The Relationship of the Development Pattern of Urban Environment and the Characteristics of Road Network

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Abstract—A good urban development environment has relation with urban development pattern, and effect the plan of urban land use. Some researches explained the influence of the development of urban land use and transportation, but lack to discuss the relationship of urban form and road network. This paper gridded the data of built-up area first, and defined the boundary of urban area by Local Indicators of Spatial Association (LISA), and used the Area-Weighted Mean Patch Fractal Dimension (AWMPFD) method to measure the form of urban area. The Space Syntax approach was then used to calculate the value of spatial characteristics of road network. Finally, urban forms in southern Taiwan were surveyed, and the result showed that the road configuration had influence on the form of urban area.

Index Terms—urban boundary, space syntax, spatial analysis

I. INTRODUCTION

After the sustainable development being an important concept of urban environment planning, urban form was a vital issue that played a main role on the aspects about the development of urban environment or the urban sprawl. In most research, good patterns of urban space development could increase the vitalities of economic development and the qualities of social environment, and it could reduce the deterioration of the environment also [1].

Urban form was a process that the residents who exercised in urban space gradually [2]-[4]. It was the result of interacting with the land and the transportation network. It was also the form of space performance that the human activities which effected the urban development. The results contained many factors such as: political, economic, community, and cultures. After the sustainable development being an important concept of urban planning, the related research which was line with urban form produce gradually.

In most research, good patterns of urban space development could increase the vitalities of economic development and the qualities of social environment. What’s more, it could restrain not only the deterioration of urban environment but also the conditions of the urban expansion and the urban sprawl. Consequently, urban form was an important issue that played a main role on the aspects about the development of urban environment or the urban sprawl. In the process of urban growth and development, the two most impact factors were transportation supply and the usage of land resources. In the past research, the impact of land use was the factor which was grasped easily. However, both of the definition of urban area and the complexities of road network were the factors which add difficulties to operations on the related research of urban form. As a result, this research was ready to investigate the two issues mainly. This paper tried to provide an operational feasibility of the development model of urban form through the construction of operation systematically.

Review the development of major cities worldwide, human activities and the process of urban cluster were closely connected to the transportation. Many scholars have believed that urban planning should focus on the mutual influence on transport system and land use at first that would define the urban form. The functioning road system had considered to an important factor affecting the substance of the city since the ancient time, it could not only determine the location and size of the city, but also affect the shapes, structures and forms. It also promoted a variety of economic industrial activity to get the best configuration in the region and did the reaction on economic activity or land-use patterns, such as land-use patterns and growth rates, being the key to carry and link every economic and non-economic activity [5]. Therefore, the road network structure was an important factor when we investigated the spatial distribution of urban structure [6], [7]. As the changes of human behavior patterns, the road network structure was becoming more complex. It affected the development of urban forms indirectly.

Therefore, in order to discuss the development of urban form, this study focused on the relationship between road network and urban form in the regional of southern Taiwan. First, this paper used GIS technique to grid the building area in urban, through LISA (Local Indicators of Spatial Association) method removed the inconspicuous building area for defining the urban area, and measured the fractal dimension of urban form by AWMPFD method. Second, to investigate the relationship between road network and urban form, it adopted the theory and method of Space...
Syntax to calculate the characteristics of road network to analyze the relation between the characteristics of road network and urban form. Finally, establish the model of relation between urban form and road network structure through the systematic analysis. This research could provide the reference when urban planning or formulating the land-use strategies in the future as well.

II. URBAN FORM AND URBAN BOUNDARIES

Urban form was formed gradually within residents exercise in urban space, and was also the result of many factors of political, economic, social, environmental and cultural land and under the road network interactions [2]-[4]. In short, urban form was the layout and design of cities that focuses on the development forms of the overall geospatial space [8], [9].

Under the rapid development of city, the structure of urban space had changed: large numbers of people moving into city that urbanization leaded to problems about land supply and demand, thus forcing the development of city spread to the suburbs. These conflicts of urbanization and suburbanization had stepped over the administrative boundaries and had become a subject about development of metro areas. To solve these problems about improving the urban development environment, we should consider how to define the urban range by referencing urban form and integrating the relationships between regional spaces.

Ranging the urban boundaries was an important part because it related to the analysis and results, however, the best way, methods or standards to define the urban gathering boundaries clearly still not be found in current.

Identifying urban boundaries involved analyzing both the functional and the morphological aspects of the human settlement system [10], with the developments of societies and economics, the demands of urban land uses had increased that was the reason why built-up areas continued to expand and spread, and it was also one of the key factors affecting urban form. Therefore, the most elementary feature of settlement forms was the spatial distribution of built-up areas what were more accurately described and characterized [11].

Locations were mutual influence on the spatial structure, but it still existing location differences in geospatial environment. In order to understand the environmental variables of urban development generate diverse influence and change in different geographical space, spatial statistical analysis was used to explore the spatial distribution relationship that could define urban boundaries more precise.

Spatial Autocorrelation Analysis was a spatial statistical method to detect spatial form to present with particularity, was also widely used in urban structure and landscape pattern analysis [12] and other domains. By simultaneously processing location and spatial attribute information, the values of similarity were calculated could describe the degree of similarity between adjacent objects effectively, and assessed the spatial distribution whether exited on some degree of correlation between the phenomenon of spatial aggregation to improve the complex geospatial relationship and realized the different effects of different geospatial generated to define the clustered range of significant region.

The approach was answered the smaller local region adapt an analysis of “local indicators of spatial association (LISA)” for spatial clustering. It indicated the extent of significant spatial clustering of similar values around a given observation, Anselin (1995a) [13] had developed the local Moran statistic, part of a larger set of statistics called local indicators of spatial association (LISA). In addition to testing the significance of spatial clustering, the local Moran statistic could be used in tandem with the so-called Moran scatterplot typology to provide information on the nature of spatial association around any given neighborhood [13], [14]. The Moran scatterplot classified each neighborhood based on whether it was above or below the mean on a variable, Y, yielding the following categories:

1) “low-low” neighborhoods with low (Y is below the mean) levels of Y that were surrounded by neighborhoods with low levels of Y;
2) “low-high” neighborhoods with low levels of Y that were surrounded by neighborhoods with high levels of Y;
3) “high-low” neighborhoods with high levels of Y (Y is above the mean) surrounded by neighborhoods with low levels of Y;
4) “high-high” neighborhoods with high levels of Y that were also surrounded by neighborhoods with high levels of Y.

\[ I_i = \frac{1}{m} \sum W_{ij} (V_i - \overline{V}) (V_j - \overline{V}) \]  

\( I_i \) is the similar values of i; \( W_{ij} \) is locational proximity matrix; \( V_i, V_j \) are the spatial units attributes of i and j; \( \overline{V} \) is the average value of each spatial units; \( m = \sum (V_i - \overline{V})^2 / n \)

III. MEASURING THE FRACTAL DIMENSION OF URBAN FORM

A variety of methods had used to measure the development pattern of urban environment in previous studies, such as density, urban population density, form ratio, compactness ratio, elongation ratio, edge-to-area ratio, complexity, concentration, porosity, scatter, leapfrogging, interspersion and other quantitative indicators to explore; however, although these indicators were correlated with patterns of urban highly, these methods also failed to take into account the variation in a phenomenon depending on the scale of reference [1], [11], [15].

The concepts about spatial structure were taken on Euclidean geometry almost, but the urban structure was the dynamic system that was difficult to describe by the traditional geometric principles of Euclidean. It must find out the characteristics of the inner space first when desired.
to know the chaotic environmental phenomena in city. Since Mandelbrot (1982) [16] introduced the fractal concept in the “geometry of nature”, it had been applied widely to describe various spatial phenomena in urban geography, urban morphology, landscape structure and transportation networks [17], furthermore, the characteristics of urban development structure was not linear but fractal [18]. Therefore, many investigations of fractal for urban environmental had dealt with the analysis of metropolitan areas and are thus conducted at a regional scale, applying the large-scale graph what detailed structure was simplified to measure [10], [19], [20].

The presentation of urban form was formed as patch which was used to be explored on landscape ecology. In order to understand spatial characteristics that utilize the concept of landscape ecology and fractal theory in this study, using Area-Weighted Mean Patch Fractal Dimension (AWMPFD) which was spatial index to measure the patch within urban environment, and adapt the dimension values on behalf of urban form.

\[
AWMPFD = \sum_{i=1}^{n} \sum_{j=1}^{m} \left[ \frac{2 \ln \left( \frac{0.25 P_i}{A} \right)}{\ln \left( \frac{a_{ij}}{A} \right)} \right] 
\]

0.25 is correction coefficient; \( P_i \) is patch’s perimeter (m); \( a_{ij} \) is patch’s area (m\(^2\)); \( n \) is the number of patch; \( \frac{a_{ij}}{A} \) is ratio of patch’s area and total area; \( 1 \leq AWMPFD \leq 2 \).

IV. EXPLORE THE CHARACTERISTICS OF ROAD NETWORK

Urban was a complex system, in order to describe and analyze the characteristics of spatial structure. Hillier and Hanson(1984) [21] developed the research methods of “Space Syntax” what basic concepts were built on the spatial structure and spatial behavior that considered from visual sensory, cognitive distance and accessibility, trying to explain human behavior and social activities with “axial map”. This method transformed spatial elements into dots and lines, using the structure and connective relation of point and line to interpret the spatial characteristics. After converting the physical space into the spatial topology structure illustration which was formed by dots and lines, it could discuss the relationship of relative depth between any structural element and others, so through quantitative analysis by Space Syntax on the road system was able to explain spatial characteristics as accessibility and connectivity in the road network when structural element was road network. Four basic measurable indicators as follows: [22]

A. Global Integration Value, \( R_n \)

Global Integration Value was a regional indicator for measuring the relative values of convenience from the sections of the road network to others. The larger value of \( R_n \) expressed higher accessibility so that this section with high unobstructed would become a public gathering place easily, such as the main road; on the contrary, the lower value expressed lower accessibility where hard to arrive, most of these were the alleys which in edge of the community.

\[
R_n = \frac{D_n}{RA_j} 
\]

\[
RA_j = \frac{(MD_j - MD_{min})}{(MD_{max} - MD_{min})} 
\]

\[
D_n = \frac{2[n \log_2((n + 2)/3) - 1] + 1}{[(n-1)(n-2)]} 
\]

\[
MD_j = \frac{\sum_{j=1}^{k} d_{ij}}{n-1} 
\]

\( R_n \) is Global Integration Value; \( RA_j \) is Relative Asymmetry; \( n \) is spatial quantity; \( D_n \) is relative depth of all spatial quantity; \( MD_j \) is average relative depth; \( d_{ij} \) is minimum of space conversions from i to j.

B. Local Integration Value, \( R_L \)

\( R_L \) and \( R_n \) were measurable indicators to perform accessibility; the value of \( R_n \) was measuring the “global” integration value of this section, and the value of \( R_L \) was measuring the “local” integration value within three nodes in this section.

C. Connectivity, \( CN \)

Connectivity also called the value of connective numbers. It was the locality index to represent the number of connecting with other sections. The value larger represented the breadth of visual permeability higher, the section connected to the road directly more, public usability stronger, and accessibility higher.

\[
CN_i = k 
\]

\( k \) is the number of connective nodes.

D. Control Value, \( C.V. \)

Control value was a locality index that explores the comparison value between a section of road and its connected roads in the road network system. If all control values of weight distribution in every sections were 1, the number of connected sections more, control value of contiguous road sections were also higher. The higher value represented the connected roads of this road section were more dependent or move out of this section.

\[
CV = \frac{1}{k} \sum_{j=1}^{k} C_j 
\]

\( k \) is the number of connective nodes; \( C_j \) is the value of connective of node i

V. CASE STUDY

Southern Taiwan contained 3 countries: Tainan, Kaohsiung and Pingtung where was the earliest developed
region in Taiwan. The forming of land-use and road network in Taiwan were the influencing factors in the history for urban developing, so Southern Taiwan was the more appropriate one than other cities in Taiwan to study.

Therefore, this study explored the situation of the development pattern of urban environment in Southern Taiwan by 2003’s built area data to analyze spatial characteristics to observe the spatial developed structure clearly. The spatial distribution of analysis units in Southern Taiwan referred to the Fig. 1.

Since LISA needed space attribute data to analyze, this study grid the data of built area, considering the urban development and land use suitability related research, the size of squares were 200M * 200M as the unit for LISA analysis (Fig. 3), and calculated the percentage of area occupied as a spatial attribute data (Fig. 4).

In order to investigate whether the built-up area of urban development were relevant of the spatial data’s attribute, this study established the Local Moran Index by LISA method, calculating the Ii index (similar values) to explore each spatial unit contribution for spatial autocorrelation that being the basis for defining the urban development affected area.

A. The LISA of Built Environments

Defining urban boundaries still faced lots of difficulties, as Fig. 2, all of the built-up area were regarded as a single object almost that couldn’t recognize whether the effect existing between A and B or C. Most of this fragment phenomenon caused of private land didn’t be developed, but it was still relevance on spatial development. Therefore, the method which used was Local Indicators of Spatial Association (LISA) to check spatial relationship and exclude no significant ones to designate the urban development area as analysis unit.
Considering the spatial affection on urban development, this study set 500 meters as affected distance between each spatial unit. The results of analysis (Fig. 5) showed that the built area ratio of 100% displayed High-High area mostly, and the transition where connected displayed Low-High and High-Low forming a related range of urban development area, the Low-Low area were non-built-up area of the region mostly, and the fragmented part of the analysis units displayed No significant.

For the analysis of the results of LISA, this study adapted High-High and Low-High transition zone area (Fig. 6) as the principles for defining the urban development range as a basis for urban form measurement.

### C. The Analysis of Spatial Characteristics of Road Network Structure

In this paper, it used the Space Syntax method to calculate the Southern Taiwan’s overall road network system for spatial structural characteristics of road network, such as Global Integration Value, Local Integration Value, Connectivity, and Control Value that the results were shown in Table II.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Numbers</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Integration Value</td>
<td>60449</td>
<td>0.29</td>
<td>1.95</td>
<td>1.17</td>
<td>0.31</td>
</tr>
<tr>
<td>Local Integration Value</td>
<td>60449</td>
<td>0.33</td>
<td>2.42</td>
<td>1.33</td>
<td>0.38</td>
</tr>
<tr>
<td>Connectivity</td>
<td>60449</td>
<td>2</td>
<td>7</td>
<td>3.11</td>
<td>1.07</td>
</tr>
<tr>
<td>Control Value</td>
<td>60449</td>
<td>0.20</td>
<td>2.50</td>
<td>1.01</td>
<td>0.17</td>
</tr>
</tbody>
</table>

According to the spatial characteristics graph, the sections of higher Global Integration Value were concentrated in the downtown area, for example Kaohsiung metropolitan and Tainan city (Fig. 8); the sections of higher Local Integration Value were dispersed in various communities and settlements area (Fig. 9), although the distributions were more chaos, it also could...
identify the communities and settlements where closer the downtown had the higher values; most of sections of higher Connectivity were important traffic junctions as the section of main road (Fig. 10); and the sections of higher Control Value were distributed inner the communities and settlements as the main lanes for residents passing (Fig. 11).

Figure 8. The distribution of the Global Integration Value of space syntax.

Figure 9. The distribution of the Local Integration Value of space syntax.

Figure 10. The distribution of the Connectivity of space syntax.

Figure 11. The distribution of the Control Value of space syntax.
D. The Correlation Analysis between Road Network Characteristics and Urban Form

Multiple regression analysis was adopted in analyzing the relationship of land use and transportation often. Through the analyzing by multiple regressions, it could determine the effects from different spatial characteristics indicators of space syntax to different urban form. As road network changing, the different situations of urban forms could be inferred by regression equation also.

The correlation analysis confirmed the relevance between the urban form and spatial indicators of space syntax. On the basis of roads around the urban environment, the study summed the value of spatial characteristics by Space Syntax calculating and link up with the urban form (Fig. 12), then conducted the correlation analysis with the urban form, the analysis result were shown in the Table III.

![Image](image_url)

**Figure 12.** The relevance between the urban form and spatial attributes of road network.

The results showed that the spatial characteristics indicators of the road network existed the affect relation with the development pattern of urban environment indeed. Through multiple regression analysis, the regression equation was established with the significant variables as follows:

\[
Y = 0.19 + 0.34R_1 + 0.51R_3 + 0.18CV \quad (9)
\]

\[
R^2 = 0.354
\]

where the value in the parenthesis is t value, * is significant at P < 0.1, ** is significant at P < 0.05, *** is significant at P < 0.01.

In equation 9, the Global Integration Value, Local Integration Value and Control Value had direct positive affect the urban form dimension, and the model overall explanation ability is 35.4%.

The degree of urban form dimension in Southern Taiwan was positive correlation with Global Integration Value, as well as it was significant through the 0.01 test of significance level; the Local Integration Value and Control Value just pass the 0.05 test of significance level that relationships were less significant. For urban developing, the place where people moving easily usually had the higher accessibility of overall road network and the higher selectivity of major roads that made the diverse land-use types and urban form.

The Connectivity was no significant in this model because the roads connection were usually happened within urban area, so Connectivity affected urban boundary and urban form dimension less.

![Image](image_url)

**TABLE III: THE DATA OF DEPENDENT VARIABLE AND INDEPENDENT VARIABLE**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Numbers</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWMPPD (Y)</td>
<td>212</td>
<td>1.20</td>
<td>1.54</td>
<td>1.35</td>
<td>0.02</td>
</tr>
<tr>
<td>Global Integration Value</td>
<td>212</td>
<td>0.36</td>
<td>1.54</td>
<td>1.04</td>
<td>0.25</td>
</tr>
<tr>
<td>Local Integration Value</td>
<td>212</td>
<td>0.92</td>
<td>1.81</td>
<td>1.26</td>
<td>0.20</td>
</tr>
<tr>
<td>Connectivity</td>
<td>212</td>
<td>2</td>
<td>4.49</td>
<td>2.92</td>
<td>0.52</td>
</tr>
<tr>
<td>Control Value</td>
<td>212</td>
<td>0.61</td>
<td>1.25</td>
<td>1.01</td>
<td>0.05</td>
</tr>
</tbody>
</table>

VI. RESULT AND CONCLUSION

In summary, there were several conclusions as follows:

In this study, it attempt ed to employ Space syntax to configure the spatial characteristics then explore the correlation analysis with the development pattern of urban environment. It was indeed feasible method to provide a more convenient planning methods and procedures mainly that not only estimated effects circumstances for planned future, but also increased the efficiency for decision-makers or planners.

Combine the relevant database of urban environment with geographic information system (GIS) could process the large and complex geospatial information rapidly and systematically, so that urban planning could be carried out more efficiently.

Investigating the relationship between road network and the urban form was the main purpose in this research. It adopted the view of topology what using the structures of points and line and illustrating the characteristics of road network by link relationships, compared to past studies, Space Syntax emphasized on the visual senses and the concepts of environmental awareness to explore characteristics such as accessibility, connectivity of road network that it fit the human actual spatial behavior and needs more. The analysis of Space Syntax showed that the relevant of accessibility within region and the urban developed environment were high.

REFERENCES


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