

# A computational approach to ‘The Image of the City’

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## ABSTRACT

In *The Image of the City* Lynch describes how individuals perceive and recall features in urban spaces. The most distinctive elements in the urban landscape - categorised in paths, nodes, edges, districts and landmarks - give shape to individuals' mental representation of the city. Lynch's approach has stimulated research into spatial cognition, urban design and artificial intelligence, and it still represents an essential pillar in the analysis of urban dynamics. Nevertheless, an explicit link between *The Image of the City* and GIScience has not been completely explored yet. In this paper, a computational approach to *The Image of the City* is proposed. Different perspectives in spatial cognition and GIS research are integrated to obtain a complete Image of the City, in which the most salient elements are shared by a large part of citizens. Nodes, paths and districts were identified through network science techniques. Methods drawn from the information approach to *The Image of the City* are used to detect landmarks, integrating the complexity of points of reference in their visual, structural and semantic components, as conceptualised by Lynch and successive research. The methods were applied to the central area of Boston and built using freely available spatial datasets. Results were compared to Lynch's maps to evaluate the methodology: besides a considerable discrepancy with regard to landmarks, a good correspondence for paths, nodes, edges and districts was found.

## 1. Introduction

In 1960, Kevin Lynch published *The Image of the City* (Lynch, 1960), one of the most influential theories in spatial cognition and behavioural geography ever written (Portugali, 2011). Lynch dedicates his work to understanding how people perceive and represent a city, and from what external urban artefacts the mental image of the city arises. Specifically, Lynch analyses two qualities of the built environment: *legibility*, ‘the ease with which its parts can be recognised and can be organised into a coherent pattern’ and *imageability*, ‘that quality in an object which gives it a high probability of evoking a strong image in’ the observer’ (Lynch, 1960, p. 60).

Studying the city form of Boston, Los Angeles and Jersey City, the author finds out that individuals' mental images can be overlapped to form a community cognitive map. The resulting skeleton is formed by five types of elements: paths, edges, nodes, districts and landmarks. The mental image mediates in the interaction between humans and their environment: ‘The environment suggests distinctions and relations and the observer (...), selects and organizes and endows with meaning what it sees’ (Lynch, 1960, p. 6). Since the 1970s, the five elements have constituted the core of spatial cognition theories, grounding the spatial

knowledge organisation in landmark, route, and configurational knowledge (Siegel & White, 1975). Successively, Lynch's model has been reformulated in behavioural geography (e.g. Sadalla, Burroughs, & Staplin, 1980; Couclelis, Golledge, Gale, & Tobler, 1987; Tversky, 1993). *The Image of the City* has furthermore inspired research in environmental psychology (Devlin, 2001) and prompted the development of contemporary cognitive mapping research (Tversky, 2003; Kitchin & Blades, 2002): cognitive maps are seen as auto-organising systems that mediate the human-environment interaction (Portugali, 1992).

Inevitably, this framework has stimulated research in artificial intelligence and robotics, where computational models such as TOUR (Kuipers, 1978) and NAVIGATOR (Gopal, Klatzky, & Smith, 1989) have been developed to reproduce and comprehend human mental processes. Nevertheless, there has not been a thorough attempt to integrate Lynch's theory directly into GIScience, nor to support a quantitative formulation of *The Image of the City* relying on conventional spatial datasets. ‘A generalisation of these (Lynch's) ideas could advance geographic thinking in general and GIS software in particular’ (Frank, Mark, & Raubal, 2013, p. 3).

The aim of this work is to provide such a quantitative formulation of *The Image of the City* to foster an inclusion of the concept of *The Image of*

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the City in GIScience. In the first part of this paper, a set of works that have attempted to reformulate Lynch's theory is reviewed. Following this, an integration of such different reformulations is devised. In the second part, a computational method, built upon conventional geospatial data, is proposed for each Lynchian element in reference to the original definitions. The methods are applied to the central area of Boston and thereafter the results are discussed and subjectively compared to Lynch's qualitative maps.

## 2. Background

A number of research communities have been involved in the quantitative formulation of memorability and in extracting cognitively salient urban features. These approaches can potentially contribute to the development of a framework for extracting Lynch's five elements.

### 2.1. Space Syntax

The relationship between the external space and social phenomena is the driving force of Space Syntax, a set of theories and techniques 'for the representation, quantification, and interpretation of spatial configuration in buildings and settlements' (Hillier, Hanson, & Graham, 1987, p. 363). In this perspective, the street layout and the configuration of space have a strong impact on the development of mental representations (Kim & Penn, 2004). The association between street configuration and cognitive mapping is not unprecedented. What distinguishes Space Syntax research is the focus on topology rather than metric properties.

Within this community, Dalton and Bafna (2003) attempt to re-define Lynch's five elements through the constructs of axial lines (Hillier & Hanson, 1984) and isovists (Benedikt, 1979). They suggest to study and detect first order (spatial and structural) elements, that give shape to the mental representation, and second order (visual) elements, that enrich the image. The elements could be captured employing axial lines and isovists sorted in order of significance.

Jiang (2013) theorises that the scaling law of artefacts (Zipf, 1949) supports the identification of the primary elements in the city. He tested his hypothesis on paths, transforming streets into axial lines and ranking them by connectivity. Consistently with his assumptions, many more less connected than well-connected and memorable streets exist, regardless the city examined and the street morphology.

The Space Syntax approach has been questioned for excluding metric information from the analysis, heights of buildings and land use properties from the analysis (Ratti, 2004). Moreover, although road-centre lines have been recently adopted (Turner, 2007), axial lines have obstructed the integration of space syntax techniques into GIS (Jiang & Liu, 2009). Yet, the emphasis on configurational aspects is an illuminating argument in the transition towards a computational approach to cognitive maps.

### 2.2. The information approach

Haken and Portugali (2003) have advanced a framework to *The Image of the City* that integrates the synergetics approach (Haken, 1983) and contemporary trends in cognitive science with Lynch's theory. The researchers make the link between the concepts of imageability and affordance (Gibson, 1979) explicit, on one side, and employ Shannon's information theory, on the other, for studying how the mental image is formed from specific urban elements. In this information approach, legible cities are composed of informative and significant artefacts or urban configurations. City nodes, paths or districts are 'information carriers' that shape the mental image. Here, the original measure of information (Shannon & Weaver, 1949) - a form of entropy that quantitatively measures the "unexpectedness" of an event - is adjusted with an index that incorporates semantic information. This component represents the result of biological, cultural, social and pragmatic categorisation processes.

Their theory reinvigorates the idea that city elements may be remembered for symbolic and social meanings (Appleyard, 1969), but also for their pragmatic functions. Moreover, it introduces a computational framework to *The Image of the City* that takes into account the combination of these traits and their contribution to the legibility of cities. The drawback of their approach is that it contemplates a measure of entropy, suitable for the city- or district-level but unfitting for computing the individual scores of the elements.

### 2.3. Automatic landmark extraction

Sorrows and Hirtle (1999) refine the notion of landmark. The authors differentiate *visual landmarks* - objects used as spatial points of reference for their visibility - from *cognitive landmarks* - relevant for their uncommon and meaningful content - and *structural landmarks* - recognisable for their advantageous and prominent position in the space. This work has inspired a vein of research in GIS community interested in automatic identification of landmarks for wayfinding design and navigational support: Raubal and Winter (2002) advance a model that measures the salience of buildings in relation to perceptual and cognitive properties. Winter (2003) ameliorates the model, recommending to consider 3d visibility as another property. Elias (2003) presents a similar approach based on machine learning algorithms that inspect geometric, topological and semantic attributes of buildings to establish landmark hierarchies. Furthermore, Winter, Tomko, Elias, and Sester (2008) integrate the previous approaches to construct a hierarchy of landmarks, emphasising the distinction between local-landmarks and city-wide (global) landmarks.

In summary, while these works have moved landmark research forward, the other Lynchian elements are of little interest and rarely mentioned here.

### 2.4. Contributions and gaps

Even though automatic landmark identification models have been disseminating (Richter, 2013), presumably due to their potential applicability in navigation systems design, none of the approaches have offered a set of methods and tools to quantitatively derive the five elements of *The Image of the City*.

- Space Syntax, when reformulating *The Image of the City*, has mostly considered visual aspects, neglecting important implications regarding the genuine human-environment interaction and focused on paths identification.
- The information approach, while being based on the usage of geospatial dataset, returns a macro-level index of legibility.
- Edges have generally received a little attention, or been considered a particular type of landmarks and assessed for their structural properties (e.g. Richter & Winter, 2014; Raubal & Winter, 2002); districts have been translated in Voronoi partitions, whose cognitive salience is disputable.
- More importantly, in the literature discussed above, when an application of the methodologies is presented, the dataset usually refers to small areas, it is created ad-hoc by the researchers or based on questionnaires, which makes it hard to reproduce the study for new areas.

## 3. Methodology

In the following section, network science techniques are presented for the detection of nodes, paths and districts, from the street configuration. In addition, a comprehensive landmark detection method is proposed following Sorrows and Hirtle's framework (Sorrows & Hirtle, 1999) and the models discussed above. These approaches were enriched performing a 3d visibility analysis and integrated with insights derived from the information approach; semantic and pragmatic

properties were here considered for the first time in a large geo-dataset. Lastly, a set of rules to extract edges is described. The scripts used to carry out the analysis are available on a GitHub repository (Filomena & Manley, 2018).

### 3.1. Nodes

*Nodes are the strategic foci into which the observer can enter, and which are the intensive foci to and from which he is travelling. They may be primarily junctions, places of a break in transportation, a crossing or convergence of paths (Lynch, 1960, p. 47).*

Space Syntax scholars have shown that elements stored in people's cognitive map are related to centrality measures (Haq & Girotto, 2003; Yun & Kim, 2007). In this framework, topological properties of degree, closeness and betweenness are usually computed employing a dual graph representation, wherein street segments are represented by vertexes and junctions by links. However, Porta, Crucitti, and Latora (2006b) argue that the primal representation approach - wherein street segments are represented by links and junctions by vertexes - is more effective in exploiting centrality indices to capture the skeleton of the urban structure and identify crucial intersections.

Centrality acts as a driving force in the development of the urban structure, and central locations are prone to become genuine urban nodes (Newman & Kenworthy, 1999). Lynch's nodes could be viewed as places that are structurally made to be traversed, nodes (vertexes) with the highest *betweenness centrality* scores in the street network. In our approach betweenness centrality was calculated in an undirected planar graph, as:

$$C_i^B = \sum_{j,k \in G, j \neq k \neq i} \frac{n_{jk}(i)}{n_{jk}} \quad (1)$$

where, in an undirected graph  $G$ ,  $n_{jk}$  is the number of shortest paths between the vertexes  $j$  and  $k$ , and  $n_{jk}(i)$  is the number of shortest paths between the vertexes  $j$  and  $k$  that pass through  $i$ .

### 3.2. Paths

*Paths are the channels along which the observer customarily, occasionally, or potentially moves. (...) People observe the city while moving through it, and along these paths the other environmental elements are arranged and related (Lynch, 1960, p. 47).*

Paths are the main lines of movement in the city; they guide people's movement, supporting orientation. In low-legibility contexts, when a path is not characterised by vivid activities or peculiar properties, perceptual continuity comes into play: people rely on this functional quality to successively travel across the city. The concept of continuity recalls the idea that people tend to choose routes that minimise angular change rather than distance (Sadalla & Montello, 1989; Golledge, 1995; Hillier & Iida, 2005). In this sense, angular betweenness is described as the best predictor of pedestrian and vehicular movement when only the street network is at disposal of the researcher (Cooper, 2015). Betweenness centrality, as defined above (see Eq. (1)), was computed for vertexes in a dual graph representation so generated:

- Street segments are converted to vertexes;
- When two street segments cross each other in the road network, a link connecting the corresponding vertex in the dual representation is created.
- The amplitude of the angle of incidence formed by two street segments is assigned to the corresponding link as weight.

Finally, the centrality values of the vertexes in such a network were reassigned to the originating segments. Therefore, it is assumed that the

major paths are those which minimise angular change in travels across the city. Here, we did not take into account the road-type class (e.g., major-road, secondary-road, etc.), assuming that the street segments which form angular-continuing lines (e.g. Porta, Crucitti, & Latora, 2006a; Figueiredo & Amorim, 2005) belong to the same category or have similar structural properties (Thomson, 2004).

### 3.3. Districts

*Districts are the relatively large city areas which the observer can mentally go inside of, and which have some common character (Lynch, 1960, p. 66). The characteristics that determine districts are thematic continuities which may consist of an endless variety of components (Lynch, 1960, p. 67).*

Space Syntax suggests that the topology of the street network is associated with people's perception of places and regions: Law (2017) illustrates a process for generating sub-graphs from the street topology applying community detection techniques. The so formed *Street-based Local Areas* (SLA) (Turner, 2007) are regions whose internal homogeneity has social and functional foundations (Girvan & Newman, 2002).

In this discussion, it is assumed that the different districts of a city can be identified analysing the road layout. The *modularity optimisation* function (Blondel, Guillaume, Lambiotte, & Lefebvre, 2008) is adopted to extract SLAs. This algorithm optimises modularity (Girvan & Newman, 2002), an index that measures the goodness of a network division. Modularity ( $Q$ ) computes the difference between the edges within a community and the expected numbers of edges in a network with the same structure but random connections. When the number of within-community edges is nothing more than random, the structure of the communities is poor and  $Q$  is equal to zero. On the contrary, high values of  $Q$  represent strong division amongst well-structured communities. The implementation of the modularity optimisation technique follows these steps:

1. Every node  $i$  is considered a community.
2. For each node  $i$ , the algorithm evaluates the gain in modularity ( $Q$ ) that would be obtained by joining the node with each of the neighbour communities  $j$ .
3. If no possible gain is detected, the node  $i$  stays in its original community, otherwise, it is placed in the community wherein the modularity gain would be maximised.
4. The nodes in the same community form a new super vertex.
5. The previous steps are repeated until the modularity cannot be optimised any more (merging communities does not produce positive gain).

The function was run in an undirected dual graph. Partitions were extracted from a network where weights were based on the angles of incidence between pairs of segments, as described above. Thereby, districts are the sub-graphs obtained from the street network by optimising modularity.

### 3.4. Landmarks

*Landmarks are point references considered to be external to the observer. They are more easily identifiable, if they have a clear form; if they contrast with their background; and if there is some prominence of spatial location (Lynch, 1960, pp. 78–79).*

The present work follows Sorrows and Hirtle's framework (Sorrows & Hirtle, 1999) in the distinction of three type of landmarks: visual, structural and cognitive (pragmatic and cultural meanings). Indeed, for Lynch, an edifice may become a landmark when it stands out from the background. Additionally, activities and historic references may

contribute to reinforcing the legibility when visual attraction is insufficient. Raubal and Winter's (Raubal & Winter, 2002) set of techniques were enriched to allow for topological relations, visibility, semantic and pragmatic aspects in landmarks identification. Our analysis was performed on a dataset containing exclusively buildings; other elements such as trees, benches or bridges were not considered.

Visual properties includes height, façade area and visibility. The maximum height of a building was used for computing a 3d visibility index: for each edifice, the length of the longest unobstructed sight-line was kept and used as a coarse value of visibility. For what concerns structural and topological properties, advance visibility - a 2d area of visibility, without obstructions, around a building -, minimum distance from the road, the number of adjacent buildings (at least partially contained in a buffer of  $x$  metres) and the area of the polygon were computed. The cultural meaning of a building was obtained counting the number of listed historic elements located within its boundaries. Finally, pragmatic significance was calculated following a simplification of the information approach, as an index of unexpectedness:

$$P_{S_b} = 1 - \frac{N_b}{N} \quad (2)$$

where, in a buffer of  $x$  metres around the building  $b$ ,  $N_b$  is the frequency of the land use class of  $b$  and  $N$  is the number of buildings. The scores of the indexes were scaled and combined in the relative component and, subsequently, in the overall score (see Table 1 for details).

### 3.5. Edges

*Edges are linear elements not considered as paths: they are usually, boundaries between two kinds of areas. They act as lateral references. Those edges seem strongest which are not only visually prominent, but also continuous in form and impenetrable to cross movement (Lynch, 1960, p. 62).*

Edges are authentic organising features whose primary trait is linear continuity. Nevertheless, edges could be permeable and crossable, they can coincide and align with paths. In the current analysis, the following linear elements, with a predefined minimum length, were extracted as edges:

- Sections of railway structures as bypasses or other visible structures.
- Sections of large roads (e.g. dual-carriageways roads).
- Sections of motorways.
- River banks or generic waterfronts (lakes, sea-coast).

### 3.6. The case study

The methods delineated above were applied to the city centre of Boston, MA (USA), on the area studied by Lynch (Fig. 1). The results of the analysis are presented, discussed and compared to the map depicted by Lynch, who asked 30 residents and workers to describe customary

itineraries and experiences, and recognise places (see Fig. 2).

Our analysis mainly relies on the street network and buildings footprints. While the datasets are Boston-specific, the sources employed are generic (and often available as open data) so to allow application of this approach for other case study areas. The sources are:

- The road network (Massachusetts Office of Geographic and Environmental Information, 2014), clipped with two buffers of 4000 and 8000 m around Boston City Hall. The smaller network was used to identify nodes and paths, the vaster to detect regions.
- Building footprints (Massachusetts Office of Geographic and Environmental Information, 2002); this dataset includes a simplified representation of buildings footprints, along with their maximum height.
- Buildings main land use (OpenStreetMap contributors, 2017) and Boston Historical landmarks register (City of Boston, 2017). The land-use classes used to compute the pragmatic score were: *attraction, commercial, cultural, eating & drinking, education, emergency service, entertainment, hospitality, industrial, library, manufacturing, medical care, military, place of worship, public, residential, sport, transport, university*.
- Railways (Massachusetts Office of Geographic and Environmental Information, 2015) and water (Massachusetts Office of Geographic and Environmental Information, 2017), to detect edges.

We subjectively defined weights for each landmark component, as specified in Table 1, coherently with Lynch's observations. Yet, the weights definition may vary with the urban structure, the social context and so forth, and can be manipulated correspondingly for other case studies. Finally, to obtain the overall Image of the City, the range of original values was rescaled in the range from 0 to 1, on the bases of the maximum and minimum features across each element; the ranges used by Lynch were applied to the scaled scores of nodes, paths and landmarks, to colour and rank them. Due to the nature of the methods, districts and edges were not ranked.

## 4. Results

### 4.1. Nodes, paths and districts

We found some crucial nodes (Fig. 3) in the city as Charles Street Rotary and the junction between State Street and Congress Street. The complex whole of ramps and interchanges nearby Charles River Road and Martha Road confers high betweenness centrality values to other intersections in the area: this cluster of nodes is represented by Lynch as one node at the south-east extremity of Charles River Road (see Fig. 2). Likewise, the Sumner and Callahan tunnels, essential links to and from East Boston, give emphasis to the nodes at their entrances and the nearby junction (Congress and North Street).

Like Lynch, we detect a lack of main nodes in the western area of the city. Nonetheless, the output of our analysis does not point Worcester Square and Union Park as crucial nodes, nor the intersections of Huntington Avenue and Columbia Avenue, respectively with St James Avenue and Stuart Street. Besides, Copley Square, Scollay Square and South Station do not stand out as they do in Lynch map (see Fig. 2). While most of this nodes were mentioned by just a few interviewees (12–25 % cluster), South Station (over 75%) and Copley Square (50–75 %) may gain their importance in citizens' mental maps for their role in the public transport network, which is not taken into account in our analysis.

Lynch describes the system of paths in Boston as confused but, notwithstanding, functional: major movement lines shape the overall Image of the City, converging in the city centre. Here, the motorway may be seen as a constraining and limiting element, endowed with organising properties rather than being meaningful for movement.

Angular edge betweenness captured the main paths detected by Lynch as Beacon Street, Boylston Street, Cambridge Street, Charles

**Table 1**  
Landmark extraction: indexes and weights.

Component	Index	Index weight	Component weight
Visual	3d Visibility	0.50	0.50
	Façade area	0.30	
	Height	0.20	
Structural	Area	0.30	0.30
	2d advance visibility	0.30	
	Neighbours (150-mt buffer)	0.20	
	Road distance	0.20	
Semantic	Historical importance	1.0	0.10
Pragmatic	Land use (200-mt buffer)	1.0	0.10





Fig. 1. The city centre of Boston and the surrounding areas.

Source: Mapbox, OpenStreetMap.

Street, Tremont Street and Massachusetts Avenue (Fig. 4). Nevertheless, Lynch also depicts as major paths Atlantic Avenue and the narrow Washington Street. While the first receives its importance from the sea bank and the harbour, Washington Street owes its legibility to the high edifices along it. The fact that architectural properties and environmental evaluations were not taken into account in our paths identification approach may explain this dissimilarity. In addition, our method did not identify Storrow Drive, a road also perceived as a barrier by Lynch's interviewees.

Districts in Boston are vivid and orientating entities: even though their structure may be confusing and unclear from a purely structural point of view, their thematic identity is strong (Lynch, 1960). Because of their connection to personal experiences and activities, many Lynch's interviewees indicated districts in Boston as the main elements in the mental representation of the city. These areas have central cores and undefined boundaries, sort of 'thematic gradient', that vanish gradually rather than precisely.

In our results, Back Bay, which morphologically exhibits an uncommon regularity compared to the rest of the city, the core of North End-Docks area and the Financial District clearly stand out from the rest of the city centre (Fig. 5). At the same time, the triangle between Back Bay and South End, portrayed in *The Image of the City* as an empty area devoid of any character, is extracted as a single entity (coloured in fuchsia) by the algorithm. These portions almost coincide with Lynch's outcomes and considerations. On the contrary, Beacon Hill and West End are here merged in a macro-region, while some micro-districts as Theatres, China Town or the Textile Leather area, are assimilated by the Financial/Shopping district in our results. Their vivid connotation, possibly

due to peculiar buildings, agglomerated activities and the presence of ethnic communities, cannot be completely captured by network techniques. Since the motorways and the system of interchanges caused some distortions, a network composed only of local roads was also used in this case; the results are displayed in the Appendix (Fig. A1)

#### 4.2. Landmarks and edges

According to Lynch, in Boston, edifices are perceived as singular entities when the city centre is admired from the banks of Charles River and only a few of them have enough vividness to be identified as singular point of references. In particular, the prominence of State House, Old John Hancock Building (nowadays Berkeley Building) and Custom House on the rest of city was mostly noticed from external points of view: their relation with the road was not as strong as their visibility and people preferred to take advantage of local landmarks (Lynch, 1960).

In our landmark results (Figs. 6 and A2 for sub-component scores), Prudential Center, John Hancock Tower, Berkeley Building, Copley Tower, Massachusetts General Hospital, South Station and the T-Garden Arena, came out as main landmarks, along with a large number of local landmarks. However, besides the Massachusetts General Hospital and the Berkeley Building, Lynch also indicates some other major landmarks - as State House, Christian Science Church, the Public Library, the Trinity Church and Custom House - that did not particularly distinguish themselves in our analysis.

Whereas major lines of movement, street configuration and nodes may have slightly changed since Lynch's original study, the city centre has undergone a more consistent evolution in terms of vertical

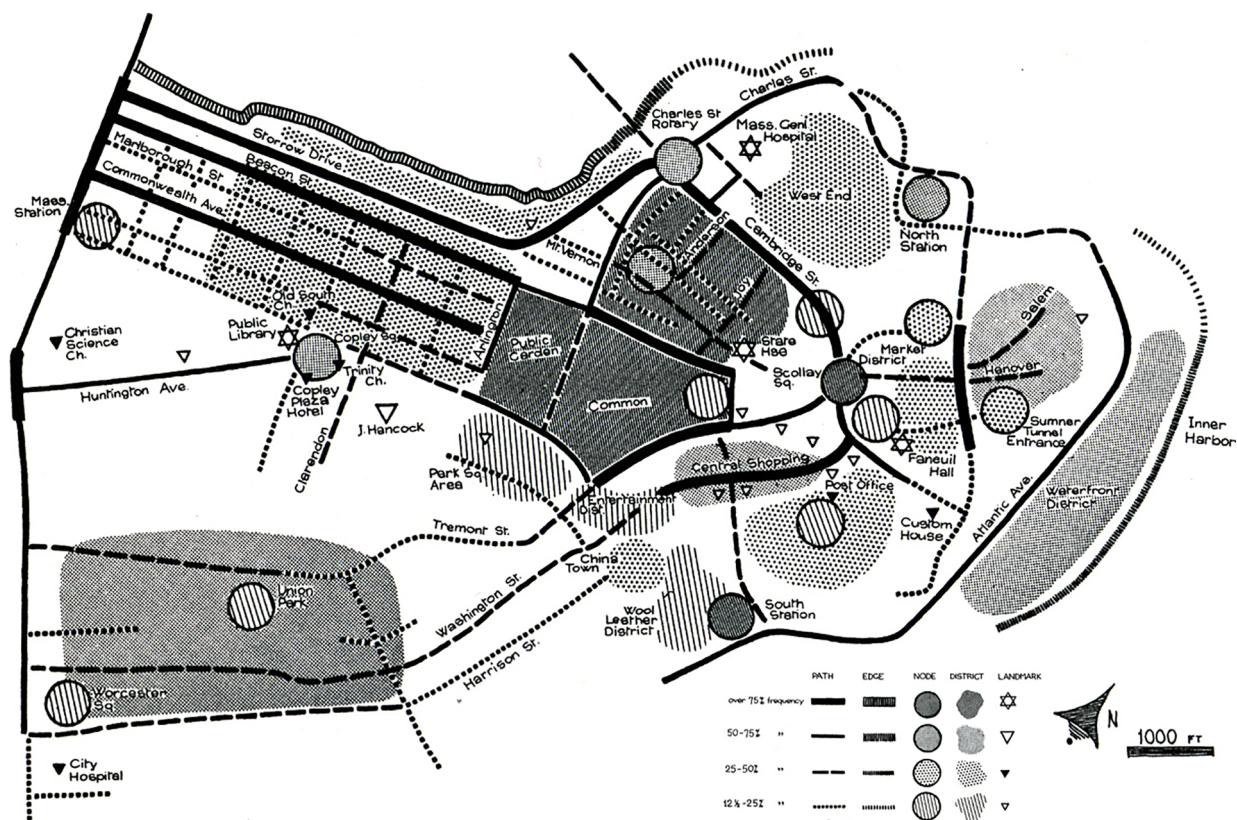


Fig. 2. The Boston community map as emerged by verbal interviews.  
Source: Lynch, Kevin, *The Image of the City*, Figure 35 and corresponding legend, pp. 145–146, 1960. Copyright Massachusetts Institute of Technology, by permission of The MIT Press.

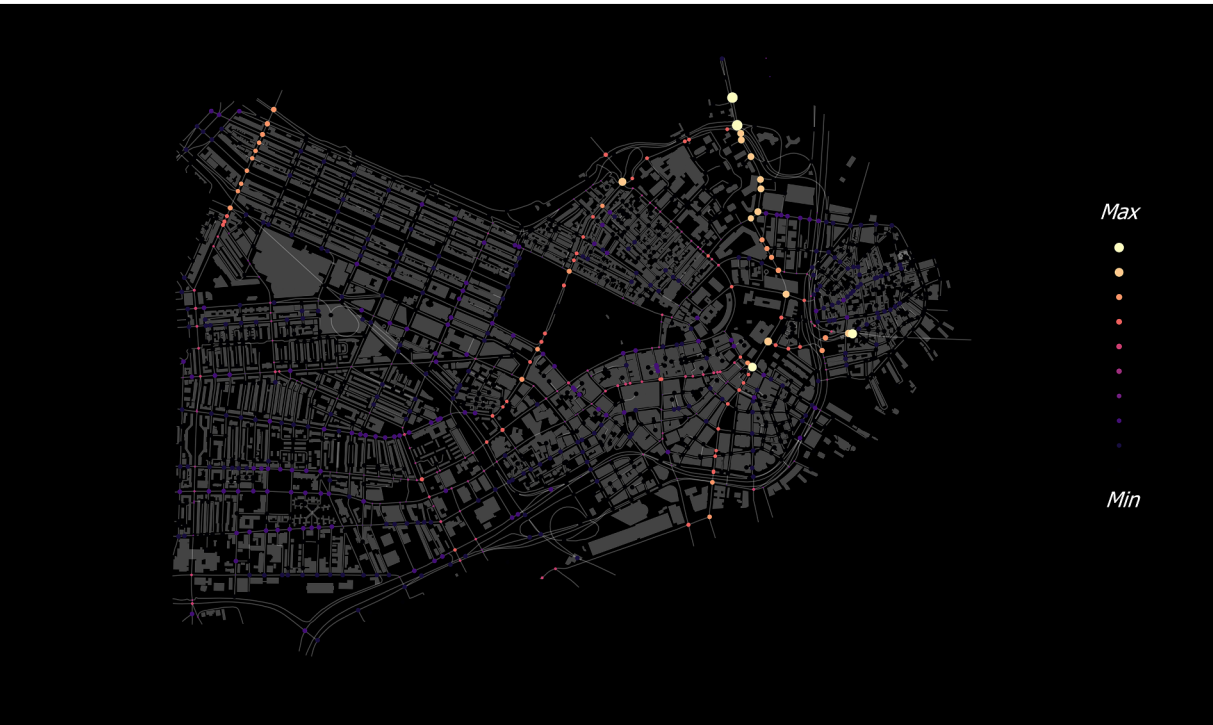
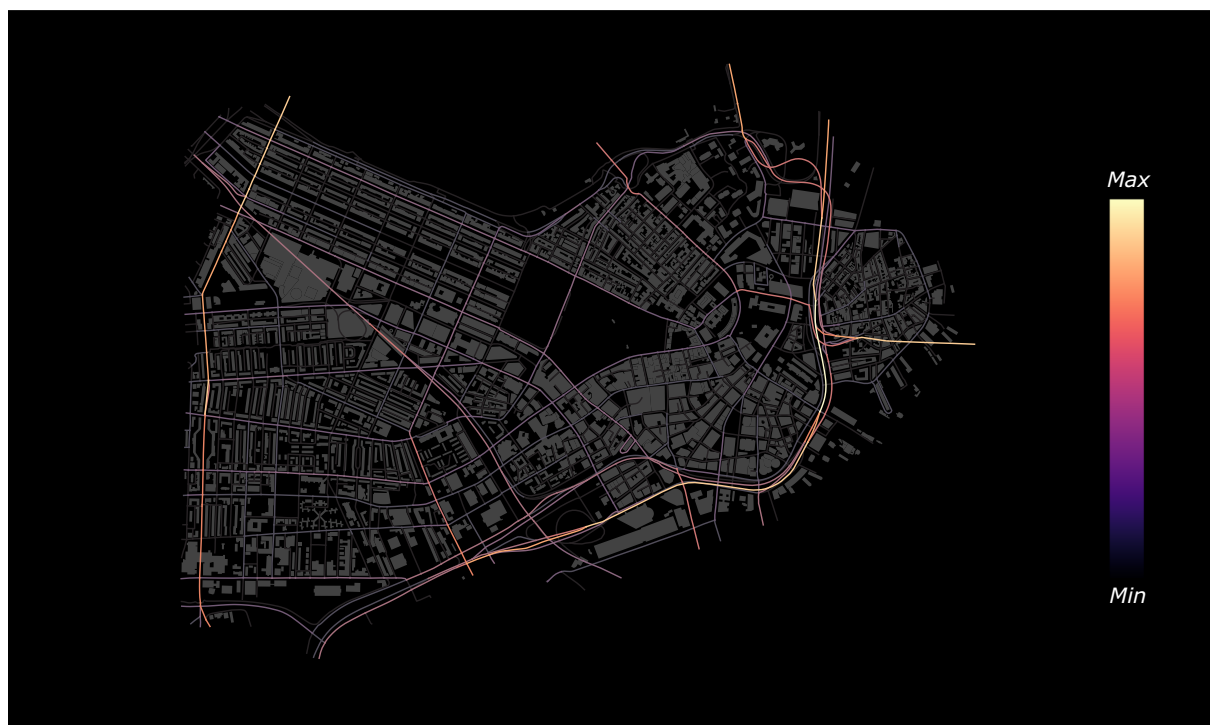
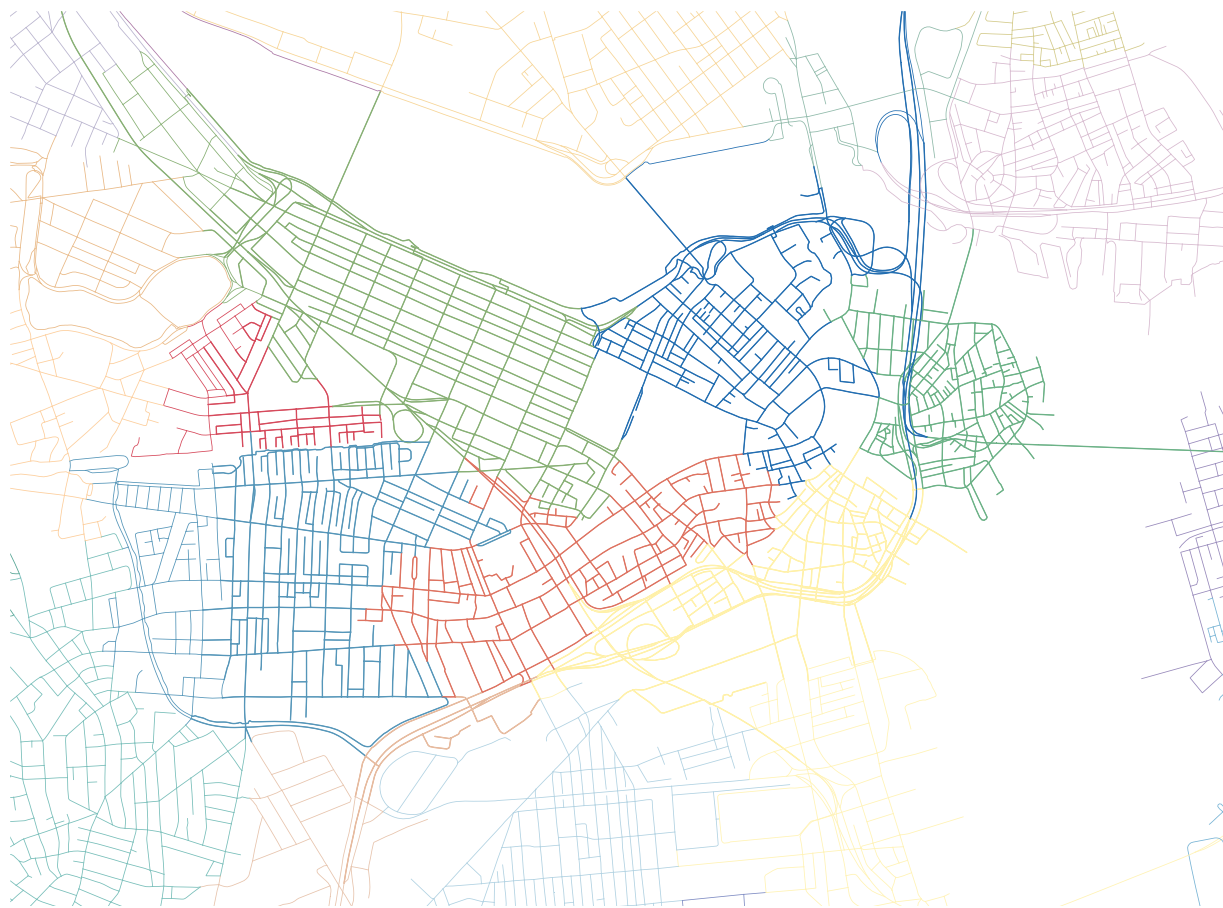


Fig. 3. Nodes: street junctions coloured by betweenness centrality. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)





**Fig. 4.** Paths: street segments coloured by angular edge betweenness. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 5.** Districts: Street-based Local Area (SLA) in Boston city centre. Each colour represents streets belonging to a single district; semi-transparent colours indicate streets outside the studied area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



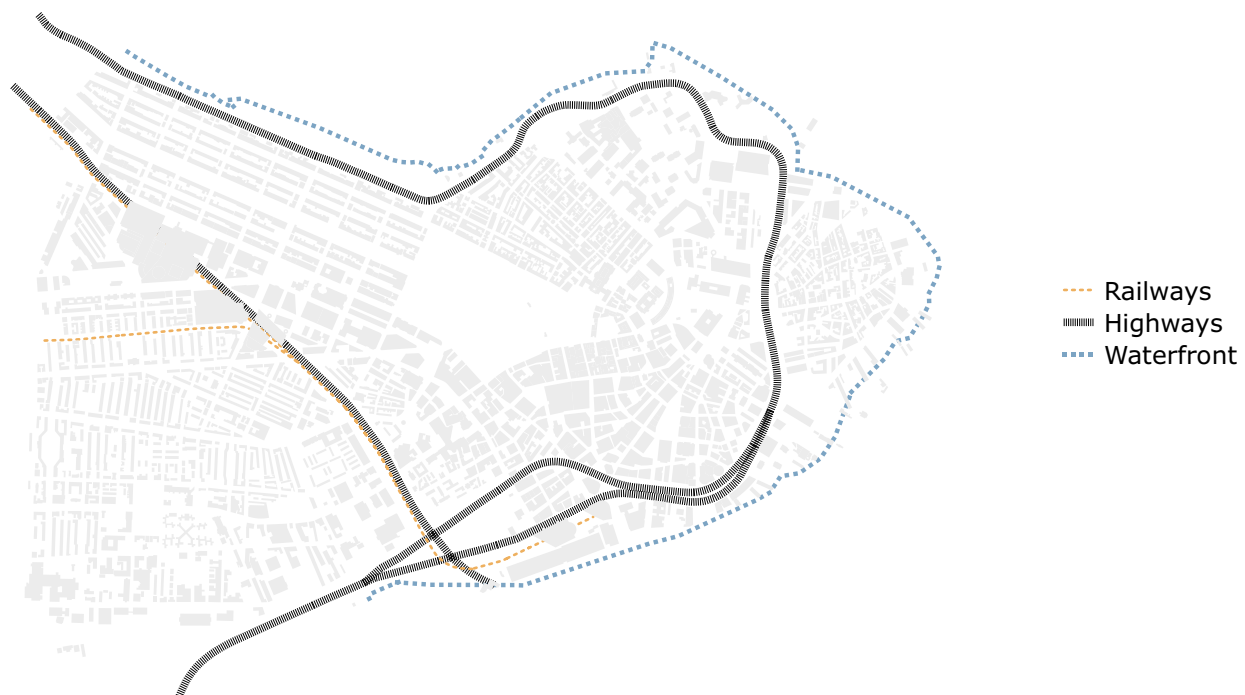
**Fig. 6.** Landmarks: buildings coloured by the overall score. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

development. The large number of skyscrapers erected throughout the last 60 years along with the general evolution of the city and a possible redistribution of the activities, partly explain the discrepancies between Lynch's and our landmark scores. Interestingly, such differences may disclose the dynamic nature of the mental image of the city, a representation that varies and readapts, embracing new elements, meanings and possibilities.

In Boston, edges seem to play two roles. On one hand, the river and the harbour define the shape of the city centre; on the other hand, the

motorways, besides reinforcing the peninsula profile, represent interruptions, separate different areas and obstruct movement. The Central Artery is described by Lynch's interviewees as a fragmentary and abstract edge: even though sometimes it is not visible, people are aware of its presence and the impossibility of crossing it. North End is a shiny example in this sense. The Central Artery completely separates this area from the rest of the city centre.

The edges identified in our analysis (Fig. 7) correspond approximately with those discussed in *The Image of the City*. The waterfront is



**Fig. 7.** Primary edges in Boston. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



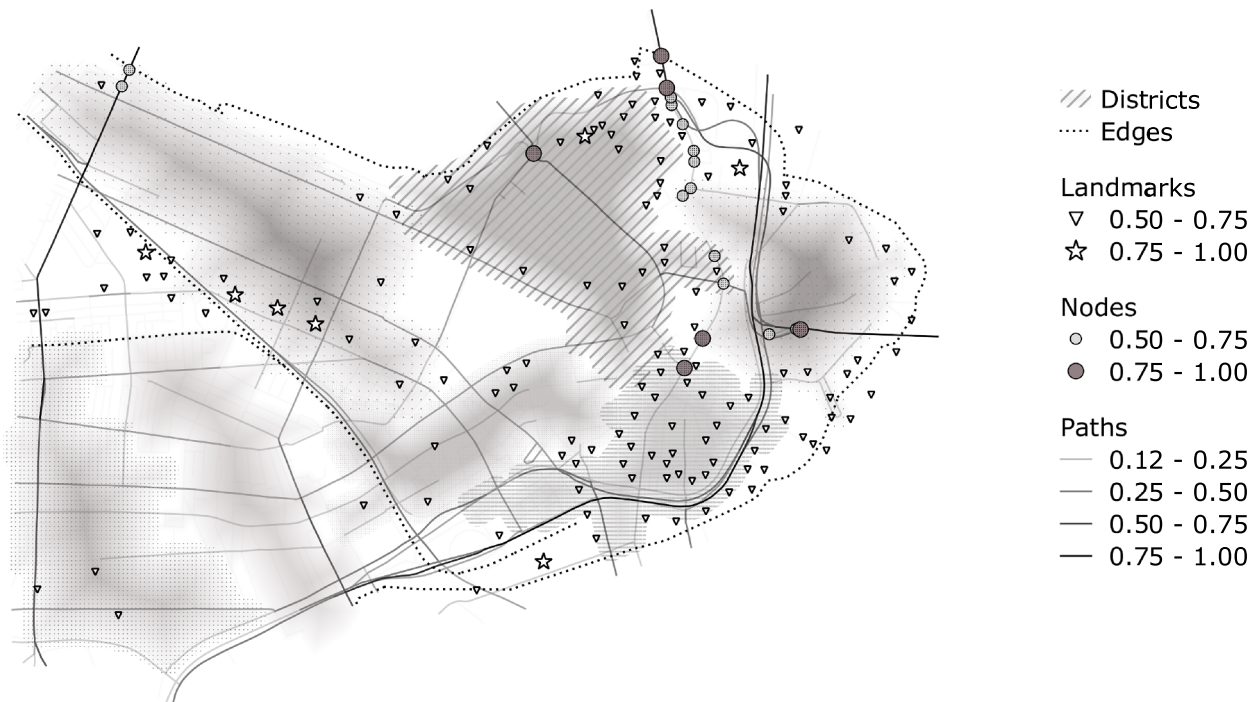


Fig. 8. The computational Image of the City of Boston.

automatically depicted as a continuous and uninterrupted edge that draws the main contour of the cognitive representation of the city. However, Lynch illustrates how citizens rarely join Charles River bank with the harbour. The water between West End and North End is hidden by several buildings and railway structures, which make the continuity of the waterfront difficult to conceptualise and mentally represent. From our analysis, the interplay between the river and Storrow Drive emerges as well: the latter reinforces the meaning of the first but, nevertheless, causes a sense of distance between the water and the districts of Back Bay and Beacon Hill. Conversely, the edge represented by the harbour is more fluid: the presence of amenities and flourishing activities make this area a vivid and liveable edge.

Finally, the computational Image of the City of Boston, displayed in Fig. 8, was obtained combining all the elements in a single, overall map in the style of the hand-drawn maps created by Lynch.

## 5. Discussion and conclusion

The aim of this work was to provide a quantitative formulation of Lynch's Image of the City, easily incorporable in GIS environments, that may favour a more explicit inclusion of *The Image of the City* in GIScience. In *The Image of the City*, Lynch introduces and describes five elements - nodes, paths, districts, landmarks and edges - that give shape to the mental representation of the city. A complete computational approach to *The Image of the City* was presented here and tested on a large and freely available urban-dataset, integrating a range of methods derived from previous research. The mental image of Boston was drawn ranking artefacts on the basis of network and geospatial measures. We explicitly took into consideration a semantic component in landmark extraction and tested a series of criteria to pick out edges. The results were visually compared with the maps of Boston presented in *The Image of the City*, outputs of Lynch's qualitative analysis. While it was difficult to find a common ground concerning landmarks, possibly due to the

changes occurred in the city in the last 60 years, there were correspondences between the other elements extracted computationally and those reported by Lynch: firstly, centrality measures consented to detect main nodes from the street network, as well as major paths; secondly, the modularity optimisation algorithm, a community-detection technique, subdivided the area studied in portions alike to Lynch's main districts; lastly, the criteria advanced to pull out edges produced satisfying results, against the ones presented in *The Image of the City*.

Having said that, the complexity of human cognition and perception cannot be fully captured with a computational approach to mental representations. Interviews and sketch-maps are more comprehensive tools when it comes to study humans' representations, their experiences and their decisions within the environment. The fact that the waterfront of the peninsula was identified as an edge, not accounting for the absence of perceptual continuity between West End and North End, shows the elusiveness of human cognition. Yet, there are various routes along which our work might be extended. The public transport network should be considered for determining crucial nodes, beyond the street junctions, by means of multi-layered or multiplex network. In this sense, Tomko and Winter (2013) advance a formal approach to urban form representation, wherein they suggest to extract *The Image of the City* taking into account the mean transport used by the observer. Moreover, the definition of districts may be adjusted through incorporation of demographic and social dimensions (for example, Gao, Janowicz, & Couclelis, 2017; Gao, Janowicz, Montello et al., 2017 have extracted urban functional regions employing Point-Of-Interests (POIs) check-ins and social-media data). Similarly, the definition of edges may require a more precise formalisation and the incorporation of elements of structural change in the urban morphology.

This framework may also undergo a more precise validation. To further generalise the validity of the approach here presented, the methodology should be tested and evaluated with other case-studies, allowing for differences in urban planning approaches. Origin-

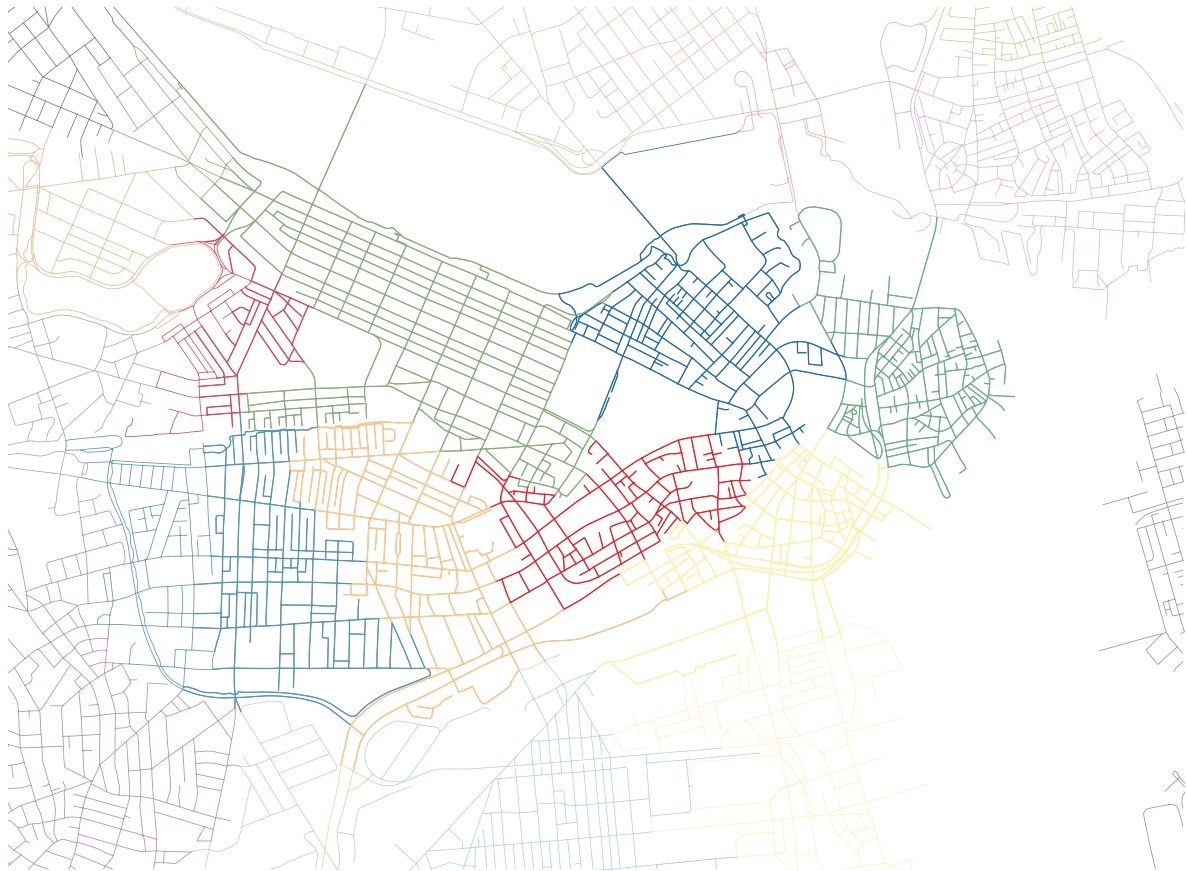
destination matrices regarding pedestrian and traffic flows, or POI check-in datasets, might give indications on paths, nodes, or regionalisation (Manley, 2014), or indicate how to calibrate the weights in the landmark extraction.

The model developed during this paper can be manipulated in any GIS package, enabling formal spatial analysis and modelling of the relationship between observed spatial behaviour and urban form. Examples might include the development of new simulation models of pedestrian or vehicular movement (e.g. Manley, Orr, & Cheng, 2015), spatial and accessibility planning, and identification of low-legibility

areas (activities, movement and orientation).

The work has shown that the development of a computational form of *The Image of the City* is feasible. The methodology devised here can be applied to other cities and urban contexts very easily, manipulating just the input data and a few parameters. This approach makes it possible to reveal images of cities, investigated so far with qualitative and time-consuming procedures. We argue that this tool may support spatial planning decisions in urban design, providing important insights as concerns city livability, quality of life (Llinares, Page, & Llinares, 2013), the adequate mix of land-uses, the ease of navigation and orientation.

## Appendix



**Fig. A1.** Districts: street-based Local Area (SLA) in Boston city centre extracted from a street-network without motorways. Each colour represents streets belonging to a single district; semi-transparent colours indicate streets outside the studied area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. A2.** Landmarks: buildings coloured by component scores. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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