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A STRUCTURAL ANALYSIS OF THE STREETS NETWORK TO URBAN FABRIC CHARACTERIZATION

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ABSTRACT

The streets' network shapes the urban layout that structures the city space and delineates homogeneous urban areas. Structural analysis of the streets' network is very useful because it usually produces additional semantic information (about urban dynamics). This allows the enrichment of spatial data. The topological and/or geometric characteristics of the network can be analyzed using some graph theory algorithms.

The aim of this work is to perform some characterization of the urban fabrics using exclusively the streets' network as input data. Indeed, the structural properties of the streets' network create several effects such as continuity, separation, centrality, proximity, connectivity, symmetry, and adjacency into the urban space.

We work on an urban primal graph where streets are considered as edges and streets' intersections are considered as nodes. On the basis of this real urban graph, we implement two additional artificial graphs. The first one is a “Delaunay triangulated network” and the second one is a “minimum spanning tree”. These graphs correspond to two extreme network morphologies delimiting a morphological continuum. The three graphs are then analyzed using shortest path algorithms. They all have been processed on both a topological and a geometric (weighting each edge by its length) ways so as to extract some structural and multi-centrality indicators (closeness and betweenness centralities).

The results can produce semantic information on the structure of the urban fabrics. They allow us to emphasize some specific morphological urban structures (organic areas, suburban tree structures) and some urban salient features (main roads and ring roads).

Key words: Streets’ network, structural, graph, centrality, urban fabric.

1. INTRODUCTION

The streets’ network has been studied in several disciplines. Among others, transports modeling, space syntax, cartographic generalization and complex networks. The streets’ network can be studied differently according to the discipline and the context of the research. So, the representation models and analysis methods may vary according to the context thematic. We mainly distinguish between structural approaches, functional ones and mixed ones putting together the structural and the functional network characteristics in the study (MARSHALL 2005).

Here, the network is studied in the context of a current renewing of the urban morphology (BADARIOTTI 2007). If we consider the three components of the morphological urban system (the streets’ network, the open spaces and the buildings), we focus on the streets’ network and especially on its structural characteristics in opposition to the functional ones. Theses structural characteristics are the result of the physical presence of the network independently of the uses we have of it.

The structural study of the streets’ network is quite common in the urban morphology research and especially in the space syntax one (socio-spatial morphology) (HILLIER 1987). Space syntax aims to study the effects of the spatial structure on the users’ spatial practices. Early research interested in the study of architectural spaces and was broadened to urban spaces especially the streets’ network. These works suppose that if there is a social logic of space, there is also a spatial logic of social practices (HILLIER, HANSON 1984).

The study of the streets’ network reveals significant relationships between the network structural characteristics (geometrical and topological) and several functional or social urban aspects: population density (TANG 2003), services localization (PEPONIS et al. 2007), walking flow (FOLTÊTE 2007), urbanity (VAN NES, ZHAOHUI 2009) (OMER, JIANG 2008), etc.

From a morphological point of view, the geometrical patterns of the streets’ network usually correspond with different types of urban fabrics. Furthermore, a cities typology has already been drawn up following their urban layout: “hippodamian” cities, organic cities, radio-concentric cities, etc (BUHL et al. 2006), (CARDILLO et al. 2006), (CRUCITTI, LATORA, PORTA 2006).

The structural analysis of the streets’ network can be very useful for semantic enrichment of spatial network data. This is due to the emergence (appearance) of some physical structural properties when the architecture of the studied network becomes quite complex.

The first part of this paper presents the context of this work and its objectives. The second part develops the methodology and the results are then discussed in the third part. In the last part, we draw some conclusions and future perspectives.

2. BACKGROUND AND OBJECTIVES

Our aim is to confront the streets network structural characteristics with the urban fabric characteristics through its two other urban morphological system components: the open spaces and the buildings.

To study a given network, we firstly need to represent it by an abstraction model (simplifying the reality) and secondly to analyze it (extract some information not provided a priori) thanks to some mathematical tools.

In a geographical database, a streets' network is represented as a spatial graph (set of lines) where every street is represented by its central line enriched by some metadata that can be geometric or semantic. Even if this representation model is simple and intuitive, it offers the possibility to model the streets' network in a formal way.

A mathematical graph G= (N, L) is composed of a set of nodes (N) linked by a set of arcs (L). This structure describes intrinsically the topology of these two sets. Furthermore, the streets network has the particularity to be a spatial or geometrical graph; it is a particular configuration of a planar graph (Figure 1).

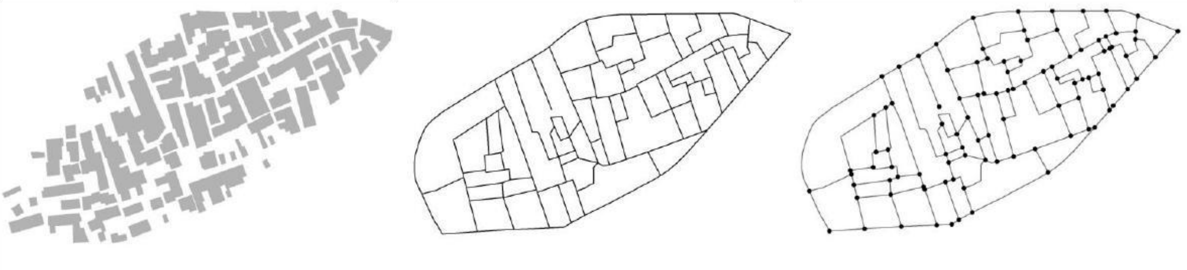


Figure 1 "Trentemoult" area in Nantes — The street network of "Trentemoult" — The corresponding mathematical graph

This representation as a mathematical graph (1D data) extends the type of spatial analysis that can be applied to this data in comparison with 2D or 3D data. Two modeling approaches can be applied to a given network (Figure 2) (PORTA, CRUCITTI, LATORA 2006a) and (PORTA, CRUCITTI, LATORA 2006b). A first one is called the primal approach where the main component of the analysis is the street segment located between two successive intersections. These intersections at the junctions of the segments represent the nodes of the graph and the street segments represent its links or edges. The advantage of this representation is that it preserves the geometry of the urban space. Unfortunately, the continuity through junctions to form urban linear features (avenue, boulevard, etc) is not guaranteed. A second approach called the dual approach allows the continuity through junctions to be guaranteed. Indeed, the streets are represented by nodes and the graph links represent the intersections between the streets. However, the main drawback of this approach is that it needs an aggregation method of the streets segments that is usually done according to semantic criterions. The dual approach is the one used in the space syntax studies where the dual representation is composed of an axial lines network (the main movement lines).

In the present work, we choose the primal approach for the following reasons:

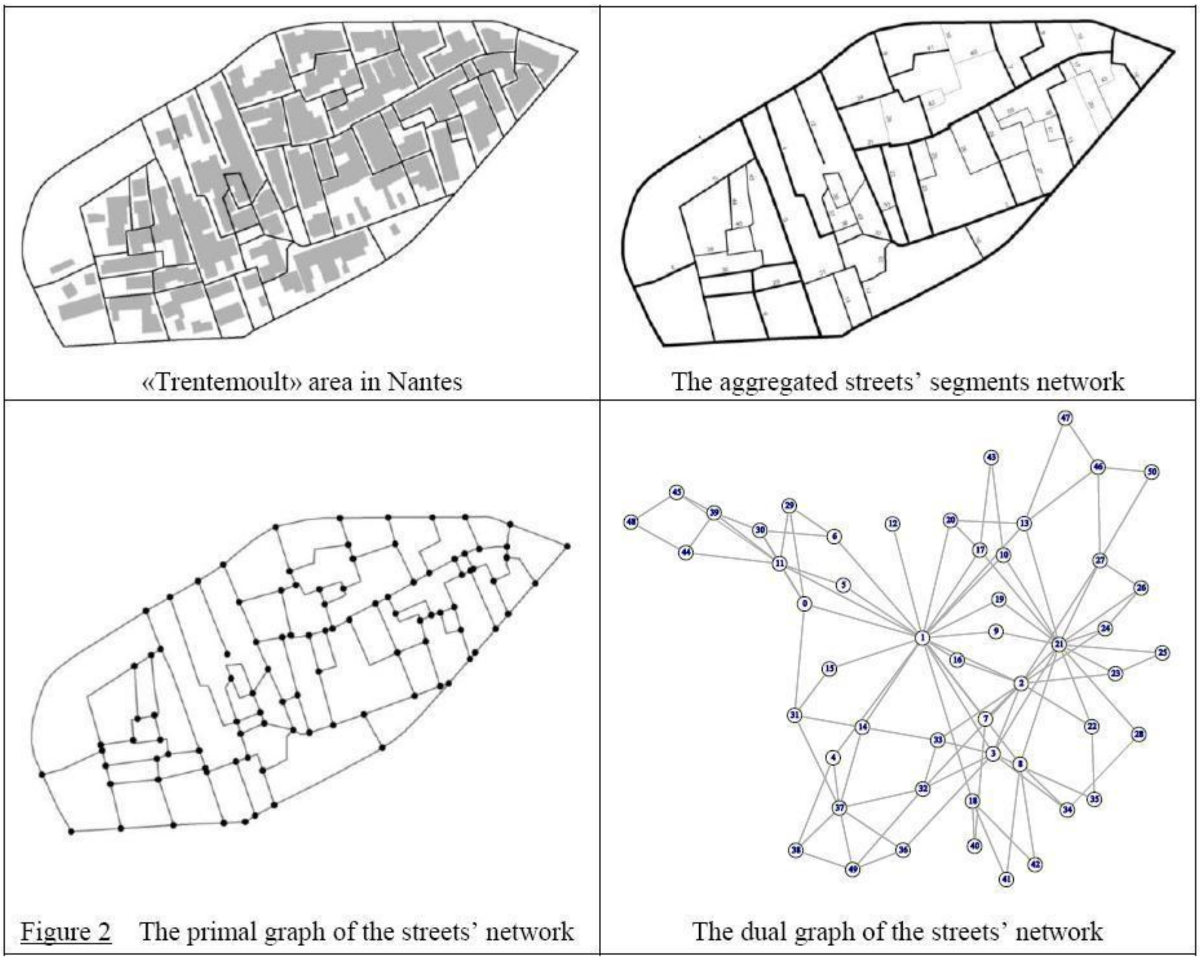
-The dualization of the street network preserves only the topological properties while the geometrical ones disappear. However, these geometric characteristics are the most important to deduce the morphological characteristics of the urban fabrics, the aim of this work;

-Simple and intuitive interpretation of the results;

-There is no need of an aggregation method that can introduce some subjective (semantic) criterions.

The aim of this work is to show that the structural properties of the streets' network takes parts in the characterization of the urban fabrics through the production of some urban effects as continuity, discontinuity, centrality, proximity, adjacency, etc.

We define an urban fabric as a spatial area of the urban space that is characterized by a morphological homogeneity (in terms of buildings, open spaces and the composition of both). It is usually delimited by structural linear features that produce some incision and discontinuity with adjacent urban areas. This morphological homogeneity also gives to the urban fabric homogeneity in terms of functional and social aspects. This way, the urban fabric finally corresponds to an urban unit suitable for the city diagnosis and management.



«Trentemoult» area in Nantes

The aggregated streets' segments network

Figure 2 The primal graph of the streets' network

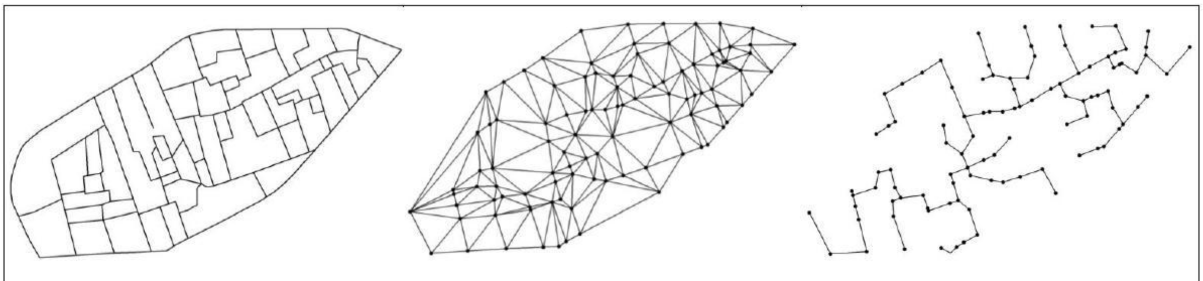
The dual graph of the streets' network

3. APPROACH AND METHODOLOGY

Our analysis of the streets' network is based on the production of three primal graphs (Figure 3). The first one, called the urban graph, corresponds to the real spatial structure of the urban space. From this real urban graph, we extract the junctions between street segments, they correspond to the urban places that have to be interconnected or served. These intersections will be used to build two artificial graphs: first, a triangulation (the most connective planar graph) and second, a tree (the least connective graph).

The Delaunay triangulation is a planar graph where the urban places are linked with a maximal density of the streets segments. The minimum spanning tree is a planar graph where these urban places are linked with a minimal density of streets segments. Therefore, these two theoretical graphs are two extreme network morphologies delimiting the boundaries of a morphological continuum inside which it is possible to position the real urban graph.

These three graphs are described by their global indicators (number of links, number of nodes, mean length of segments, characteristic length of paths, mean degree of nodes, frequency distribution of segment lengths and nodes degree). These global indicators provide a general description of the nature (density, connectivity, robustness, etc) of the network.



The urban real graph of «Trentemoult» The corresponding Delaunay Triangulation The corresponding minimum spanning tree

Figure 3

The three graphs are then analyzed using a shortest path algorithm (Dijkstra implementation) to build the set of all shortest paths between all pairs of nodes of each graph. This set of the shortest paths is used to extract some multi-centrality indicators (FREEMAN 1979) for each node and segment in each graph.

First, we process the closeness centrality that indicates some gradient of geometric accessibility. It is calculated for each node as the inverse of the length of the characteristic path between the given node and all other nodes in the network (1).

$Ci = (v-1) / \sum_{j \neq i} Dij$ (1)

Where «v» is the number of nodes and «Dij» is the distance between the given node «i» and any other node «j».

Second, we compute the betweenness centrality that emphasizes some hierarchy linked to the importance of the street segments and a degree of physical discontinuity produced by each of these street segments. It is calculated for each street segment as the sum of the ratios between the number of the shortest paths passing through the given street segment and the number of shortest paths between each pair of nodes of the network (2).

$Ba = \sum_{i \neq j} Diaj / Dij$ (2)

Where «Dij» is the number of shortest paths between the nodes «i» and «j»; «Diaj» is the number of shortest paths between the nodes «i» and «j» going across the given street segment «a».

Two types of multi-centrality indicators are used. First, the topological centralities for which the length of a path is equal to the number of the segments that compose this path. Second, the metric centralities for which the length of a path is equal to the Euclidean length of this path.

The purpose of this is to reveal both the effects produced by the network topology and those produced by the network geometry. This is the case of the ring roads (or beltways) that are highlighted only by topological indicators.

The study area is delimited by the beltway boulevard of Nantes city. Indeed, (this choice is motivated by the fact that) this freeway produces a physical (and functional) incision in the urban space and delimits therefore a homogeneous urban area in its interior.

4. RESULTS

The global characteristics of the real urban graph, its associated Delaunay triangulation and the minimum spanning tree are presented in this table.

	Number of links	Number of nodes	Total length	Mean degree	Clustering coefficient	Characteristic path
Urban Graph	17448	12795	1418 km	2,7	0.065	6013 m
minimum spanning tree	5505	5506	589 km	2	0	13858 m
Delaunay triangulation	38341	12795	3667 km	6	0.376	5064 m

The morphology of the real urban network takes place somewhere between the morphology of the triangulation and the morphology of the corresponding tree. We can notice that the characteristic length (of the mean path) in the urban graph is very similar in the triangulation even if its clustering coefficient is lower. By analogy, it is possible to place the network of any urban area within a morphological continuum going from its correspondents in the triangulation and in the minimum spanning tree.

This coarse characterization from the global indicators is still insufficient and poor for some applications and is not suitable when the network morphology is highly heterogeneous. Therefore, it is suitable to use local indicators.

These local indicators are the topologic and metric multi-centralities. They concern the street segments in the case of the betweenness centrality and the nodes in the case of the closeness centrality.

To link between the network characteristics and the urban fabric typology, we assume that there is a close relationship between the network density and buildings density. This is the result of the urban regulation imposing that a plot should be connected with a street segment to be built in the future.

4.1. Closeness centrality (Figure 4)

The metric closeness centrality in the urban real graph follows a well uniform center-periphery gradient that can be associated with the gradient of buildings density. Four concentric distinct areas are highlighted and can be associated to: down town -> immediate center neighborhood delimited by the first ring boulevard -> terraced houses -> suburban areas.

If we compare the results of the metric and topological closeness centrality, the topological closeness centrality makes the uniformity of the concentric areas highlighted in the metric closeness less clear. So, these new areas in the topological closeness may therefore correspond better to the urban fabrics typology.

For example, the downtown area is better identified (due to the topological peculiarity of its organic network).

In the west of the study area, a wide part doesn't match any longer (or less clearly) the concentric gradient. It is formed in its majority by an urban fabric of towers blocks and high rise housing.

Finally, the beltway boulevard and its adjacent areas are also highlighted. In these areas, the industrial and commercial activities are localized near the city doors so as to benefit from the high accessibility and centrality produced by this freeway.

It is worth to make the same comparison between the topologic and metric closeness centrality in the Delaunay triangulation because a concentric gradient (quasi perfectly circular) highlighted in the metric centrality is swapped in the topological centrality.

Therefore, the downtown area in this case is topologically less accessible (so it becomes de facto less central) while the areas near the beltway boulevard become more accessible and de facto more central.

This can be used to highlight the urban fabrics having an organic structure as the downtowns (using for example the difference between some normalized values of these centrality indicators).

In the minimum spanning tree network, the difference between the topologic and metric closeness centralities is less highlighted; because the hierarchy of the network is homogenized for all segments in the network (all the street segments have the same importance when connecting urban places), the continuity of street segments through junctions to form hierarchically superior features is broken and the physical incisions are no longer produced.

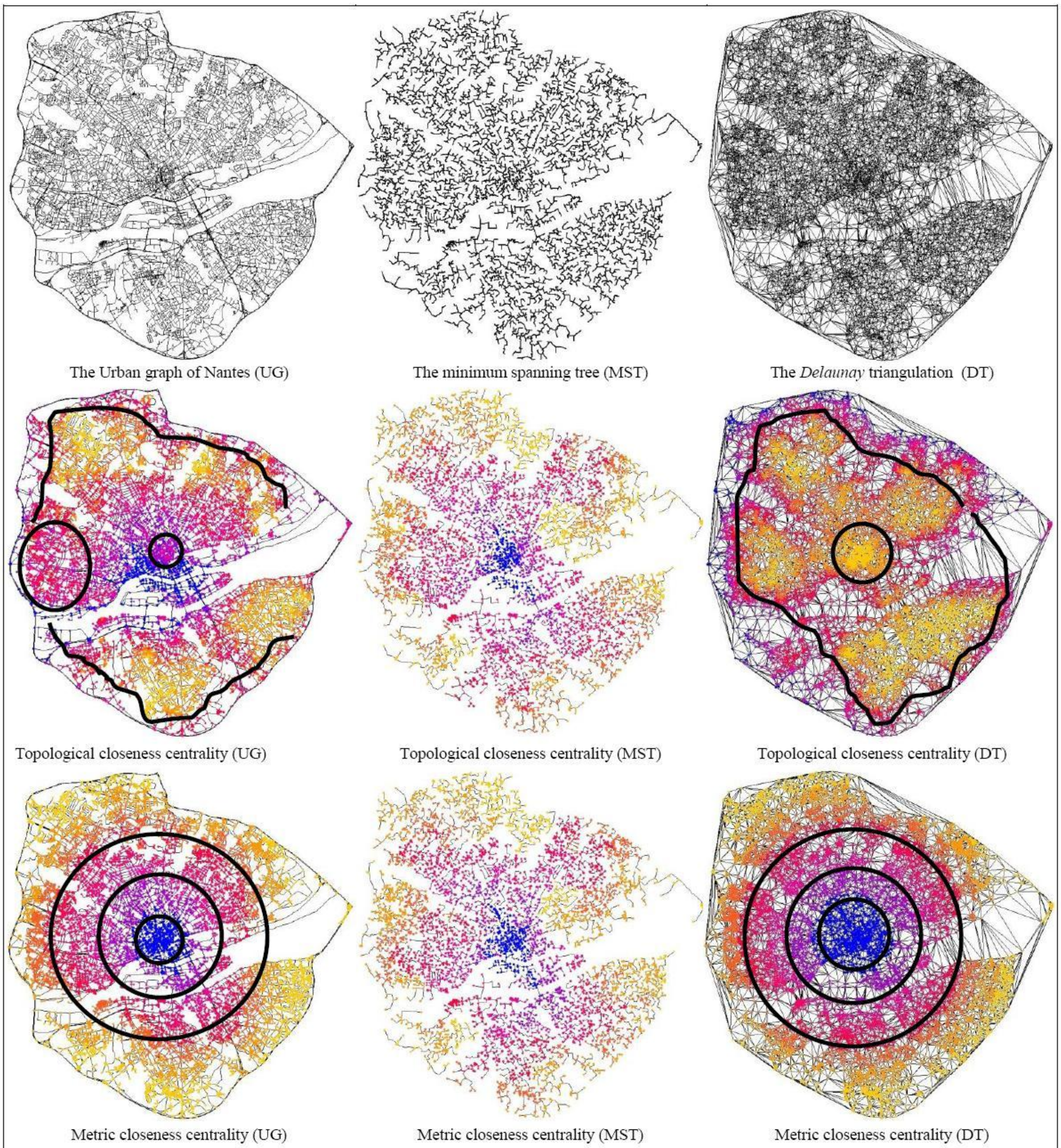


Figure 4: Results of the closeness centrality in the real urban and two artificial graphs

4.2. Betweenness centrality (Figure 5)

The betweenness centrality in the real urban graph highlights the discontinuities produced by the streets' network in the urban space. It is possible to establish a hierarchy of the street segments and to subdivide the city into homogeneous areas that can be considered as suitable urban fabric delimitations.

The production of this hierarchy and zoning can be done iteratively to respectively highlight the streets that are more structuring and more important into the urban structure at each iteration and to recognize urban fabrics that are more (bottom-up) or less (top-down) wider at each iteration.

The topologic and metric betweenness centralities should be used together in this process of the recognition of structuring streets (beltway boulevards, radial roads, avenues, main crossings, etc.).

In the minimum spanning tree graph, the topologic and metric betweenness centralities are the same. Therefore, the comparison of these two values for a given urban area network can be used to see if this area is similar or not with a tree structure where there are many dead-ends. In our study area, this is usually associated with "enclosed terraced houses".

In the Delaunay network, the triangulation homogenizes the hierarchy of the streets and deletes the effect of discontinuities due to the structuring routes (this concept disappears in this case). Indeed, the routes that get importance are those adjacent to wide open spaces (not provided with a network) and corresponding in our study area to watercourses, green areas and peculiar topographic landforms.

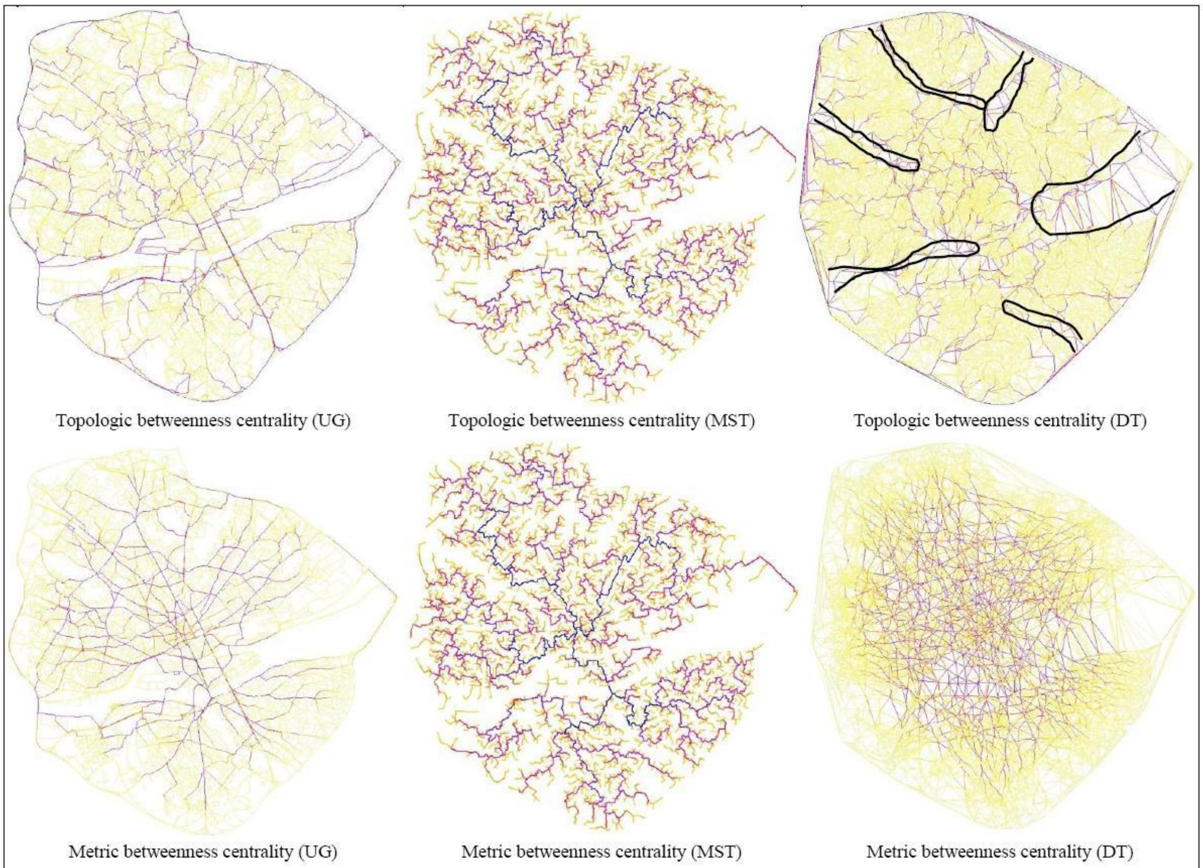


Figure 5: Results of the betweenness centrality in the real urban and two artificial graphs

5. CONCLUSION AND PERSPECTIVES

It is possible to produce some urban fabrics characteristics from a geographic representation of the streets' network without a priori any semantic information. The approach is fully structural and creates semantic knowledge from simple interpretations. However, it is necessary that the network in study is large enough so that these semantic properties can be highlighted.

This methodology is theoretically transposable as it is to any other cities. Therefore, it is possible to characterize any type of urban fabrics without prior knowledge about its historical context of urban development.

We can characterize better the urban fabrics with such an approach that is only based on linear urban data. Therefore, in the urban fabrics characterization, it will be less essential to use 3D buildings or 2D open spaces data that are both very hard to analyze spatially.

The characterization of the urban fabrics presented here can be improved by introducing some semantics about the streets (width, hierarchy and morphology), topographic data, etc; and should be completed by some urban plans regulations to produce a suitable and coherent urban semantic knowledge.

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