Functional and Structural Analysis of an Urban Space Extended from Space Syntax

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Abstract—Space syntax provides a set of empirical theories and computational techniques for the analysis of the spatial structure of urban spaces that emerge from streets network. However, space syntax still does not reflect all the properties of an urban space, especially some of the functional and service-based activities that might reflect some urban patterns. The research presented in this paper extends the conventional approach of space syntax by a functional analysis of the city that reflects transportation facilities and services. Several operators are suggested and developed, and illustrated by an application on top of Open Street Map data. We believe that such integration provides a better view of the structural properties of an urban space, and allows to compare the urban spatial structure with the function of the city.

Index Terms—GIS, Space syntax, Structural and Functional Analysis

1 Introduction

Over the past thirty years space syntax has been relatively successful in the development of empirical and applied studies that have been helpful in improving our understanding of the spatial structure that emerges from urban networks. The main principle behind space syntax is that space is modeled as a network where street intersections are modeled as nodes, streets segments between those nodes as edges. Graph-based operators can be applied and provide a series of computational measures that qualify global and local structural properties such as centrality, clustering and connectivity properties. Another important property of space syntax is based on the relations that emerge from the underlying graph, and not on the locations of the urban network nodes and edges[1]. Many empirical studies have demonstrated the interest of space syntax for the modeling and understanding of urban patterns and structures [2], [3] and its potential for urban analyses [4], pedestrian modelling [5], and transportation studies [6] to mention a few examples. Despite its success and wide diffusion worldwide, space syntax mainly relies on the spatial structure that emerges from the urban network, without taking into account some additional metric properties, and even the functional properties that also reflect a sense of organization of the city. By functional properties we mean services provided to inhabitants as well as transportation facilities [7]. We believe that such services and functional properties also reflect a level of organization of the city that should be modeled, and even compared to the underlying properties that emerge from space. The modeling framework developed considers three complementary layers: the urban street network, transportation network and services. Several operators are suggested and the whole framework is applied to several littoral cities in France. The experimental study is developed on top of Open Street Map (OSM) data. The rest of the paper is organized as follows. The second section introduces the modeling background. Section 3 develops the multi-level modeling of an urban space. Section 4 presents the experimental evaluation while section 5 concludes the paper and outlines further work.

2 Related Work

During the past century, the city at large has become a wide field of research [8]. The city is a complex object per nature, and a support for many urban related sciences. A city can be interpreted according to different points of view, and at different scales, this leading to a modelling challenge when attempting to provide a modeling framework that encompasses all these dimensions, and a growing complexity of manipulations at the computational level. Several operators are commonly used in space syntax studies, from local to global measures. The local measure of connectivity, also called degree, evaluates the number of nodes directly connected to each individual node. It is given as follows:

$$C_i = k \tag{1}$$

Where k denotes the number of nodes directly linked to the node i. Without the objective of being exhaustive let us mention another local measure, that is, the measure of clustering, that evaluates to which degree connected nodes to a given node also tend to be connected themselves [**?**]. Betweenness centrality is a common example of centrality measure that gives for a given node the number of traversing routes that connect one node to another in the graph [2]. The betweenness centrality of a given node i is given as follows:

$$C_i = \frac{1}{(N-1)(N-2)} \sum_{i,j \in G, j \neq k \neq i} n_{jk}(i)/n_{jk} \tag{2}$$

Where n_{jk} is the total number of shortest paths from nodes j^{th} to node k^{th} and $n_{jk}(i)$ is the number of those paths that pass through the i^{th} node. Despite its rapid development and the efficiency of its empirical modeling principles, the graph-based properties of space syntax do not take into account all the spatial and temporal properties of an urban network. In particular, Space syntax cannot quantify the relationships between urban objects and some social patterns in the city [9]. Also, space syntax does not take into account urban transportation facilities and services. Thus, current structural and computational representations of the city suffer from a lack of integration of human displacements, activities and housing opportunities. In order to take into account additional functional properties not limited to structural ones, several recent works have integrated the notion of accessibility at large. Accessibility such as closeness to main services in the city allows to take into account the role of transportation capabilities and opportunities in the city [10]. Such an integration might provide some additional insights on the understanding of the distribution of services and transportation networks and the relationship with the spatial structure that emerges from the urban network. This might help urban planners to analyze to which degree services and transportation in the city are correlated or not to the urban network structure.

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3 MODELING BACKGROUND

An urban structure provides many services and transportation facilities that contribute to the function of the city. Those services are distributed according to population needs, and should be ideally planned to maximize the utilization of space. Citizens interact with such an urban space in different ways but some overall patterns might emerge. The urban structure of a well designed city should have lower sprawl [11] and a transportation network that covers all the spaces buildings in order to guarantee the accessibility of services to inhabitants. Let us consider a given city distributed in space and that encompasses an urban transportation network, multimodal public transportation networks and some additional services.

3.1 Urban transportation network

An urban transportation network is a key player in the development of human displacements and activities, as well as it largely contributes to the shape of the city. Such network is largely used by cars, pedestrian and bicycles. An urban transportation network can be represented as a graph made of a set of nodes and a set of edges. A node models an intersection between streets, while an edge models a connection between two street intersections. Explicitly, an urban transportation network is modelled as a graph made of a set of streets R_s and a set of street intersections R_i:

- A finite set of streets segments R_s in the city with $R_s = rs_1$, rs_2, ..., rs_n and n being the number of street segments in the city. Each street can be characterized by further attributes such as maximum impedance to denote speed limitations.

- A finite set of street intersections $R_i = ri_1, ri_2, \ldots, ri_w$ with w being the number of intersections in the city.

3.2 Public transportation network

A city's public transportation network can be seen as a functional structure which allows humans to move in the city and perform different activities. A public multimodal transport network is closely connected to the urban transportation network, it is made of a set of routes generally modeled as a sequence of stops, those being important modelling abstractions providing displacement services to the inhabitants. Without loss of generality let us consider that a public tranportation network that can be either a bus, tranmway or metro network depending of the facilities available in the city. Each mean of transportation have a set of stops and streets. Therefore, the modelling of each public route of transportation Ptr is modelled as follows:
PTr = stop1, stop2, ..., stopn where stopi is a public stop and s gives the number of stations of that public route PTr. Overall, the set of public routes PTr1, ..., PTrn gives the network of public transportation, where n denotes the number of public routes.

3.3 Services network

Services are distributed in the city and are accessible to inhabitants. We model a service as a salient and located abstraction closely connected to the street network from which it can be accessed. The set of services S is modelled as: S = s1, s2,..., sZ where z is the number of services in the city. In order to analyze the spatial distribution of the services network, services should be closely connected to the urban transportation network in their immediate neighborhood. Relationships between services and their nearest streets can indicate to which street a given service is connected to. The idea behind this principle is to provide a sort of homogeneous representation of the city that integrates different networks and services facilities.

4 MANIPULATION OPERATORS

In conventional space syntax studies, centralities or cluster properties are derived from the urban transportion network. The main idea behind our modelling approach is to apply centralities and other graph-based measures to not only the urban transportation network, but also to the public transportation and services networks (whose principles can be extended to addtional transportation networks). Two global and local operators have proven to reveal some valuable patterns in the city when analysing the structural properties of a network: betweenness centrality and connectivity. First, betweenness centrality reveals the topological importance played by a given node in the network [2]. The second operator, connectivity is rather local and denotes the local role played by a given node. These operators are applied to the different networks identified by our approach. The idea behind is to reveal centrality and connectivity patterns for each of the network modeled, as well and as more important to study differences, those potentially denoting dependencies between structural and functional patterns (the way for example an urban transportation network is structured), and compared to the properties that emerge from the public transportation and services networks.

4.1 Centrality measures

Each of the networks modelled encompasses some specific properties, denoted particularly by the most central nodes as identified by betweenness values and given as follows:

- Cu is the node having the highest betweenness centrality value in the urban transportation network,

- Ct is the node having the highest betweenness centrality value in the public transportation network,

- Cs is the node having the highest betweenness centrality value in the services network.

As a first approximation, each of the above nodes reflects a very central node with respect to its underlying network, and then represents a sort of emerging centrality property. These central nodes can be considered as strategic places in the city from a structural point of view, having higher accessibility values.It has been observed in urban and transportation studies that under daily situations most people perform mobility tasks up to a distance constraint of *500* metres [12]. This distance is considered as a very short distance perceived by a pedestrian. This distance is used to characterize a centrality region for each network, we define a centrality area for each of those central nodes (approximated by a buffer of 500 meters). We consider that these centrality areas have close structural properties than the the ones of their respective centres. For each network, its centrality area is given as follows:

- $C_{transport}$ is the centrality area of public transportation network

- $C_{service}$ is the centrality area of services network.

- C_{urban} is the centrality area of urban network.

The study of the respective location of these centrality areas might give us some valuable patterns that characterize the respective distribution and interaction of the streets, transportation and services networks. For instance, one might compare the relationships between the centrality areas of the streets and public transportation networks, services and public transportation networks, and then reveal some significant trends for urban planning. Services often general transportation demands, therefore it might be worth comparing the intersection of the centrality areas C_{urban} and $C_{service}$, as well as the centrality areas $C_{transport}$ and $C_{service}$ that should reveal the capabilities to reach services using public transportation.

4.2 Centrality clusters

Although the most central nodes of each network provide a first approximation of the respective centrality of each network, the approach can be generalised to the most central clusters of each network. Indeed, the nodes having high connectivity values should play an important structural role in the city. Nodes with high connectivity values can be clustered as usually applied in cluster analysis, and even generate subgraphs [13]. For each network several centrality clusters are generated as follows. First, all nodes of a given network are classified according to their connectivity values. The one with the highest connectivity value is considered as a root of the cluster, and the ones with high connectivity values up to a given threshold distance (e.g., 500 meters in the experimental study developed) are connected to the root in order to generate a subgraph of high connectivity value whenever possible, if not disconnected clusters are generated. The algorithm is applied recursively and generates a set of clusters of high connectivity values. The process generates a set $C = (C_1, C_2, C_3, .., C_K)$ of k-clusters from the graph G. Each cluster Ci in the graph is identified as $G[C_i] = (C_i, E(C_i))$ such as $E(C_i) = u, v \in E, u, v \in N$. The intra-cluster edge denotes the number of edges in the cluster as $m(C_i) = |E(C_i)|$. Next, the coverage parameter evaluates the size of each centrality cluster with respect to its whole network. The highest the coverage value, the larger the size of the considered cluster with respect to the whole network. The coverage value of each cluster is given by the proportion of the number of edges in the centrality cluster to the total number of edges in the graph G as follows:

$$coverage(C) = \frac{\sum_{i=1}^{k} m(C_i)}{|E|} \quad (3)$$

5 EXPERIMENTAL STUDY

The principles of our modeling approach are applied to the different networks identified for each sample city selected in order to show the characteristics of each network, and some sort of cohesion between the urban spatial structure of the city, public transportation and services. The cities selected are Brest, Toulon and Dijon, middle size cities in France. The first step of our approach is to model and create the different networks that reflect the urban streets structure, public transportation and services accessibility. Let us first introduce the centrality analyses developed for each city. The computation of the betweenness centrality values of the three networks of Brest provide for each node its centrality. The node that has the highest value of betweenness centrality is considered as the center of its own network. The generation of the centrality areas in these cities is shown in Fig.1. It appears that the centrality areas in Brest are relatively close: $C_{service}$ intersection with $C_{transport}$ gives a region (a) which can be considered as a region of high accessibility to services for the public transportation users. Another intersection between $C_{service}$ and C_{urban} shows good accessibility to services for either pedestrians or cars users in the region (b). It also appears that the locations of these centrality areas are situated relatively far from the sea, this denoting a specific characteristic of the city of Brest, where several urban networks are not completely "interacting" with the harbour from an urban planning point of view. The same study is applied to Toulon, a city in the South of France. Fig.1 shows the intersection between the centrality areas $C_{service}$ and C_{urban} denoted by the region (c). In contrast with Brest, this regions nearby the coastline shows the importance of the sea on the location of services. However, $C_{transport}$ is situated relatively far from $C_{service}$, this denoting a relatively poor interaction between public transportation and services. The last study is applied to the city of Dijon, from which emerges a close proximity between the centrality areas of services $C_{service}$ and public transportation C_{urban}, but a rather disconnection between the streets networks $C_{transport}$ and those services. This probably denotes a relatively efficient urban planning where the public transportation has been organised more closely to the location of the services in the city, and not in function of the underlying streets network.

The second aim of our study is to locate the regions with high connectivity values, that is, the centrality clusters. It clearly appears as shown by Fig.2 that the number of clusters varies from one city to another. Also the urban transportation networks have higher connectivity values, this being a direct result of their underlying structure. Those are then more likely to have more clusters when compared to service networks. Brest is characterized by a specific position of the different clusters that emerge. As shown in Fig.2, these clusters are distributed along the coastal line which is an area of relative high urban density, and also moderate our first finding. The second trend is revealed by high connectivity values next to the river that separates the city in two distinct urban parts. However, this does not prevent the presence of a few more clusters in the North East and South West characterized by high urban connectivity on services, urban and public transportations. Toulon also has a specific distribution of clusters located next to the seaside, this reflecting the functional activities in those places, as well as the interdependence of the different networks considered, either services, public or urban transportation at large. Dijon shows some different patterns. The clusters that emerge show a sort of star distribution in all directions. The different values of coverage of the resulting sub-graphs of clusters show figures that vary between 0,19 and 0,32 for Brest, 0,17 and 0,21 for Toulon and 0,16 and 0,32 for Dijon. The average of coverage values gives 0,26 for Brest followed by Dijon with 0,24 and then Toulon with 0,21. Thus, Brest has a relative more compact coverage. It also appears that Brest has a relatively larger coverage that than the two others cities this denoting a larger distribution of services and transportation facilities. Overall, this experimental study shows some preliminary examples of potential application of the modelling approach suggested in this paper. The findings are of course preliminary, and should be considered as illustrative examples. But the approach offers the possibility to study and compare different cities according to some centrality values and areas, as well as several clusters derived for each network. The approach is general enough to be extended to other cities under similar principles.

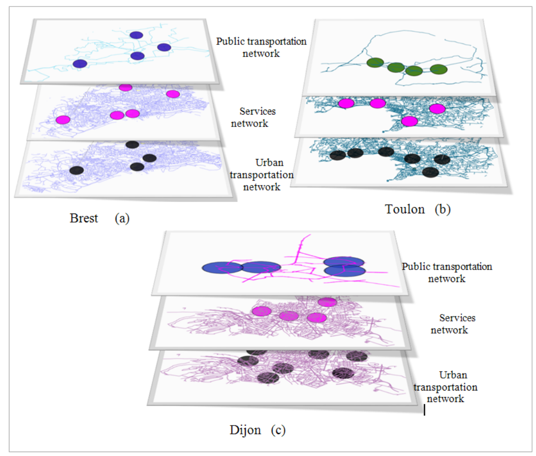

Fig. 2. Functional and structural networks of Brest, Toulon and Dijon

6 CONCLUSION

The research presented in this paper introduces a multi-level graph-based modeling approach of the city. The developed framework is based on the assumption that centrality patterns of the city are influenced by human activities as well as the distribution of services and transportation accessibility. In contrast with current space syntax researches, e.g.[14] or with transportation studies, e.g. [15], this modelling approach takes into account the functional dimension of the city. We introduce several graph-based representations of the urban transportation network, transportation networks as well as services. Several space syntax operators are applied, and complemented by several measures that derive different degrees of centrality as well as areas of influence in the city. Connectivity clusters are derived from the most connected nodes and a threshold value for each considered graph. The operators applied show different degrees of centrality in the cities and how the urban spatial structure is distributed, and correlated or not to the distribution of transportation facilities and services. The whole approach is illustrated by some preliminary experimental studies applied to several medium size cities in France. We plan to extend those preliminary experiments to different small, medium and large cities in order to observe the patterns that emerge at different levels of scale. Those experiments should be conducted in different regional

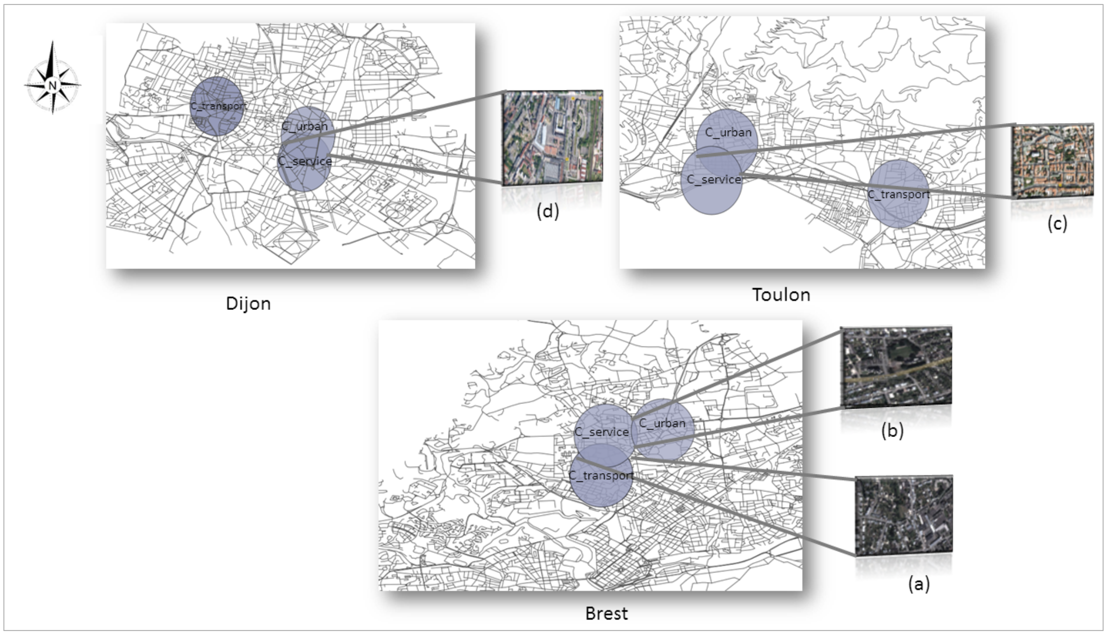

Fig. 1. Centrality areas of Brest, Toulon and Dijon

and country contexts in order to validate and extend the scope of the different operators identified and applied so far.

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