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Quantitative Analyses of Street Network Density in Diverse Urban Contexts

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Abstract

Each network graph possesses two kinds of morphological characteristics: the geometric characteristics that consider the size or shape of the graph; and the topologic characteristics that consider the structure or relation of the graph. This paper developed a set of new devices based on network density analysis to quantify and visualize the geometrical characteristics of network layouts. Tow research steps are taken in the analysis approach: the explorative research developed a basic description method, which is named as 'the density gram', while the empirical research applied the method in actual urban network examples, Tianjin in China. The quantitative research of this paper finally provides an effective method for urban researchers and designers to gain an insight into the spatial correlation of urban street networks.

Keywords: street network density, density-gram, geometric properties, quantitative description

Keywords:

Corresponding Author:

Street plays an important role in defining the urban landscape and characterizing the local special identity of cities. To use the words of Kostof, 'Without it (the street), there is no city' (1992:194). Since the writings of some urban researcher, for instance, Lynch, Jacobs and Alexander, streets and street networks have been identified as the most critical element for organizing urban space. During the second part of the 20th century, the needs to be explicit in description of street finally result in an evolution of research method from verbal description to the quantitative devices in the most recent decades. Bill Hillier and associates developed Space Syntax as a method of configurational analysis, which has been applied to the structure of urban street networks. Steven Marshall developed Netgram/Hetgram later and defined the constitution typology of street networks in his book Streets & Patterns (2005). The analysis devices mentioned above provide researchers efficient tools to capture topological properties of the network such as integration or structure-function relations. However, for each street observer, cognition of network layout still requires an account of geometric properties of street networks – for example the street width, the block size or the distance between junctions.

This paper focuses on the geometric properties of urban street networks. It developed a set of new devices based on network density analysis to quantify and visualize the geometrical characteristics of network spatial distribution. Combining two variable of network density - network length density and network area density – allows us to construct a density diagram. By plotting the density values of the street networks, the diagram can help to recognize different types of networks.

The density analysis devices are applied on a real Chinese city example, Tianjin. It is characteristic for its foreign concession districts. The analysis of the city centre represents the fragmentation of street networks due to the different context background of each separate district. The datasets based on quantitative definition of the geometric characteristic of city centre are combined in one diagram to visualize differences of urban districts in spatial distribution.

Just as indicated by Marshall, 'clear prescription first requires adequate description of pattern' (2005: 39). All the density studies in this paper aim to suggest an efficient analysing tool for urban researchers and designers. It will help to gain an insight into the spatial patterns of urban street networks.

Street Network and Network Density

Historically, designing the shape of street networks has always been considered as a main approach to manipulate the settlement form. Either the Greek grid from ancient world or the "Baroque" Diagonal reflects the ambitions of urban planners in urban development. While the practicing on street designing has a long tradition, the systematical study on street networks as a spatial entity was started in the modern period.

Network Density Measurement as a Description of Street Patterns

Last two decades witness the emergence of a series of new quantitative description methods, which can be distinguished from conventional transport quantifying by it's concerning of the spatial experience and urbanism function. Analysis devices such as space syntax and route structure analysis (Marshall, 2001) have been developed to analyse topologic structure of network. By contrast, network density measurement has been applied as an essential method in geometric structure analysis. Giuseppe Borruso (2003) explored a method to delimit the boundaries of city centres by considering the distribution of network density within an urban area. Network density of urban space also been used as a crucial parameters in Meta and Haupt's (2009) density research on urban form.

But two problems arise. First, it seems that there is no standard method to measure the value of network density. In the research of Network Analysis in Geography, Hagget and Chorley take proportion of space occupied by transport channels as an indicator of network density. (1969) By contrast, Meta and Haupt calculate network length per area unit as a measurement of density. Following Borchert's (1960) study of Minneapolis-St. Paul Giuseppe, instead of using length of road per unit, Borruso suggests a method that using point data for the junctions of the urban road network to assess the network density in urban area. Although all of these network density measurements have a kind of correlation with each other, it is unlikely to procedure comparative analysis between the cases applying different network density measurement.Second, the network density measurements are mainly used as tools of illustration of some kinds of urban phenomenon, but have not been system examined as a description parameter of street networks, which are suggested as distinct urban elements by Hiller (2005).

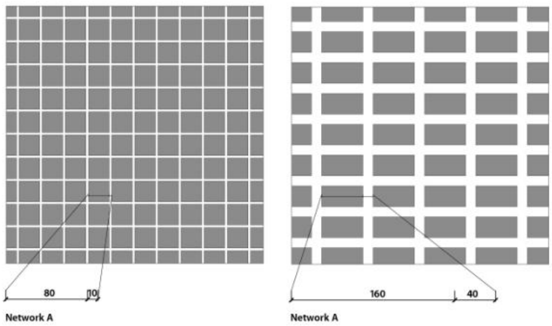
To figure out the problems, it is necessary to dig around the foundations of spatial meanings of network density. Actually, Marshall has suggested a compositional property, which is termed as permeability, as a kind of description of network geometric structures. As defined by Marshall, permeability of networks 'refers to the extent to which a two-dimensional plan area is 'permeated' by accessible space – this relates to distance (circumlocution) and area (available for circulation)' (2005: 89). According to this definition, it is possible to correlate network density measurement with the property of permeability to characterize street networks from the geometric perspective.

Density Indices for Urban Studies

In this study network density is used as the parameter to develop a new instrument in urban network characterising. Marshall's definition of permeability is translated into a density parameter with two variables – network length density and network area density. These provide us a new angle of vision to understand the geometric structure of street system.

Tow research steps – explorative research and empirical research - are taken in the analysis approach. The explorative research generates a basic description method from the comparison between two simplified network prototypes, in which real world constraints and complexities are ignored. The empirical research applied the basic method in actual city examples –as Tianjin in this paper – with considering the influence of all kinds of real-world constraints. By examining the changing uses of the basic method in each unique sample, generic knowledge of characterizing density properties of actual network layouts can be achieved. The combination of both of these research methods provides us a systematic analysis framework.

Figure 1. T*wo Network Prototypes*

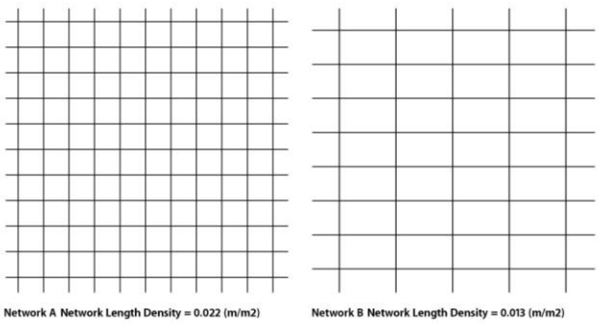


Explorative Research on Network Density Measures

'The critical relationships between the magnitude of the network and its areal environment are expressed in terms of density measures…' (Haggett and Chorley, 1969:74). The methods of network density measurement of urban streets are examined in this section.

Tow simplified orthogonal network prototypes are adopted to illustrate the algorithm of density measurement. The network A is a checkerboardcomposed of square blocks, which measures 80 m on the side. The streets have the uniform width of 10 m. The network B is a gridiron arranged in long narrow blocks, which measures 160m on the long side and 80m on the short side. The streets in network B have the uniform width of 40m. Network A and B both cover an area of 1 Km^2. (Figure 2)

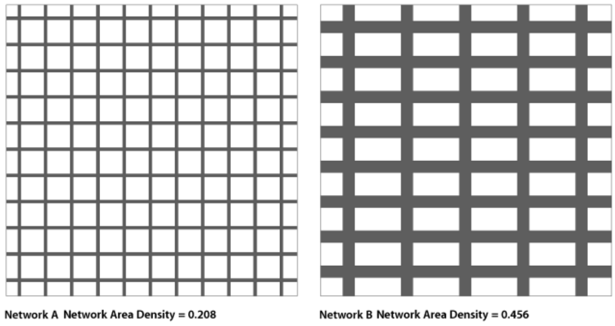
Figure 2. *Network Length Density Calculation for Two Network Sample*



Network density is defined as the amounts of network per area unite. In conventional traffic engineering definition, the network density is usually measured as metres of network (length) per square metres of ground area (surface). The unit of the outcome is metre of network per square metre of unit area. According to the algorithm, we can have the density value of Network A at 0.022 (m/m^2), whereas the value of Network B at 0.013(m/m^2)(Figure 3). '

$N_l = \sum l_x / A$ (1) where
N_l=network length density
Lx=length of the routes
A=area of the district

Figure 3. *Network Area Density Calculation for Two Network Sample*



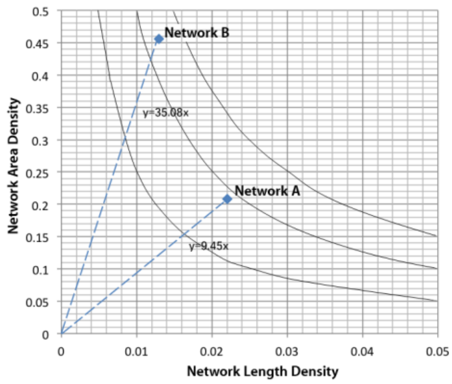
Could the calculation of network length density of Network A and B lead to a definite conclusion that the network density of Network A is higher than B? On the one hand, compared with Network B, Network A possesses finer framework and more routes, which means the network could access to deeper region in a certain zone. On the other hand, the accessible space in Grid B is compensated by its broader street profile. It is impossible to define the permeability of a network by a single variable such as network length density. Therefore, we introduce a second variable-network area density- into the measurement of network density.

The area density of a network is calculated as the sum of the network area divided by the base land area. The outcome of the calculation is the proportion of network area from the unit area, which has no unit followed. As presented in Figure 4, the density value of Network A is 0.208, whereas the value of Grid B is 0.456.

$N_a = An/A$ (2) where
Na=Network area density
An=Area of the network
A=Area of the site

We can project the value of two variables of network density (network length density and network area density) in a coordinate system –the density gram– to reveal the general trends of network open space hidden in the relation between network length and network area. As shown in Figure 5, the x-axis denotes the network length density of the urban layout, while the y-axis denotes the network area density. The data point of the Network A represents a layout of urban plan combined small mesh size with narrow streets, which can be experienced in medieval towns; in contrast, the data point of the Network B represents broad streets layout with large islands filled in the grid, which is commons in modernism urban plan. It is also possible to recognize the spatial properties of permeability of the networks. Since defined as the combination of network length and accessible area, permeability could be measured as the product of network length density and area density. So the hyperbolas shown in the density gram could be considered as the reference lines for comparing the property of permeability. Furthermore, the slopes of the data point represent the approximately value of average street profile width of two networks.

Figure 5. *Network A and B in Density-gram*



Up to now the grid has been treated as a symmetrical grid where the islands are conceptualized as square or rectangular. However, real urban street networks never present street form as regular as the sample networks. The following section will demonstrate the application of network density measurement in two real city samples by using GIS techniques.

Empirical Research in Tianjin

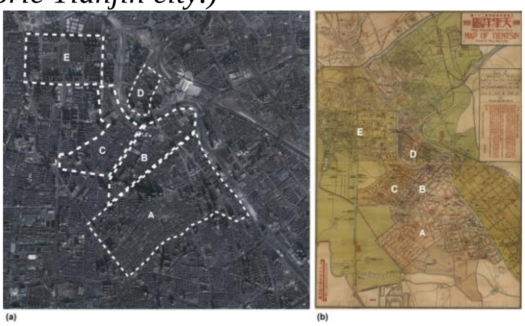
The selection of urban sample, Tianjin, provides various types of street networks. Tianjin is a Chinese city which had 9 historical foreign concessions established successively at the turn of 19th and 20th centuries. At that time period, Chinese government (which was known as Qing dynasty) was forced to permit extraterritoriality for foreign nationals and allowed the foreign concessions territory built up over some cities, such as Tianjin, Shanghai, Hankou, Guangzhou, etc. The first 3 concessions in Tianjin were established 3km east to the historical Tianjin city along the Hai river around 1860s. And after that, other 6 concessions were established during the following 50 years, which made Tianjin possessed the most foreign concessions territory in one city in that period of China. (Table 1) The concession territories, which were constructed mainly under their native culture and planning background, provide extremely diverse urban contexts coexisted with each other.

Table1. *Concessions in China*

	British	French	Japanese	Italian	German	America	Austro-Hungarian	Russian	Belgian	International Settlement
Tianjin	1860-1943	1860-1946	1898-1945	1902-1947	1895-1919	1861-1880	1903-1919	1898-1924	1902-1929	
Shanghai	1845	1849								1863
Xiamen	1852		1899-1945							1902
Hankou	1861-1927	1896	1898-1945		1895-1919			1896-1924		
Guangzhou	1861	1861								
Suzhou			1897-1945							
Hangzhou			1896-1945							
Shashi			1898-1945							
Chongqing			1901-1945							
Fuzhou			1899-1945							
Jiujiang	1861-1927									
Zhenjiang	1861-1929									
Wuhu										1902
Zhifu										1910
Qingdao					1898-1922					

Because of social unrest of China in the first half of the 20th century, not all concessions in Tianjin were fully developed, and the management of some of these concessions were terminated and swift to other foreign nations or to the Chinese government. So in all nine Tianjin concessions, there are four concessions were relatively fully developed and remained in modern Tianjin urban context, which are British concession, French concession, Japanese concession and Italian concession. (Figure 6)

Figure 6. *Foreign concessions and historic Tianjin city in (a) the modern Tianjin urban context (based on Google satellite map) and (b) historic Tianjin city map in 1934 (Tianjin planning & land and resource bureau, 2004:34). (A. British concession; B. French concession; C. Japanese concession; D. Italian concession; E. historic Tianjin city.)*



The development of foreign concessions is terminated after the founding of PRC in 1950s. After that, Tianjin expanded on the basis of original urban area under the centralized planning. In recent three decades after the Chinese economic reform, although been protected by policies, the Tianjin traditional city centre (including four foreign concessions and historical Tianjin city) are still under the pressure of the commercial land development, which made the characteristic urban scape of Tianjin is eroded by the construction.

This research focuses on the traditional Tianjin city centre and the adjacent modern urban district and explores the characteristic spatial pattern of this diversity urban texture. The city area provides us a unique research sample as well as a chance to apply the morphological research in urban conservation.

Method

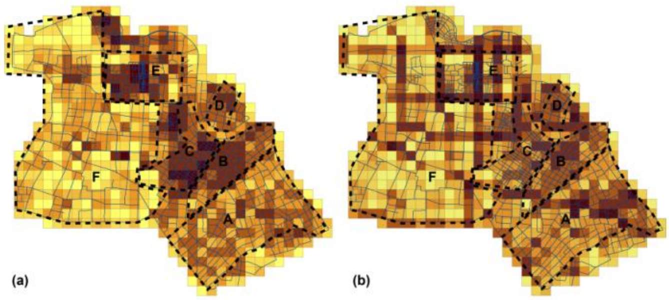
The differentiation between the real network and the network prototype is that the real world never shows homogeneousness. In the complex context of real network layouts, it is not easy for observers to achieve a sense of the whole layout from a certain part of it. According to Bill Hillier, ‘the defining dimension of our experience is of how the parts form a more complex whole’. (2005) A grid-based sample method is implemented to help to build up a relationship between the whole network layout and its differentiated parts. The sample square was used to count the sum of route length and route area in local region to provide a density dataset of whole network. This makes the calculation of network density value easily but remarkable affected by the chosen grid cell size. To gather sufficient information from the network maps at both macro and micro scale, the grid cell size should adapt to the coarseness of networks. In other word, a large size grid mesh should be applied on a coarse network while a small size grid mesh should be applied on a fine network. By considering the scale properties of Tianjin network layouts, a grid mesh of 200m on side was used to sample the urban road network. Similarly, position and orientation of the grid mesh would also affect the calculation results to some extent. But the statistic results of grid-based analysis with different position or orientation would tend to have similar spatial patterns. So the alternation of the position and orientation of the grid meshes would not be further considered in this paper.

GIS technique is introduced in the process of empirical research to assist in computing the length and area data of irregular network routes and to visualize the network spatial distribution subsequently

Network density measurement in Tianjin centre

The grid-based method allows the visualisation of different density value using the cell as a homogeneous means of representation and allows an easy comparison between different density distribution patterns. We can visualize the density value of each square cell over the whole map of Tianjin (Figure 7). A Spectrum from dark brown to bright yellow represents the value of grid cells from relatively high to relatively low either in length density map or in area density map. As can be read from the length density map in Figure 7(a), the street network of Tianjin city centre shows several grade of length density level, which clearly suggests the different characteristics of each urban district. Historic Tianjin city and Japanese concession territory presents the highest network length density in the diagram, which appears as dark brown in their sample grids. The sample grids from France concession represent tan, which means its network length density is lower after the further two urban areas. British concession territory presents as a mixture of light brown and aurantius in the diagram, which suggest a relatively lower length density than other historic district. The Modern urban district mainly appears aurantius and light yellow. It represents the lowest length density area in Tianjin city centre.

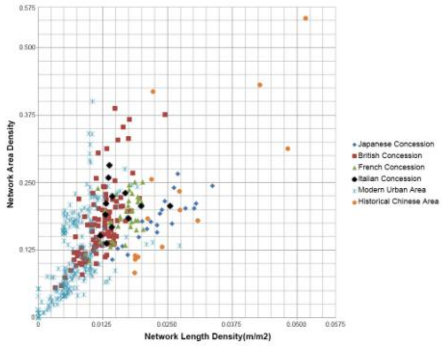
Figure 7. *The density map of Tianjin centre street network. (a) Network length density map; (b) network area density map. (A. British concession; B. French concession; C. Japanese concession; D. Italian concession; E. historic Tianjin city; F. modern city district)*



The area density map of the network of Tianjin city centre demonstrates a different pattern with length density map (Figure 7(b)). It presents an overall differentiation between the historical network and the modern one. The density value of foreign concession areas is higher than modern and historical Chinese areas in general. And it also shows a kind of homogeneity compared to the latters. In contrast, the modern urban area of Tianjin Centre shows extremely heterogeneity in area density measuring. The highest area density grids appear as while as the lowest area density grids in the modern area of the map. It indicates a transit-oriented hierarchy of the modern road network. The primary distribute route would be developed broadly for the high efficiency of the transport, while the access routes and streets are insufficient inside the urban block at local scale.

Figure 8 shows the Density-gram on which the data of each sample cells from city centre of Tianjin network plan is plotted. A wide spread of continuous data sets can be recognized from the gram. The geometry characteristic of the network of Tianjin city centre are demonstrated more specific in the gram. The plots of modern city area spread in the lower left quarter of the gram and spread widely on y axis, which suggests relatively low network length density value (from 0m/m^2 to 0.025m/m^2) and volatile network area density value (from 0 to 0.4). The plots of four foreign concession territories distribute on the different region of the density gram, which suggests their unique characteristic. A little bit righter and higher than the modern urban area, the plots of British concession spread from 0.0025(m/m^2) to 0.025 (m/m^2) along the x-axis and from 0.05 to 0.4 along the y-axis. The plots of Japanese concession spread on the most right area compare to the other concessions, which valued from 0.013(m/m^2) to 0.035 (m/m^2) along the x-axis and from 0.1 to 0.27 along the y-axis. The historical Chinese area distributes mainly in the similar region with the Japanese concession, but some grids of this district show extremely high value of length and area density. The other two concessions, the French and Italian concessions, exhibit density characteristics fall in between the British concession and Japanese concession. The length density of two concessions spread between 0.0125 (m/m^2) and 0.0225 (m/m^2), while the value of network area density spread between 0.125 and 0.275.

Figure 8. *The distribution patterns of network density value in Tianjin*

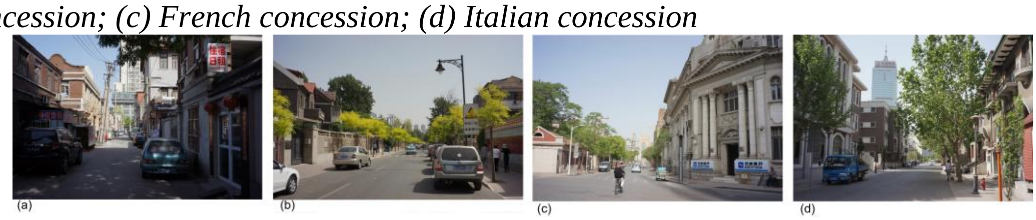


Findings

The network phenomena revealed by the network density analysis to some extent echo the contexts and culture background in which the urban layouts were generated. Although developed in similar era and place with other concessions, Japanese exhibit its oriental concept in urban planning, which lead to a similar geometric characteristic – high density of street network, small scale of streets and blocks - with historical Chinese urban area.

Western concessions represent larger scale of street sections and blocks compared to the Japanese concession. Most typically, the British concession, which is characterized by its residential town house block, is planned and constructed in relatively loose network structure. Streets were retained spaciously and residential buildings are limited under 4 floors. The garden city liked urban landscape of British concession contrast sharply against the narrow streets of Japanese concession. (Figure 9).

Figure 9. *The typical street views of (a) Japanese concession; (b) British concession; (c) French concession; (d) Italian concession*



According to the network density analysis, the modern urban district of Tianjin shows disparate spatial characteristic with the historical urban areas. It represents a kind of highly stratified but incoherent hierarchical system. The different between modern and historical urban network structure lead to spatial discontinuity at the border of urban area, which can be easily read from the network density map. This also made the concession areas, which are surrounded by modern urban districts, are isolated in the core of Tianjin city centre.

Conclusions

This paper has examined the issues related to the geometric characteristics of network layout. A quantitative description device, which is named as density-gram, was created and used to illustrate the density properties of networks. In the density-gram, the network area density and length density are plotted on a simple Cartesian plot. It's possible to use the density-gram to distinguish the geometric statues of a network by recognizing the plotting area of its density data.

A grid-based analysis method is developed subsequently. It builds up the correlation between the single parts and the whole networks. Data derived from each grid cell of the network map can be plotted in the diagram. A spectrum of dataset can thus be seen as the DNA, or spatial fingerprint, of a specific area. This allows us to distinguish the different network layouts with different density-relate properties by recognizing the distinct spectrums of datasets. Moreover, the grid-based analysis method also allows the visualisation of density value over the whole network map and allows an easy comparison between different network layouts.

The application of density analysis in Tianjin city centre reveals the geometrical internal diversity of this urban area. The characteristic of each district are clarified in quantitative ways and visualized on a grid map. And the morphological definition of different urban districts would also provide guidance and assessment criterion for the future conservation and urban renewal in the city. Moreover, the visualization method also illustrates the contradiction between the modern city area and the historical areas (concession districts and historic Tianjin city). It shows an island effect of these areas which are isolated by the modern districts in the core of the city due to the low continuity at the boundary between them. This can explain the dilemma of all these historic districts: on the one hand, only low-income population settle in the districts and endure terrible residential environment; and on the other hand the historic areas lack of commercial vitality and are difficult to establish the sustainable system of redevelopment of historic building resource.

In conclusion, the development of the network density analysis methods is the main result of this research. All of these quantitative devices finally provide us a new description method that is alternative to conventional subjective and qualitative descriptions of network geometric properties. The analysis of the network density would not answer all the question when we trying to characterize an identical urban network layout, but it can be used as a parallel tool of topological depiction method, such as space syntax, to achieve more and precisely properties from existing or future urban environment.

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