Recognize urban spatial hierarchical structure based on overlapping functional region structures

東北大学　非会員　○李　想
東北大学　正会員　福本　潤也

1. Introduction

As government, to manage urban area is not an easy task because it is a complex system. In order to design rational policies, it is necessary to grasp the mechanism of urban system. One of the typical features of urban system is urban spatial structure. The well-known analytical Central Places Theory insists a hierarchical structure for urban system. To recognize urban structure, the first thing is to divide the urban area by setting boundary for different types of administrative units (e.g. CBD, residential area). Functional region is qualified to do the job for it is characterized by high frequency of interaction (e.g. commute). By analyzing different partition of urban area, the hierarchical structure may exist. In this paper, we developed a network based overlapping functional region delineation method which can delineate different size of functional region. The case study shows the hierarchical structure in Tokyo Metropolitan Area.

2. Existing functional region delineation method

Since 1950s, lots of functional region delineation method are proposed and can be classified into two categories[0]: rule base methods and algorithm base methods. Recently, the network based methods which use modularity function have been developed for the concept of functional region is similar with community structure in network. Modularity function approach is popular for it can be easily extended (e.g. for directed or weighted network, detect overlapping regions) and lots of corresponding algorithms are available to use (e.g. high calculation speed, check the robustness). Since the existing methods have different characteristic, none of them can delineate different size of functional region so that it is hard to recognize urban hierarchical structure by using theirs results.

3. Formulation of new method

The new method is developed based on an existing community detection method[0] which takes 4 factors into consideration. (Ⅰ) Add geographical factor in order to require multiple results by one method. (Ⅱ) Allow overlapping structure because functional region may overlap with each other in metropolitan area. (Ⅲ) Generate bipartite commute network[0] to distinct the role of Origin and Destination in order to describe the commuting situation accurately. (Ⅳ) Add similarity factor because units should be formed in same functional regions if they have same role in network.

In the bipartite commute network, each unit i is treated as an agent and can receive utility from functional region. The utility depends on which functional region he belongs to and includes ‘Gain’ and ‘Loss’ two parts.

$$U_i = Gain_i - Loss_i \tag{1}$$

$$Gain_i^O = \frac{1}{2M}\sum_{j\in[D]}(OD_{ij}\cdot\delta(c_i,c_j) - P_{ij}\cdot\left|L_i \cap L_j\right|) + \beta\times[\frac{1}{M}\sum_{\substack{j\in[O]\\ j\neq i}}^{n} C_{ij}^O\delta(c_i,c_j)] \tag{2}$$

In addition, OD_{ij} is the commute number from unit i to j; P_{ij} is the expected commute number from unit i to j; C_{ij} is the similarity between unit i and j (for O units or D units); β is the similarity degree parameter; M is the sum of commute number; c_i is the functional region which i belongs to; δ is the index which judge whether two units i and j belong to same functional region or not; $\left|L_i \cap L_j\right|$ is the number of functional region which both unit i and j belong to.

$$P_{ij} = a_i b_j O_i D_j \exp(-\gamma \bullet TC_{ij}) \tag{3}$$

In addition, $a \& b$ are the normalization parameters; TC_{ij} is the transportation cost; γ is geographical parameter.

$$C_{ij}^O = \frac{1}{N\sigma_i^o\sigma_j^o}\sum_{k\in[D]}(OD_{ik}-\mu_{ik})(OD_{jk}-\mu_{jk}) \tag{4}$$

In addition, σ_i^o is the standard deviation of each unit; μ_{ik} is the average commute number departure from unit i.

キーワード　大都市圏，空間階層構造，オーバーラッピング機能地域
連絡先　〒980-8579　仙台市青葉区荒巻字青葉 6-6-06 人間・環境系教育棟 406 号室　ＴＥＬ022-795-7498

The ‘Gain’ function (2) of O units (the function of D units is similar with (2)) is consisted by two parts, strength of commute pattern and similarity degree. The utility of commute pattern strength is calculated by the modified modularity function[0]. If the modularity value ($OD_{ij}\cdot\delta(c_i,c_j)-P_{ij}\cdot\left|L_i\cap L_j\right|$) between two units is positive, they are willing to stay in the same functional region. On the other side, the similarity degree is calculated by Pearson correlation coefficient (4). Large value means the pairs of unit have similar role in network and willing to form together.

$$Loss_i=(\left|L_i\right|-1)\cdot c \tag{5}$$

In addition, c is the loss function parameter.

The ‘Loss’ function (5) is a linear function which the utility represent the payoff in functional region.

With the certain parameter setting, in each step, units can change the functional region they stay in to increase own utility. In equilibrium, no one can increase anymore and the finial structure is the overlapping functional region structure.

4. Case study

The study area is around Tokyo Metropolitan Area which includes 14 prefectures with 1063 administrative units under 2000 year division. With changing the parameter γ, multiple results are achieved. After checking the robustness[0], 4 functional region structures (A, B, C and D) are elected. The following Figure-1 (yellow means O & D units, dark green means O units, light green means D units) show the results of Tokyo and Saitama Prefecture from A to C (D is same as C) and demonstrates hierarchical structure (Figure-2). The functional region in Saitama is divided into small parts while the large functional region around Tokyo CBD always exists. Both local and long distance commute pattern are grasped.

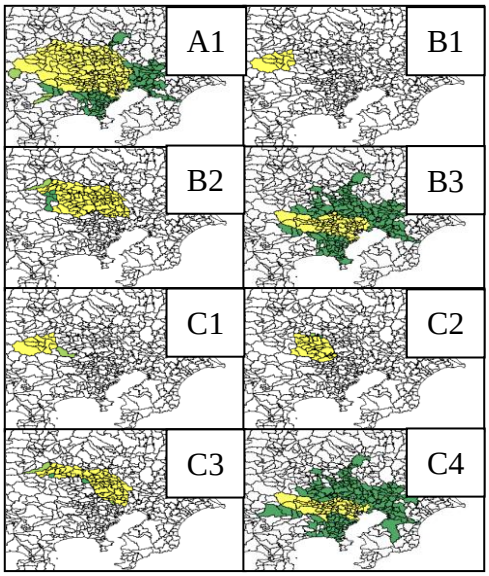

Figure-1 Functional regions

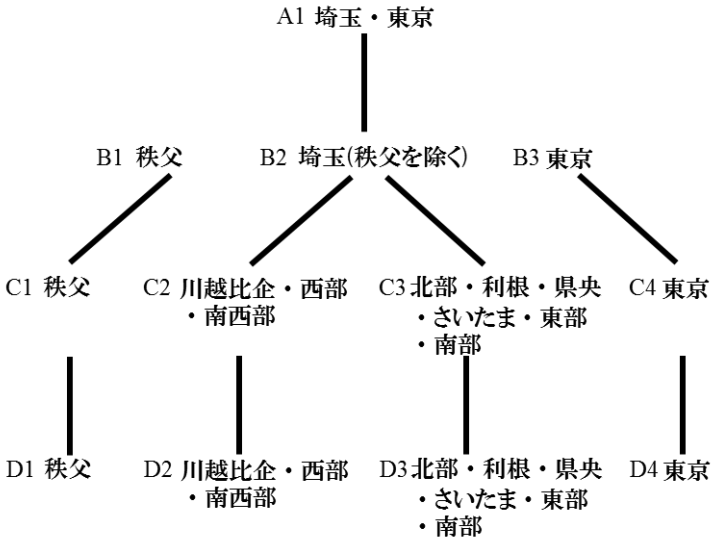

Figure-2 Dendrogram of result in Saitama and Tokyo Prefecture

5. Conclusion

In this paper, we develop a new method which can delineate different size of functional region and then recognize urban hierarchical structure for Tokyo Metropolitan Area. In the future, we want to apply it for whole nation commute network in order to explore the sensitive of new method when facing different size of network.

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