# Morphological Comparison on Historical and Modern Cities

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**Abstract**

Topological analysis of urban street network was made to study city's underlying pattern. Three European cities Amsterdam, Avignon and Hamburg were chosen as one sample group and they all have well preserved city center. The study aims to find different hierarchical patterns of urban street networks for both preserved area and large modernized area of the same city. The other sample group contained four areas which played the role of fortification at Renaissance time and they were Naarden, Neuf Brisach, Palmanova and Philippeville. For most street networks, universality was revealed that about 40 % of their streets had connectivity greater than the average value while 60 % had connectivity less than the average value. No matter for preserved city areas, modernized areas and fortified towns, streets with largest connectivity were a small part of the street network. It was found that the urban street networks for all study areas had small-world property but the degree distribution for some of them did not exactly fit a power-law distribution. These street networks were detected to have different number of communities.

**Keywords:** Topological analysis, head/tail breaks, hierarchical levels, small-world, and scale-free

## 1. Introduction

Spatial analysis is an important step within GIS for processing the data and uncovering the underlying structures. GIS which is a computer based system is used to deal with georeferenced data and it contains data acquisition, data management, deeply analysis, visualization and other procedures. There are about three steps within GIS; first one is to acquire the data which can be gotten through surveying, GPS, laser scanning and volunteered geographic data (VGI). Second one is processing, for this step data are analyzed. Spatial analysis can do the transformation from information to knowledge and it can help people to have better understanding of the information. The third step is called output; it contains visualization, map production and other measures to get the structure of geographic space. Take a look at the web, Google is a new paradigm now. Based on topology, people can find out which page is related to which one and which the most important page is and the topological analysis is going to be applied to study urban street networks. Knowledge is useful information, spatial analysis provides a way to obtain and manage the information. Data, information and knowledge can be represented with a pyramid. Data is put at the bottom and it is the basic thing. Information is above the data. Through data acquisition, you search what you want and can make transformation from data to information. Knowledge is located at the top of the pyramid, by spatial analysis; information is turned to knowledge. This study focuses on the spatial analysis of street networks in order to uncover underlying patterns of the sample areas. Topology and scaling are the two keys for spatial analysis.

Topology is used to describe how objects are related to each other and it is a study out of geometry which focuses on figure's size, shape or position. Scaling reveals that there are far more small things than large things. Topological analysis has been widely applied in the geographic spaces to get the object's structure, for instance it has been used to uncover the patterns of street networks for self-organized urban settlements (Buhl et al., 2006). For the scaling, Jiang (2007) had deal with 40 US sample cities and got the universality that about 20 % streets of the network have their lengths or degrees greater than the average value while 80 % streets have their lengths or degrees less than the average. Geographic space is in contrast with small space like table-top space, and it is beyond human body perception. It is large enough and too complicated that cannot be seen from a single point. For something is very large, they need to be partitioned into small pieces to be studied. The geographic space is partitioned into small ones to achieve understanding of the whole. Small pieces of the space should be set the topology which is treated as relationship. To understand the geographic space, people need to know the symbol, meaning and relationship of them. Space syntax could provide a way to study the spatial configuration and give better understanding of the geographic space.

Precise computations of urban patterns about their shapes, semantics and meanings can be performed by modern GIS system (Jiang, 2010). GIS modeling for raster and vector is machine understanding and to make a human understanding of the space, graph is produced and applied with space syntax to study the morphology. This study focuses on revealing the morphology for preserved area and modernized area and uncovering the underlying patterns that are not perceptive by people in reality. Avignon, Hamburg and Amsterdam whose center area are well preserved and Naarden, Neuf Brisach, Palmanova and Philippeville which were built as fortification at Renaissance time are chosen as the sample to carry out the study of various urban morphologies. During the Renaissance period, some European cities or towns built the urban defensive systems which involved inter-dependent bastions and forts to defend attractors and they were treated as fortified garrison (Morris, 1994). The outlines of rampart or moat of the four fortified areas still have good appearances and they keep the geometry, so they are selected to make the topological analysis about this urban type. Other three European sample cities have well preserved urban center, they are considered to make a comparison to the large modernized area of the same city and reveal the difference of urban morphology for these two areas.

Street connectivity of axial lines is the focused factor to uncover the hierarchical patterns of different urban styles. The aim of this study is to make topological analysis of previously fortified towns and the cities with well preserved center area and to study the various urban morphologies. This study will uncover the underlying patterns of different urban styles and discuss their universality or find their differences. Small-world, scale-free and community structure could be the characteristics of a network and these properties will also be examined for the study of street network. The hierarchical representation of this study can be used for further city planning, wayfinding and navigation.

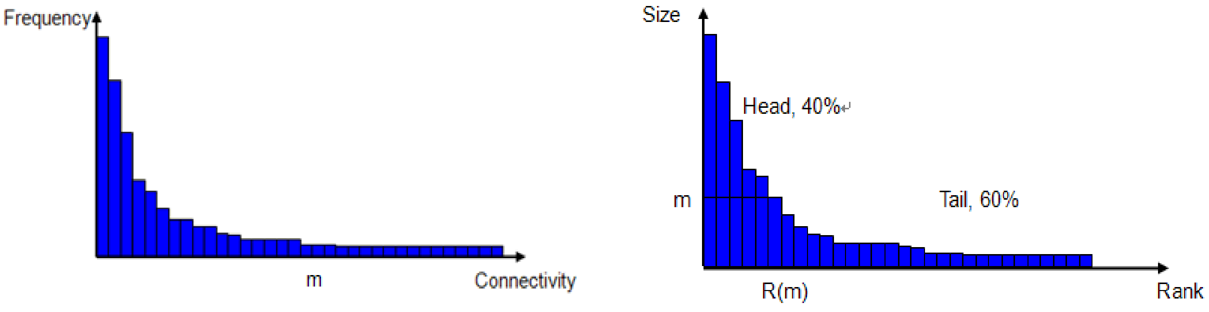
The remainder of this paper is composed of five parts. In section 2, theoretical concepts are described. In section 3 materials and methods for the topological analysis are introduced. The methods are about processing data in ArcGIS, measuring the average path length and clustering coefficient of small-world, examining power-law degree distribution and making community detection. Results of hierarchical patterns of these case studies, measures of small-world and scale-free properties and community detection are showed in section 4. Finally, the study is discussed and concluded in last two sections.

## 2. Theoretical concepts

For this study, there are some theoretical concepts, such as rank-size distribution and head/tail breaks and they are described in this section. Rank-size distribution provides another way to study the frequency events. Head/tail breaks is applied to rank-size distribution to uncover the hierarchal level of an urban street network.

### *2.1 Rank-size distribution*

Rank-size distribution is the distribution that rank numbers are along x-axis and corresponding values are on y-axis. For this study, frequency distribution of street connectivity is converted to rank-size distribution (Figure 1). In rank-size distribution, number 1 represents the lowest frequency event which has largest connectivity value; number 2 represents the second lowest frequency event and so forth. Rank-size distribution has the unbalance that the head part which is above the mean value is minority and the tail part which is below the mean value is majority. To uncover the hierarchical patterns of urban street networks, head/tail breaks is applied to rank-size distribution.




(a) (b)

Figure 1: (a) Frequency distribution and (b) Rank-size distribution

### *2.2 Head/tail breaks*

Head-tail breaks is a classification method for the data and it is used for the rank-size distribution (Jiang, 2012). The head/tail breaks applies the division rule to break the data into two parts. One part is data above the arithmetic mean and another part is data below the man value, as (b) of Figure 2 shown. This breaks method iteratively partition the data with the arithmetic mean value in the head part until the head part is no longer minority or does not follow heavy-tail distribution. For this research, due to the street networks of some cities represented with axial lines do not have obvious hierarchy, the head part is continually partitioned if it is less than 50 % of the whole. Head-tail breaks is used to classify the distribution to uncover hierarchical patterns of this urban morphological study.

With the introduction of rank-size distribution and head/tail breaks, people can generally know the analysis method of this study. By knowing head/tail breaks which is another classification method, the uncovered hierarchical levels will be easy to be understood. There are also some technical terms and they are described in the following text.

## 3. Materials and methods

Street data of seven sample cities or towns were obtained from CloudMade which focuses on the using of OpenStreetMap (OSM) data. VGI is voluntarily distributed by individuals; it includes geographic data creating, assembling and disseminating (Goodchild, 2007) and is widely used now. OSM provides such freely edited and used map data and it offers the way to collect data for specific studies that makes it to be a most useful way for customers (Haklay & Weber, 2008). Some researchers had analyzed the credibility of VGI. A comparative study showed that the quality of VGI could be treated as reaching a good level and the participants that distribute VGI are diligent and committed (Haklay, 2010).

Space syntax is conceived originally by Bill Hillier, Julienne Hanson and their colleagues to help simulating the architectures' social effects, it contains the theories and techniques to analyze the geographic space and it has been used to measure the spatial configuration (Hillier & Hanson, 1984). In other words, syntax is the relationship, and the relationships of small pieces need to be estimated to study the morphology of the geographic space. Spaces are broken down into components and analyzed as networks; here axial map is intended to describe the connectivity of those spaces. Axial map consists of least number of longest visible lines and they have been used to analyze the spatial configuration (Turner, Penn & Hillier, 2005). Axial lines are drawn from the longest one to the shortest one and the lines are made sure that they are interconnected. Now, the axial line is focused on walkability and drivability. Topology of these lines are made to study the spatial configuration and Hillier and Iida (2005) showed that the configuration of urban street network primarily determine the movement flows. Considering the importance of street networks, they are necessary to be analyzed to study the underlying structures. Connectivity is an effective space syntax parameter for uncovering hierarchical levels of the networks.

Besides uncovering the hierarchical levels, an urban street network can be examined to see if it has small-world or scale-free properties and the measures can be applied to make topological analysis. Small-world network is the graph that most nodes which are not neighbors can be connected from every other with a small number of steps. According to two measures: average path length and clustering coefficient, a graph could be examined to see the small-world property and for a small-world network, the separation which is characterized by average path length between any two nodes is very small and the clustering coefficient is a high degree value (Watts and Strogatz, 1998). Scale-free network is the network that the degree distribution fits a power-law distribution. Power-law implies that small events are commonly occurred and large events are rare as the scaling Jiang (2007) uncovered from 40 US cities and it can be seen as a straight line on a log-log plot that both sides of the equation are taking logs. Barabási and Albert (1999) pointed out the emergence of this scaling in random networks that their degree distribution fits a power-law distribution. Jiang and Claramunt (2004) conducted an investigation on the topological analysis of urban street networks and they examined the properties of urban street networks.

In the study of networks, some characteristics such as small-world property, power-law distributions of degree are found to occur commonly and community structure is another common characteristic of the networks (Girvan & Newman, 2002). The street network can be detected to see their communities that with dense connections internally and sparse connections externally. The number of clusters which is the same meaning of communities is a measure to identify how many sub-structures a network is divided. The study of communities can provide insight into the network and detect the network's structure. It can also give a way to find the function of the network and identify how the topology of communities affects each other. This topological analysis of street networks relies on GIS system and it can apply different measures to examine the characteristics of the networks.

ArcGIS with Axwoman extension was used to carry out the topological analysis. Axwoman which is developed by Professor Bin Jiang and his colleagues provides a way to automatically generate axial lines and calculate space syntax parameters. According to the topology of urban street network, the hierarchical pattern of a city will be represented. To examine whether an urban street network is a small-world network or not, two structural features average path length and clustering coefficient were taken into consideration (Watts & Strogatz, 1998). These two parameters could be calculated with Pajek software. The number of clusters of the networks was also calculated in Pajek. MATLAB was used to check if the degree distribution of urban street network fits power-law distribution. Jiang and Claramunt (2004) carried out the similar research about topological analysis on urban street networks.

### *3.1 Processing data in ArcGIS*

The processing steps within ArcGIS are described in this section. The steps include pre-processing street data, building up topology, generating natural roads and axial lines, calculating street connectivity, classifying the data with head/tail breaks. The raw street data gotten from OpenStreetMap needed to be selected with the tool in ArcGIS and only kept the data within the interested area. Street data for fortified garrison towns of Naarden, Neuf Brisach, Palmanova and Philippeville were collected according to the outlines of rampart or moat. Street networks of both well preserved central areas and large modernized areas of Avignon, Hamburg and Amsterdam were prepared separately. The downloaded data from CloudMade were in WGS 84 reference system and an appropriate projected coordinate system should be selected for them to make less geometric distortion. After making map projection, isolated arcs within the raw data which will lead to the stop of processing were deleted.

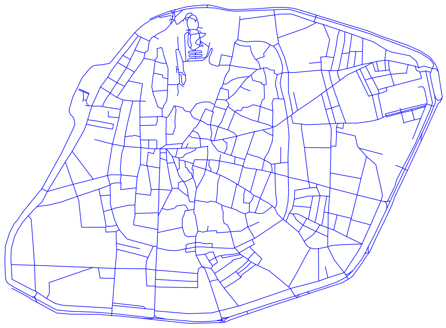
In terms of GIS, chopping arcs at each junction into segments was called building up topology and this step was conducted based on Data Interoperability Tool within ArcGIS. It was done in order to tracking natural roads which are the roads of any cities and exist before transformation by space syntax method. The raw streets were chopped at each junction into segments and decisions would be made at these junctions for generating natural streets (Figure 2).

(a) Streets before building up topology (b) Streets after building up topology

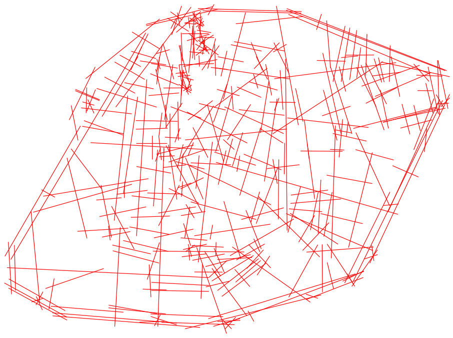
Figure 2: Demonstration of chopped streets at each junction

Natural roads are road segments connected to their adjacent one at the junction with Gestalt principle for good continuation (Jiang, Zhao & Yin, 2008). In ArcGIS with Axwoman extension, the road segments would be automatically joined if the deflection angel between them was within a predefined threshold angle and the process was continuing until there was no adjacent segment or they did not fit the condition. For this study, 45 degree was set as the threshold angle for tracking natural roads.

Tracking natural roads was the previous step for generating axial lines and it was a recursive process. Both steps for generating natural roads and axial lines could be automatically done with Axwoman (Figure 3). Street connectivity, a space syntax parameter was calculated with Axwoman for urban street networks. The connectivity value would show how many streets are connected to this one. The distribution of street connectivity for this study was supposed to be a heavy-tail distribution which has a long tail than normal distribution and usually is skewed towards the right and the distribution would be examined to see if they have scale-free property.



(a) Natural roads



(b) Axial lines

Figure 3: Automatically generated (a) natural roads and (b) axial lines

Head/tail breaks rule was applied to the distribution in order to reveal the hierarchical patterns. The data was portioned into two parts by the mean value. The break was iteratively applied to the head part with the mean value until the distribution was no longer a heavy-tail distribution. After the classification, different hierarchical levels of the street networks were represented. The streets with highest connectivity were showed with red color and streets with lowest connectivity were showed with blue color. By looking at the axial lines with different colors, the underlying urban patterns were clearly recognized.

Axwoman has the function to automatically classify the data with head/tail breaks and it holds the principle that the head part should less than 40%. For this study, some cities did not have obvious hierarchical levels and the head part was greater than 40 % of the whole distribution. About these special cases, they were stilled applied with head/tail breaks and the mean value was used to manually partition the distribution into nominal head and tail parts (Table 1). For manually classifying the data, a criterion was held that if the head part was greater than 50 % of the whole after first break, the partition would be stopped.

Table 1: Head/tail breaks for Avignon city center (Note: # = the number, % = percentage)

| # Axial lines | # In head | % In head | # In tail | Mean value |
|---|---|---|---|---|
| 396 | 156 | 39% | 240 | 5.5 |
| 156 | 57 | 36% | 99 | 8.5 |
| 57 | 19 | 33% | 38 | 12.0 |
| 19 | 8 | 42% | 11 | 15.7 |
| 8 | 3 | 37% | 5 | 18.2 |
| 3 | 1 | 33% | 2 | 21.3 |

### *3.2 Measuring small-world and scale-free properties*

Small-world network is network with a small separation globally and highly clustered locally. Average path length and clustering coefficient of urban street networks could be calculated as vectors in Pajek and according to the measures, urban street networks would be examined to see if they have small-world properties. For comparison, these two measures were calculated for a random graph which has the same degree per vertex and same number of nodes. $L_{random}$=ln $n$/ ln$\overline{m}$, $C^{1}{}_{random}$= $\overline{m}$ / $n$, where $\overline{m}$ is the mean value of degree and $n$ is the total number of vertices.

Besides small-world property, an urban street network could also be analyzed to examine if it is scale-free network. There are different types of centrality that include degree, closeness and betweenness. Degree is the same as connectivity that used in ArcGIS and it describes the number of links that a node has. Closeness is the measure of distance from one node to all other nodes and betwenness shows the number of times a node is used for any other two nodes as bridge along the shortest paths. These centrality measures were calculated in Pajek and they were used to determine the importance or the status of a node in the graph. The degree distribution was examined to see if it fits a power-law distribution and to check if the urban street network is scale-free network. Closeness and betweenness could also be used to analyze the urban street network and to find the properties of them.

### *3.3 Detecting community structure*

After examining small-world and scale-free properties of street networks, Louvain method was applied to detect if the network has community structure. For a street network with community structure, streets of it can be easily grouped into sets of communities and streets of each community are densely connected internally. Community detection could be done with Pajek software. Multi-Level Coarsening + Multi-Level Refinement algorithm was used to obtain the number of clusters. Modularity is a measure of the network's community structure and high modularity represents that streets of the network are densely connected within communities and sparsely connected in 12 different communities with modularity value 0.76. The streets within the same community would be assigned the same number. These obtained communities were represented with different color in ArcGIS. Took Avignon as an example, the number of clusters was 12 and these communities were represented with twelve different colors (Figure 4).

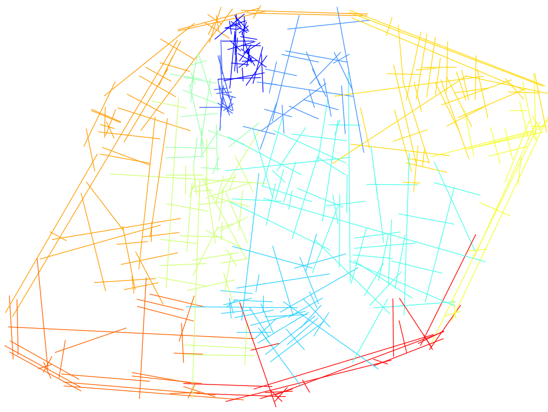


Figure 4: Twelve communities for the street network of preserved Avignon center

## 4. Results and discussion

### *4.1 Hierarchical levels of fortified towns, preserved and modernized city areas*

For the sample data, two groups were made. One group included the cities that have well preserved center area. The urban morphology of the preserved city center was compared to its modernized area. The comparisons within this group were made between two different urban types of the same city. The results showed that the hierarchical level of preserved Avignon center was 7 and it was the same as large modernized area. The number of hierarchical levels for preserved city center of Hamburg and Amsterdam were 7 and 8 respectively and the number for both the two cities' large modernized areas was 9 (Table 2, Appendix A). For this study, head/tail breaks was not strictly applied. About some cases, the head part was continually classified even though it was not less than 40 %, but the classification stopped if the head part was more than 50 %.

Table 2: Head/tail breaks for preserved city center of Amsterdam (Note: # = the number, % = percentage)

| # Axial lines | # In head | % In head | # In tail | Mean value |
|---|---|---|---|---|
| 1 101 | 361 | 32% | 740 | 7.1 |
| 361 | 131 | 36% | 230 | 13.1 |
| 131 | 49 | 37% | 82 | 18.9 |
| 49 | 21 | 42% | 28 | 24.7 |
| 21 | 8 | 38% | 13 | 29.6 |
| 8 | 3 | 37% | 5 | 35.3 |
| 3 | 1 | 33% | 2 | 40.7 |

The other group contained these fortified towns which have geometrically regular outlines. The fortified garrison towns which had urban defensive systems with bastions and moats at Renaissance time have regular layouts. These areas retain their outlines and keep the geometry and streets are relatively orderly distributed. It was found that the hierarchical levels of Naarden, Neuf Brisach, Philippeville was 4 and Palmanova had 5 hierarchical levels. For Neuf Brisach and Philippeville, the head parts of their connectivity rank-size distribution were not minority and they were greater than 40 % of the whole at the first partition. In fact, they were still manually classified with head/tail breaks in order to uncover the hierarchy (Table 3).

Table 3: Head/tail breaks of Philippeville (Note: # = the number, % = percentage)

| # Axial lines | # In head | % In head | # In tail | Mean value |
|---|---|---|---|---|
| 36 | 17 | 47% | 19 | 3.8 |
| 17 | 5 | 29% | 12 | 5.2 |
| 5 | 2 | 40% | 3 | 6.8 |

After classifying the street data with head/tail breaks, the hierarchical patterns of different urban street networks could be uncovered through ArcGIS. For this study, streets with highest connectivity were represented with red color and streets with lowest connectivity were represented with blue color (Figure 5, Figure 6). The results clearly showed to people which streets have highest connectivity and are most important in the network and how many hierarchal levels a city has. The hierarchical patterns provided a perceived way for people to study a city's morphology. It could be seen that streets with highest connectivity were a very small part of the network and it supported the idea that vital streets are minority and few streets can form a backbone of the network (Jiang, 2007). This minority part of streets play an important role for human life and a research showed that the 20 % of top streets accommodate a majority of traffic flow (Jiang, 2009).

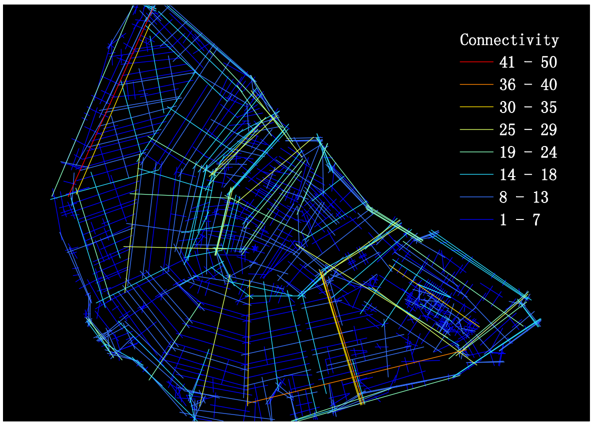



Figure 5: Hierarchical pattern of preserved area of Amsterdam

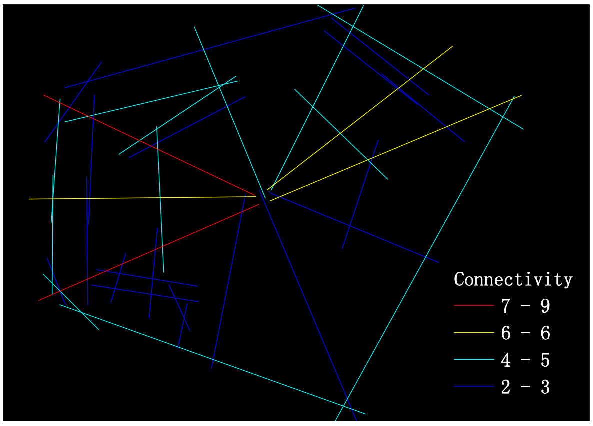



Figure 6: Hierarchical pattern of Philippeville

### *4.2 Small-world property of urban street networks*

After uncovered the hierarchical patterns of the sample data, small-world behaviors of the street networks were evaluated. Average path length and clustering coefficient of two studied groups were calculated as shown in Table 4. The two measures for their random graphs were also calculated in order to make a comparison.

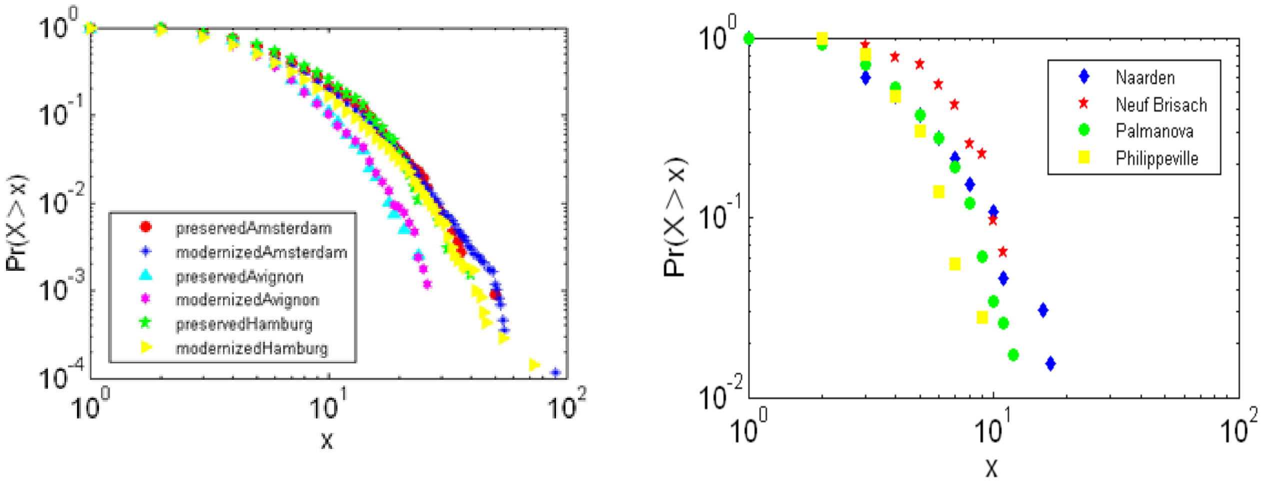
Table 4: Calculation results of the sample areas (Note: # = the number)

| City/Town | # Streets | $\overline{m}$ | $L_{actual}$ | $L_{random}$ | $C^1_{actual}$ | $C^1_{rando}$ |
|---|---|---|---|---|---|---|
| Amsterdam_preserved | 1 101 | 7.1 | 6.14 | 3.57 | 0.2401 | 0.0064 |
| Amsterdam_modernized | 8 562 | 6.6 | 11.10 | 4.78 | 0.2485 | 0.0007 |
| Avignon_preserved | 396 | 5.5 | 5.36 | 3.50 | 0.3069 | 0.0139 |
| Avignon_modernized | 1 692 | 5.3 | 9.35 | 4.48 | 0.2836 | 0.0031 |
| Hamburg_preserved | 653 | 7.3 | 5.21 | 3.26 | 0.3302 | 0.0112 |
| Hamburg_modernized | 7 044 | 6.0 | 11.18 | 4.92 | 0.3140 | 0.0008 |
| Naarden | 65 | 4.5 | 3.71 | 3.19 | 0.2903 | 0.0490 |
| Neuf Brisach | 31 | 6.0 | 2.37 | 3.98 | 0.0903 | 0.1282 |
| Palmanova | 116 | 4.3 | 4.65 | 3.09 | 0.3038 | 0.0266 |
| Philippeville | 36 | 3.8 | 3.42 | 2.91 | 0.3493 | 0.0809 |

The calculated results showed that the urban streets networks have small degree of separation. Besides large modernized areas, the separation characterized by average path length of the sample areas was smaller than 7. For all street networks, the average separation between any two nodes in the random graph was less than 5. All cases displayed the same condition that $C^1_{actual} >> C^1_{random}$ and all the networks were highly clustered locally. These measures returned the fact that these street networks had small-world property.

### *4.3 Distribution of street degree*

Besides small-world property, the urban street networks were analyzed to examine their scale-free property. The degree distribution was check to see if it fits a power-law distribution that follows the equation $y=cx^{-a}$. For the equation, y is the cumulative probability of occurrences of different degree x. Power-law can be seen as a straight line on log-log plot and with a slope –a. Figure 7 showed the log-log plot of the studied cases within two groups. A value p generated in MATLAB was used to check how well the degree distribution fits a power-law distribution or it does not fit. The results showed that p values for modernized area of Amsterdam, preserved city center of Hamburg and modernized area of Hamburg was 0 (Table 5). It meant that these three cases did not have scale-free property and their degree distributions were not power-law distributions. Except the three networks, other street networks had scale-free behavior.




(a) (b)

Figure 7: Log-log plots of the sample data (Note: (a) and (b) show the two groups)

Table 5: Statistical tests of the sample data

| City/Town | $x_{min}$ | a | p |
|---|---|---|---|
| Amsterdam_preserved | 12 | 3.5 | 0.020 |
| Amsterdam_modernized | 13 | 3.5 | 0.000 |
| Avignon_preserved | 6 | 3.5 | 0.458 |
| Avignon_modernized | 7 | 3.5 | 0.068 |
| Hamburg_preserved | 7 | 2.9 | 0.000 |
| Hamburg_modernized | 11 | 3.5 | 0.000 |
| Naarden | 5 | 3.1 | 0.144 |
| Neuf Brisach | 5 | 3.3 | 0.084 |
| Palmanova | 4 | 3.0 | 0.002 |
| Philippeville | 3 | 3.2 | 0.194 |

### *4.4 Community detection*

There would be more connections within each community than between different communities. An urban street network could have several clusters which are the same meaning of communities and these clusters were connected by a few streets. The communities of street networks could be detected by Louvain community detection algorithm. The sample street data were tested respectively to get the number of clusters. This result showed to people how an urban street network was structured and how many communities it had (Table 6, Appendix C).

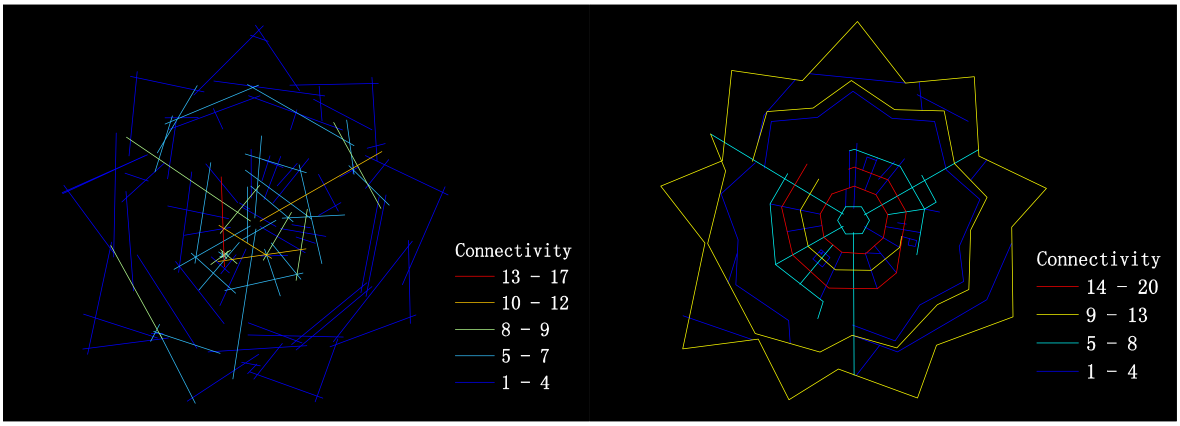
Table 6: Results of community detection
(Note: # = the number, NC = number of communities, Q = modularity)

| City/town | # Axial lines | NC | Q |
|---|---|---|---|
| Amsterdam_preserved | 1101 | 14 | 0.79 |
| Amsterdam_modernized | 8562 | 29 | 0.90 |
| Avignon_preserved | 396 | 12 | 0.76 |
| Avignon_modernized | 1692 | 23 | 0.87 |
| Hamburg_preserved | 653 | 13 | 0.76 |
| Hamburg_modernized | 7044 | 29 | 0.90 |
| Naarden | 65 | 7 | 0.52 |
| Neuf Brisach | 31 | 3 | 0.26 |
| Palmanova | 116 | 9 | 0.68 |
| Philippeville | 36 | 4 | 0.55 |

## 5. Further discussions on the study

By studying the history of Palmanova, it is found that Palmanova was a fortified garrison outpost for Venice's defences, the perimeter of it is a nine-sided polygon and its central square is a regular hexagon (Morris, 1994). Take the regular geometry into consideration, outside streets should encircle the central square in human mind, but from the axial map of Palmanova the ring roads are not regular any more (Figure 8). This result dose not better show a hierarchical pattern of the street network of Palmanova and it does not fit human thinking that the continual streets surrounding central square should be treated as a unit. About this case, another axial map is created manually based on natural roads and axial lines generated from the same ring road are connected (Figure 8). In human perceptual way, the hierarchical pattern of Palmanova is clearer than the previous one and the street with highest connectivity is a ring road while not only the road segments.

From the results, it can be seen that the streets with highest connectivity are very few within street networks no matter for fortified town, preserved city center or modernized city area. The results are not totally conform to the one pointed out by Jiang (2007) that 80 % streets of its street networks have connectivity less than average value and 20 % have connectivity greater than average value. The head/tail breaks for this study does not exactly follow 20/80 principle, but it keeps the idea that vital streets are minority part. There is a special case that the rank-size distribution of street connectivity of Neuf Brisach does not have heavy-tail behavior and the head part is about 55% of the whole at first break (Appendix A). About this case, head/tail break is still applied in order to uncover the hierarchical levels while not only focus on the head part. Another special case is Philippeville and more than 40 % of its streets have connectivity greater than the average value (Table 3). Except the two special cases, this study could reveal that vital streets with larger connectivity are a minority part of whole street networks and trivial streets are majority.




(a) Automatically generated axial lines (b) Manually created axial lines

Figure 8: Original hierarchical pattern of Palmanova and human perceptual pattern

It is found that the fortified towns have a small number of hierarchical levels. One reason could be that there are not so many streets covered these towns and another reason is that streets of the networks do not have obvious differences for their connectivity. The two groups' study shows that fortified town, preserved city centers and modernized large city areas have small-world properties and it supports the idea Jiang and Claramunt (2004) pointed out. Not all the street networks follow the emergence scaling (Barabási & Albert, 1999) that the degree distribution has power-law behavior. One reason for this phenomenon may is a few special streets with largest connectivity which is far greater than the second largest connectivity value exist in the clipped study area and they make the degree distribution does not to be a regular power-law distribution. It can be seen from the left of Figure 9, street represented with red color is only one and its connectivity value is 90 while the second largest connectivity is 55.


Figure 9: Hierarchical pattern of large modernized area of Amsterdam

From the hierarchical representation, people can recognize which streets have high interconnection and could be useful for the choice of their travelling. Özbil, Peponis and Stone (2008) had carried out a research and showed that the configuration of street network is the fundamental factor that affects the pedestrian movement at street level. The underlying structure of geographic space which affects human movement patterns (Jiang, Yin & Zhao, 2009) can be further applied to analyze human movement behaviors. Street networks can govern the use of land (Peponis et al., 2007) and people can consider the position and characteristics of the streets to select their living houses. The hierarchical pattern of urban street networks will be important for people to understand their city from a topological perspective.

## 6. Conclusions

Two groups which include preserved city centers, modernized large city areas and fortified towns are used to carry out a topological analysis of urban street networks. It reveals that vital streets with larger connectivity are minority for street networks. The hierarchical patterns of the sample cities or towns can be uncovered by head/tail breaks. This study does not exactly follow 20/80 principle for classification, for most street networks, streets with their connectivity greater than the average value are less than 40 % and the streets are partitioned into two unbalance parts with average value. This unbalance pattern reveals the underlying structure of urban street networks and it provides a way for human perception. The hierarchical patterns of street networks are uncovered to study the morphology of cities or towns with different structures. The street networks of all the studied cases have small-world property, but three of them do not have the scale-free behavior which only be considered with p value, and all the street networks have their community structure.

From the hierarchical representation of urban street networks, people can find out which streets have relatively large connectivity and will be useful for their path selection. The underlying pattern is useful for people to select a residential area. If they want to have a quite living environment, they should not choose the house near the streets with largest connectivity which is represented with red color in this study. According to the hierarchical pattern, the traffic company can decide to set more stations along the streets that have high interconnection and accommodate more pedestrians. People could also use this pattern to better study their city's morphology.

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## Appendix A

Areas with different structures have different number of hierarchical levels. The statistic results of head-tail breaks for the sample data are showed below. The percentage of head and tail part can also be seen. Note that # = the number, % = the percentage.

Table A 1. Modernized area of Amsterdam

| # Axial lines | # In head | % In head | # In tail | Mean value |
|---|---|---|---|---|
| 8 562 | 3 033 | 35% | 5 529 | 6.6 |
| 3 033 | 977 | 32% | 2 056 | 12.2 |
| 977 | 318 | 32% | 659 | 19.1 |
| 318 | 111 | 35% | 207 | 26.9 |
| 111 | 38 | 34% | 73 | 35.2 |
| 38 | 15 | 39% | 23 | 45.4 |
| 18 | 4 | 22% | 14 | 53.8 |
| 4 | 1 | 25% | 3 | 63.5 |

Table A 2. Modernized area of Avignon

| # Axial lines | # In head | % In head | # In tail | Mean value |
|---|---|---|---|---|
| 1 692 | 609 | 36% | 1 083 | 5.3 |
| 609 | 228 | 37% | 381 | 8.9 |
| 228 | 87 | 38% | 141 | 12.4 |
| 87 | 29 | 33% | 58 | 16.2 |
| 29 | 13 | 45% | 16 | 20.2 |
| 13 | 4 | 31% | 9 | 23.1 |

Table A 3. Preserve area of Hamburg

| # Axial lines | # In head | % In head | # In tail | Mean value |
|---|---|---|---|---|
| 653 | 234 | 36% | 419 | 7.3 |
| 234 | 102 | 44% | 132 | 12.9 |
| 102 | 37 | 36% | 65 | 17.2 |
| 37 | 14 | 38% | 23 | 21.8 |
| 14 | 4 | 29% | 10 | 25.6 |
| 4 | 1 | 25% | 3 | 32.5 |

Table A 4. Modernized area of Hamburg

| # Axial lines | # In head | % In head | # In tail | Mean value |
|---|---|---|---|---|
| 7 044 | 2240 | 32% | 4 804 | 6.0 |
| 2 240 | 768 | 34% | 1 472 | 11.7 |
| 768 | 295 | 38% | 473 | 17.7 |
| 295 | 106 | 36% | 189 | 23.7 |
| 106 | 41 | 39% | 65 | 30.1 |
| 41 | 14 | 34% | 27 | 36.4 |
| 14 | 4 | 29% | 10 | 44.9 |
| 4 | 1 | 25% | 3 | 54.5 |

Table A 5. Naarden

| # Axial lines | # In head | % In head | # In tail | Mean value |
|---|---|---|---|---|
| 65 | 24 | 37% | 41 | 4.5 |
| 24 | 10 | 42% | 14 | 7.9 |
| 10 | 3 | 30% | 7 | 10.8 |

Table A 6. Neuf Brisach

| # Axial lines | # In head | % In head | # In tail | Mean value |
|---|---|---|---|---|
| 31 | 17 | 55% | 14 | 6.0 |
| 17 | 8 | 47% | 9 | 7.9 |
| 8 | 3 | 38% | 5 | 9.5 |

Table A 7. Palmanova

| # Axial lines | # In head | % In head | # In tail | Mean value |
|---|---|---|---|---|
| 116 | 43 | 37% | 73 | 4.3 |
| 43 | 14 | 33% | 29 | 7.1 |
| 14 | 4 | 29% | 10 | 9.5 |
| 4 | 1 | 25% | 3 | 12.5 |

The hierarchical representations of preserved center area and modernized area of Avignon and Hamburg are displayed. The patterns for fortified town Naarden and Neuf Brisach can also be seen from Figure A.1. The number of communities for street network is detected with Pajek. The communities are represented with different colors in ArcGIS (Figure A.2). The sample street networks have different number of communities.

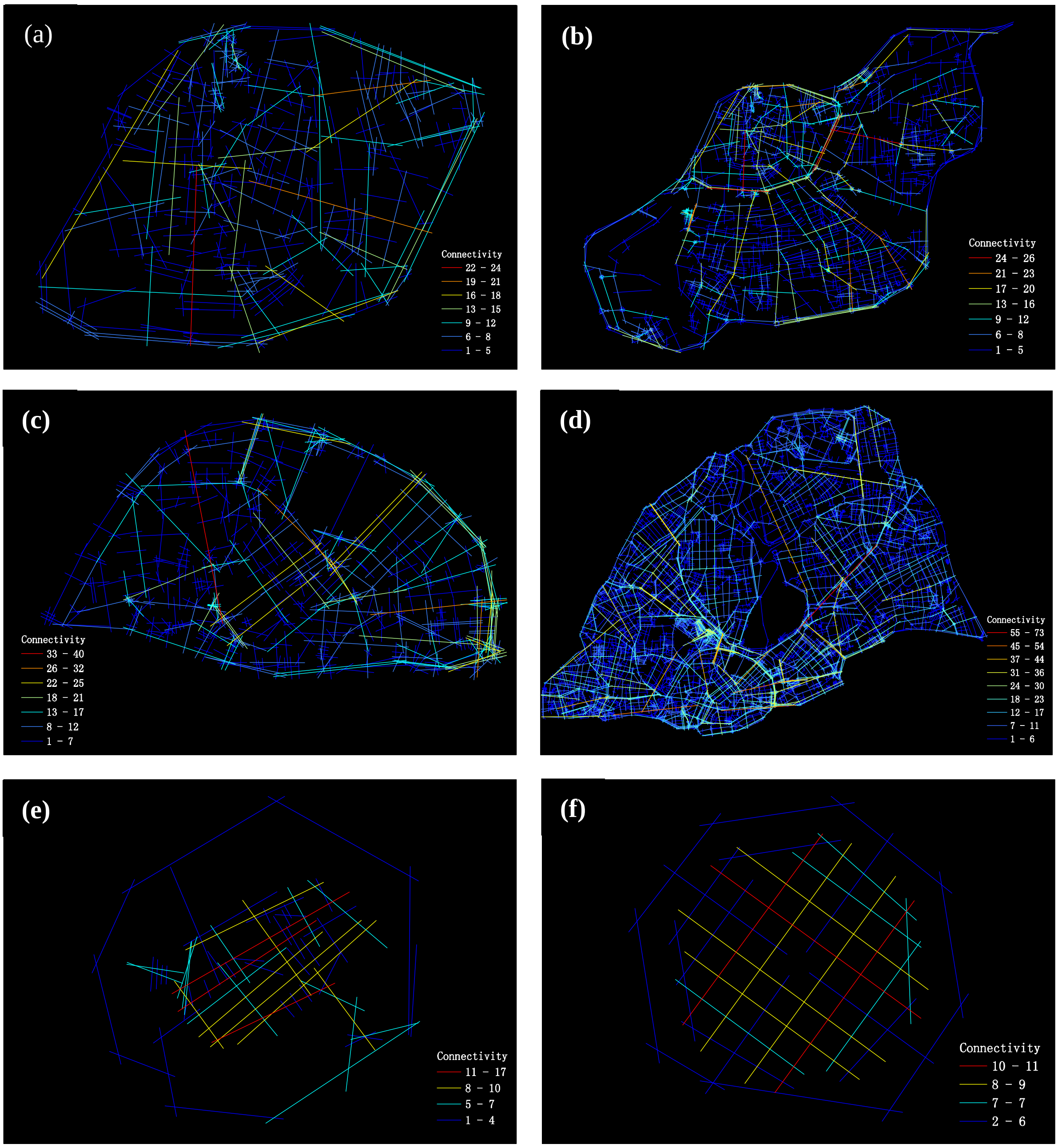
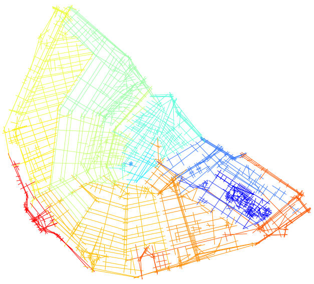
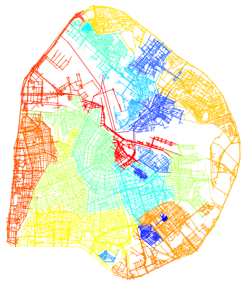


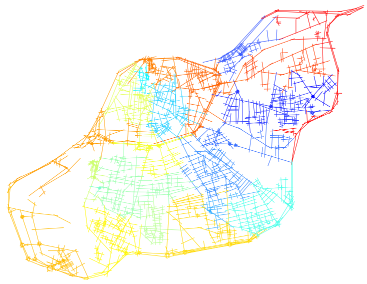

Figure A.1: Hierarchical representation of the sample street networks
(Note: (a) is preserved area of Avignon, (b) is modernized area of Avignon, (c) is preserved area of Hamburg, (d) is modernized area of Hamburg, (e) is Naarden and (f) is Neuf Brisach)



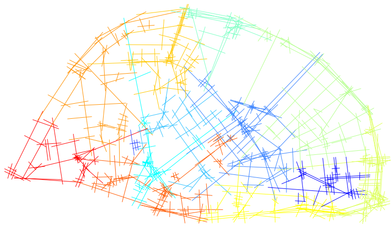
(a) Preserved area of Amsterdam



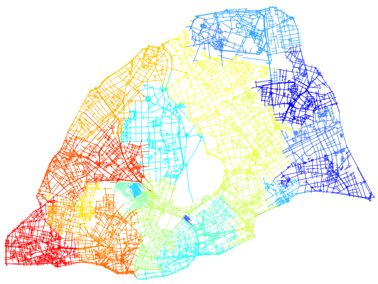
(b) Modernized area of Amsterdam



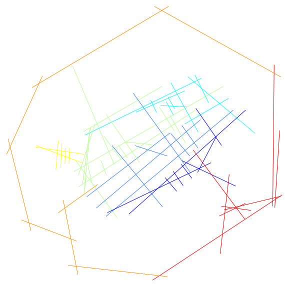
(c) Modernized area of Avignon



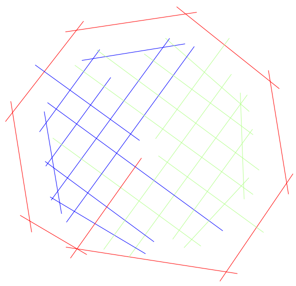
(d) Preserved area of Hamburg



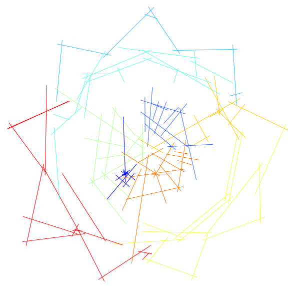
(e) Modernized area of Hamburg



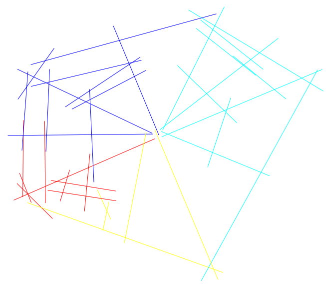
(f) Naarden



(g) Neuf Brisach



(h) Palmanova



(i) Philippeville

Figure A.2: Community detection for the cities

## Appendix B: A short note on the date produced from the study

For this study, two mxd files that contain all the data studied in this paper are generated. The first file, namely hierarchy.mxd, includes ten data frames. There are three data layers under each data frame: axial lines, natural roads and original raw street data. Only the axial lines are visualized by spectral colors, blue being the least connected streets, while red being the most connected ones. Among the ten data frames, six are for the cities which have historical and modernized areas and the four others are for fortified towns. They can be visualized from both the *Data View* and the *Layout View* within ArcGIS.

All data have been set right projection properly before the analysis and computation. The raw street data downloaded from the cloudmade site are with WGS 84 coordinate system. In this study, we chose the projected coordinate system Europe Lambert Conformal Conic, and applied it to the axial lines and natural roads shapefiles. This is the projection for the datasets. On the other hand, we have to choose the same projection for the display. This is done through the *Data Frame Properties*. To focus on the axial line layer, right click the layer and select *Zoom To Layer*.

The second file community.mxd file contains ten data frames, one layer under each data frame. These layers are visualized according to the communities detected for different cities or towns. The colors do not carry significant meanings and they are just used to distinguish different communities. Among the ten unique data frames, six are respectively for the preserved areas and modernized areas, and the four others are for the fortified towns. These layers have been nicely designed in the *Layout View* for producing figures used in the paper.

One issue that needs to be mentioned is that, when you store the .mxd file, you should tick the little box of *Store relative pathnames to data sources* within *File/Map Document Properties.* Both hierarchy.mxd file and community.mxd file contain all the street data studied in this study. Hierarchical patterns of the street networks can be viewed from the Hierarchy.mxd file. Community detection results are visually represented within community.mxd file. Cross check the data files while reading and studying the paper.