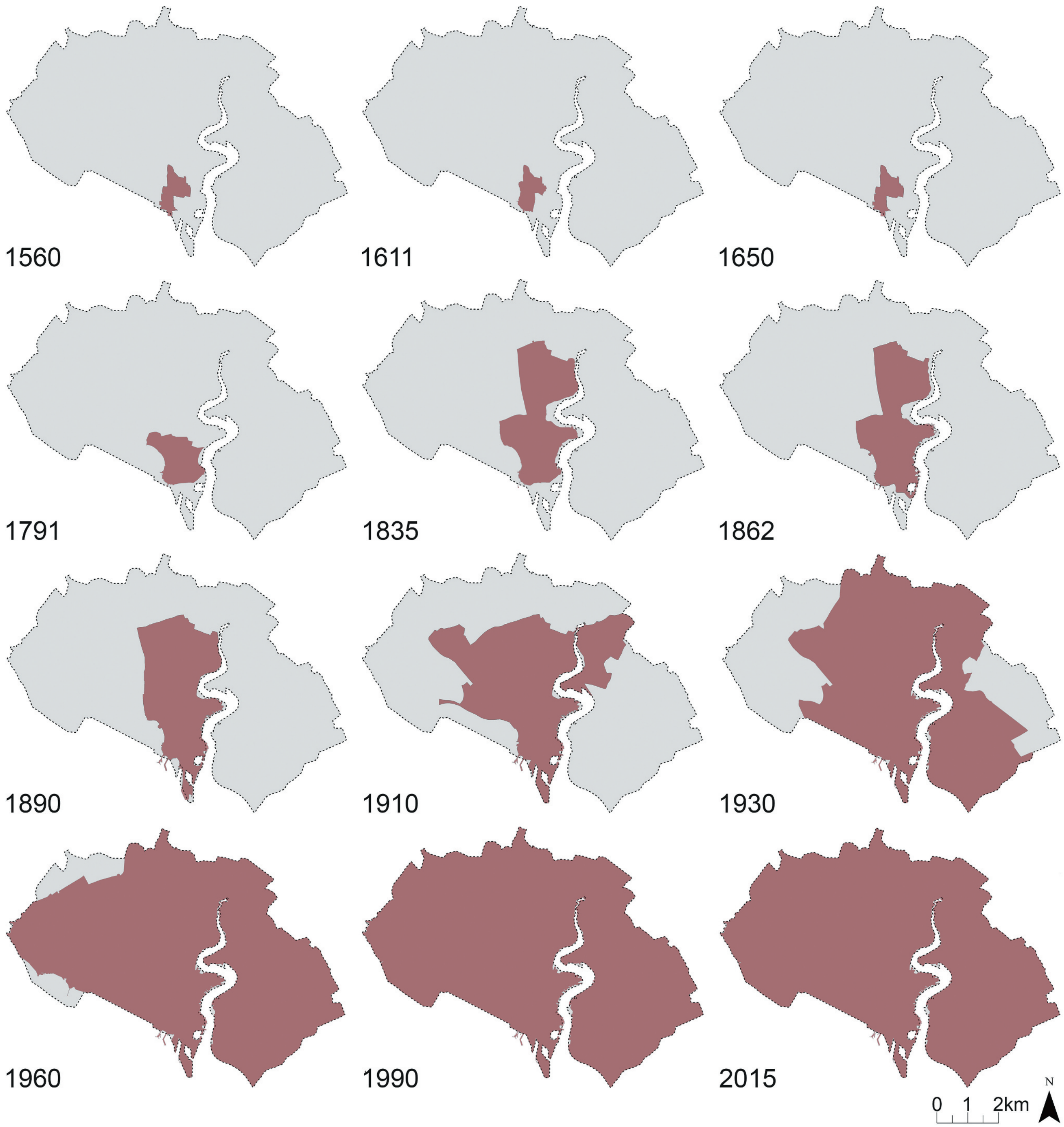

Figure 3. Evolution of Southampton's urban boundary (1560–2015). The brown shaded area shows the boundary at the time superimposed on the extent of modern-day Southampton city. Scale bar and north arrow in all years as for 2015. For detailed maps, see Appendix A in Supplementary Materials.

pulling the centroid toward them beyond the old town walls. The presence beyond the walls was further established by the growth of bathing areas, associated facilities and the castle on the west.

By the beginning of the 19^{th} century (1835), the city center had moved 63 m toward the northeast. The 19^{th} century was marked by intense urbanization and further expansion of the town toward the east. The construction of the rail line connecting Southampton with London and the terminus station on the east part of the town was a turning point because it attracted further development, such as the construction of the docks to the south of the train station. Its presence attracted further typicality features (e.g., shops, leisure areas and offices) to the east part of the town. At the same time, however, the center of the town was reinforcing its presence to the

Table 4. Number of typicality features digitized from each map and used to define the location of the city center.

Map year	Number of typicality feature points digitized
1560	18
1611	40
1791	48
1835	43
1862	93
1866	74
1890	98
1910	82
1930	83
1960	79
1990	68
2015	102

north, through shops, theaters and some offices. As a result, the city center moved around 117 m to the northeast from 1835 to 1862 and later in the century moved another 106 m northwest, coinciding with East Street, known at the time as a vibrant commercial street, full of shops with exquisite and unique products (Neal, 2014).

During more than half of the 20th century, the location of the city center remained stable despite several expansions of the town's boundary, moving only 20 to 30 m until 1960. Between 1960 and 1990, Southampton (elevated to city status in 1964), witnessed another period of intense urbanization. This growth led to the emergence of new infrastructure such as the Bargate Shopping center (recently demolished), that contributed to the movement of the city center 81 m northwest. Since that period, the city has continued to experience expansion and growth of its central area, the main examples being the construction of the West Quay retail park, West Quay shopping center and Ikea, that led to the movement of the city center another 104 m northwest (Figure 4).

Movements of the city center through time may be placed in context by comparison with shifts in the centroid of the city boundary (Figure 5). In 1560 and 1611, the distances between the city center and city boundary centroid were on average only 174 m. In 1791, the distance between city center and city boundary centroid more than doubled from 174 m to 467 m (Figures 4 and 5). This increase happened as a consequence of the extension of the town's boundary northwards (Figure 3) due to the beginning of a construction scheme (the Polygon scheme: Appendix B in Supplementary Materials) that intended to help the upper class escape the rougher parts of the town, by offering expensive family houses and a hotel (Neal, 2014; Appendix B in Supplementary Materials). Significant increases in the distance between centroids were registered in the 18th century and again between the 19th and 20th centuries. The first increase coincided with the period of intense urbanization with the city expanding largely beyond its ancient walls. The second and largest increase in distance between centroids not only reflects the continuous urbanization, but also the expansion of the city boundaries due to the absorption of surrounding neighborhoods and land reclamation at the coast. Overall, there is clear evidence of strong inertia in the movement of the city center when compared with the growth of the city as summarized by the location of the city boundary centroid (Figure 5).

Discussion

The aims of this paper were to assess whether historical maps can provide consistent information on the location of the city center over time, whether the city center shows inertia to change and to consider the implications of this inertia for present-day city zoning.

Our analysis reaffirms the value of using georeferenced historical maps as a way to understand how a city has grown and developed through time (Lafreniere & Rivet, 2010; Liu et al., 2018; Maio et al., 2013; Pindozzi et al., 2015). The process of georeferencing historical maps will always leave residual errors (Tucci & Giordano, 2011) resulting from factors such as the cartography and surveying techniques used when the map was drawn, the deformation of paper over time, and whether a previous mosaicking operation was performed (Brovelli & Minghini, 2012). Therefore, assessment of the accuracy of any georeferencing process through the analysis of the RMS error obtained is crucial to assess uncertainty in the outcome before interpreting change (Brovelli & Minghini, 2012; Liu et al., 2018; Manzano-Agugliaro et al., 2013). The RMS errors obtained here (without cross-validation for comparison with others) for the six historical maps ranged between 46.8 m for the 1560 map and 9.9 m for the 1611 map, with a mean value of 21 m, within the range of values obtained by other authors. For example, Pindozzi et al. (2015) obtained a RMS error of 14.4 m for a map from 1817 and 18.2 m for 1875; San-Antonio-Gómez et al. (2014) 22 m and 20 m for 1775 and 1835 maps; Vuorela et al. (2002) 27 m for a map from 1690; and Bromberg & Bertness (2005) a mean value of 245 m and a range of 160–440 m for maps from 1773 and 1832. In urban change studies, Tucci and Giordano (2011) obtained a value of 7.7 m for a 1884 map and Maio et al. (2013) < 9.7 m for 1775 and 1847 maps. With the exception of the 1690 map used by Vuorela et al. (2002), these studies all refer to maps from the late 18th and 19th centuries, whereas the Southampton analysis started in 1560. Excluding the map from 1560, the mean RMS error

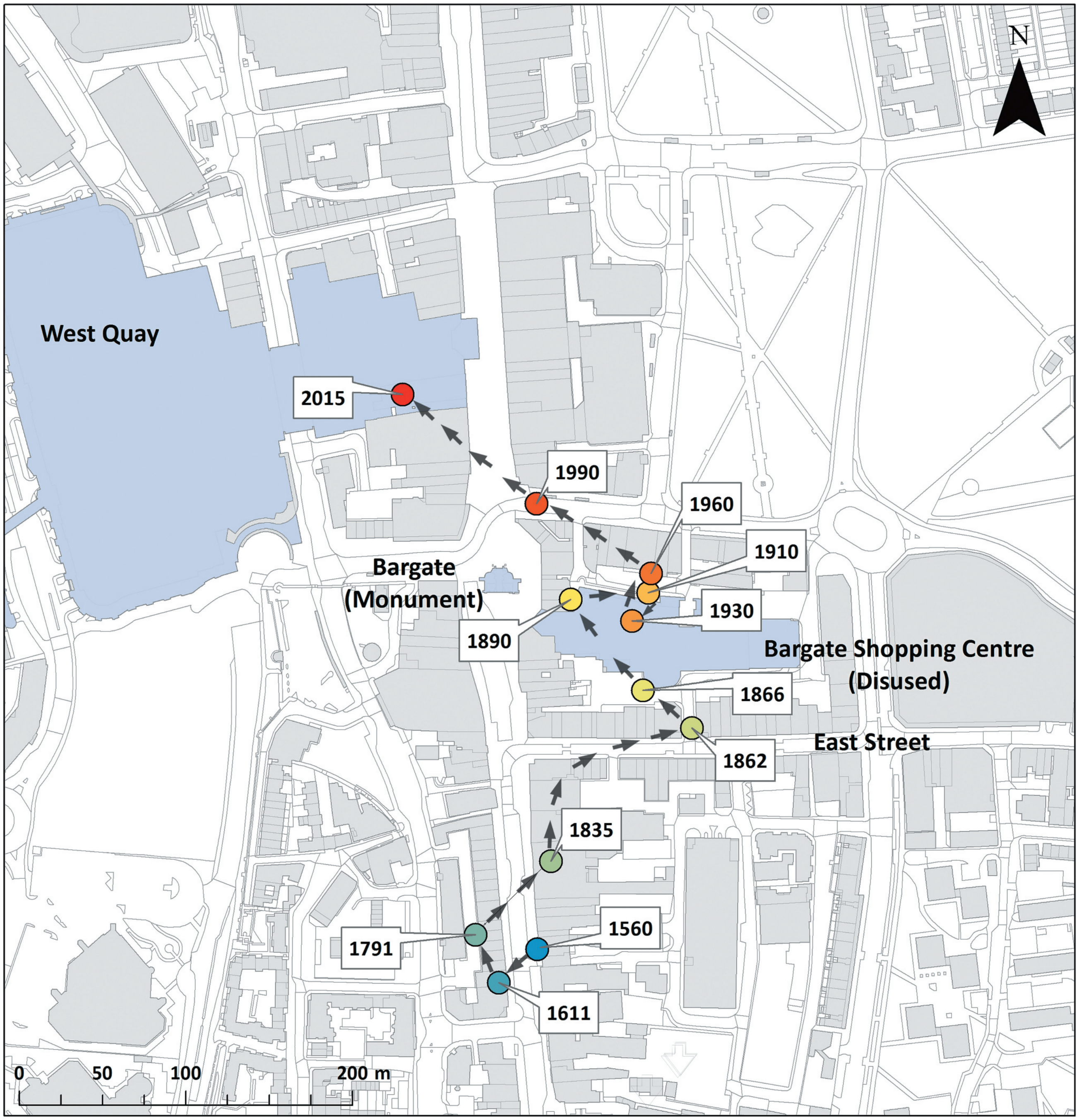

Figure 4. Position of the city center centroids through time overlaid on a current map. Main background features are highlighted in light blue and other buildings are shown in light gray.

for the Southampton maps would be 15 m, approximating the values obtained by Pindozzi et al. (2015). Overall the RMS errors obtained here are small enough to give confidence in the analysis performed, especially as the scale of changes in the city were much greater than the likely errors left after the georeferencing process.

With this confidence in the historical mapping, it was possible to digitize and plot 18 to 102 typicality points per map and use them as a simplified and alternative version of the approach used by Lüscher & Weibel (2013) to identify the city center through time. Instead of representing the city center as an area, our approach reduced the central core of the city to a point or center of gravity calculated from the weighted average of city center typicality features. In general, the location of the city center tended to be close (<100 m) to a landmark feature at that time (e.g., East Street in 1862 and now the West Quay shopping complex). This makes sense as our

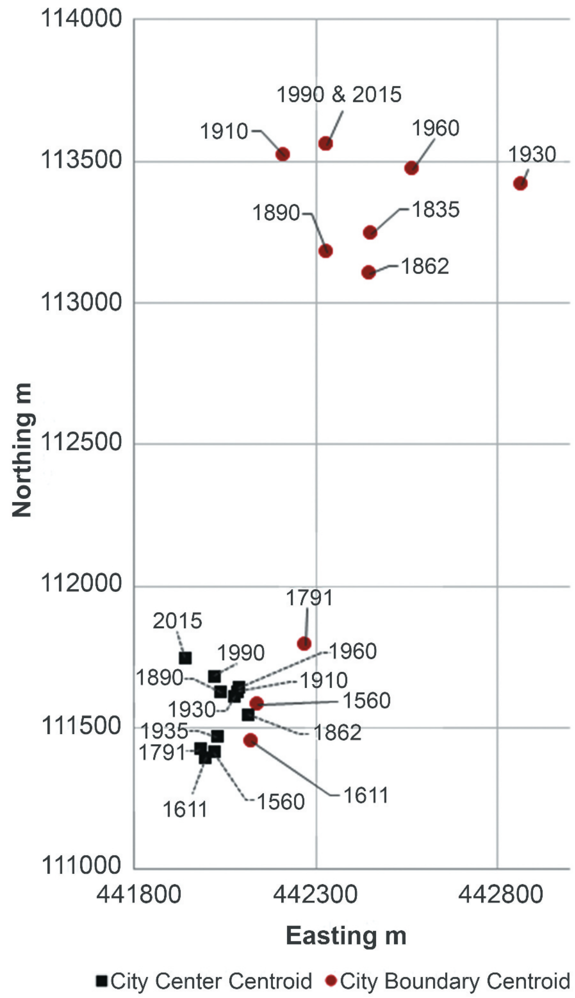

Figure 5. Movements of the city center (CCC) and city boundary centroids (CBC) through time.

approach reverse-engineered the idea of main attractants acting as centers of gravity, that draw further typically features (often businesses) to settle around them. It also lends weight to the suggestion of Lüscher and Weibel (2013) that the city center may perhaps be defined by a single representative point, or in their terminology "the cognitive center of gravity", that overlaps with a landmark development. One potential limitation in using typicality features from historical maps to define a city center is bias introduced by the cartographer. Historical maps are often subject to the individual interpretation of the surveyor (Schaffer et al., 2016), reflecting their own scientific and geographic knowledge, cultural background and in many cases political ideologies (Brovelli & Minghini, 2012). Any temptation to include more detail in one area as opposed to another would bias the location of the city center as defined here unless, of course, that temptation arose *because* the area was known as the city center at the time.

In contrast to Masucci et al. (2015), this study has found that using administrative boundaries and demographic information does allow the consistent capture and measurement of dynamic aspects across the city, and the approach is well-suited to historical maps. For example, using administrative boundaries allowed us to assess when the city reached its physical capacity and therefore how continuous growth of the population has been accommodated through densification. It was also possible to use the administrative boundary as a simple consistent way to define the geographic center of the city (the city boundary centroid). Comparison of the locations of the city center with the city boundary centroid demonstrated strong inertia in movements of the city center over time. In nearly 500 years, the higher-order city center (Zhong et al., 2014) of Southampton has moved only 343 m but now serves a population at least 80 times larger over an administrative area 60 times greater, while its geographic center has shifted 1985 m.

This mismatch between a city center's location, strongly rooted in history, and the population it now serves has potentially profound consequences for sustainable development. Although Southampton is strictly a polycentric city (neighboring villages with their own centers being absorbed as it grew), the range of goods and services available in the main city center far outweigh those in its district centers. Indeed, centrally-focused regeneration was used as a deliberate strategy to increase the footfall in Southampton's city center (Lowe, 2005a, 2005b, 2007), reflecting the "Town Center First Policy" adopted in 1996 (Cheshire et al., 2018). Concern over the economic viability of city centers arose partly as a result of significant pressures from out-of-town retail centers, online retailing and the evolution of the "convenience culture" (Wrigley & Lambiri, 2014). Southampton's historic city center thus remains the focus of commercial and social activity and today's Southampton behaves much as a monocentric city. Ironically, the Town Center First Policy was partly motivated by a desire to reduce carbon footprints (Cheshire et al., 2018). Yet debate on whether monocentric or polycentric cities necessitate greater commuting distances has not reached consensus (Li et al. 2018) with some work suggesting that a single city center increases territorial carbon footprints (Makido et al., 2012). This is supported by studies showing that temporal variations in urban carbon dioxide fluxes correlate with traffic intensity (Kleingeld et al., 2018) and that transport is a key year-round component of carbon emissions in cities (Wang & Zeng, 2019; Ward et al., 2015).

Unfortunately, Southampton's situation is made worse by the city center's unique geographic position on a peninsula of land close to Southampton Water (Figure 1). This requires road transport to take much longer journeys than would be necessary to the geographic center of the city boundary. Consequently, transboundary carbon emissions (Wright et al., 2019) that account for transport bringing goods into the city for sale must also be higher although to our knowledge the extra carbon cost of a city center's location has not been quantified. We concur with Makido et al. (2012) that better information is needed on the relationship between the spatial pattern of urban form and carbon emissions, including a city center's location within urban conurbations. The combination of a "coastal" city center that has maintained its historic location and monocentricity presents the modern city of Southampton with challenges in traffic congestion, air pollution and noise. These are the unforeseen consequences of historical changes in the morphological dimensions of the city resulting from consecutive political decisions to expand the city's boundaries without moving its center. Decisions taken in the past set limits on what is possible in the present, and analysis of historical maps provides insight on whether these are a straitjacket or an opportunity. We encourage other authors to undertake similar studies in their cities, perhaps taking advantage of the automated approaches to georeferencing recently suggested by Burt et al. (2020) as a means to reduce both the labor cost and errors associated with manual digitization.

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The authors have no conflicts of interest to declare.

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Data availability statement

The data that support the findings of this study are available in Mendeley Data, V2, at http://dx.doi.org/10.17632/m97mdfyf5j.2. These data were derived from the maps detailed in Table 1, available in the public domain or from https://digimap.edina.ac.uk/.

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