APPLICATION OF FUZZY LOGIC AND TRANSSHIPMENT MODEL TO SPATIAL LOAD FORECASTING

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Abstract: *This paper presents a novel landuse based spatial load forecasting method. Two major improvements have been made for the landuse simulation process, which is the core of spatial load forecasting. Firstly, fuzzy logic technology is applied to address the suitability evaluation problem, then transshipment model is used to produce an optimal landuse allocation scheme. The proposed method has been applied to a real distribution system, and reasonable results have been achieved.*

Keywords: Spatial load forecasting, landuse simulation, suitability evaluation, landuse allocation, fuzzy logic, fuzzy multi-attribute analysis, transshipment model, geographic information system (GIS).

1. INTRODUCTION

The first step toward successful distribution planning is the correct anticipation of load growth which the system is expected to serve. The distribution load forecast must predict not only the future loads, but also their locations, in sufficient geographic detail to allow the planners to locate and size distribution equipment additions such as substations and feeders. During the last decades a broad spectrum of computerized approaches, called spatial load forecasting (SLF), have been developed for accomplishing such forecast, ranging from simple extrapolation-based trending methods to the most complicated landuse simulation based SLF [1-6]. No matter which method is employed, the SLF aims to provide a forecast of spatial load distribution which establishes the loading requirement that long and short range planning must meet [5].

SLF is accomplished by dividing the utility's service territory into a grid of small areas, either uniform or irregularly shaped, and then forecasting future load for each area [1]. The trending methods predict each small area's load by extrapolating its historical load curve into the future, and are only applicable to short-range planning [1,2]. Almost all modern SLF methods for long-rang planning are based on allocation of previously forecasted total system load into a grid of uniform small areas. There are two reasons to do so [1, 2, 6]: 1) Compared with small area load, which seldom exhibits smooth continuous growth, system load is easier to be predicted; 2) Load forecast for distribution system should be consistent with that for transmission and subtransmission system, which are planned on system load forecast.

In order to simulate which kind of customers and how much landuse will be developed in small areas, simulation-based SLF methods divide electric customers into several classes, called landuse classes, according to their load and landuse characteristics [1]. Given typical load curves, landuses can be easily converted into loads, and vice versa. Therefore, the landuse simulation process, which simulates the future development of small areas, is the core of spatial load forecasting [1, 6]. This paper will focus on addressing this process.

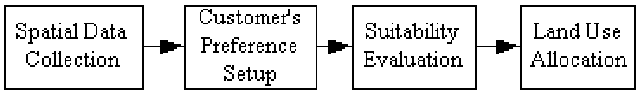

Figure 1. Land Use Simulation Process

As shown in Figure 1, landuse simulation process involves four stages [6]: 1) collecting spatial attributes for each small area, such as distance to urban pole, highway, etc.; 2) setting up each kind of customers' preference and requirement on spatial attributes, for example, industrial sites preferred to be close to highways; 3) evaluating how a small area is suitable to develop some kind of customers by matching small area's attributes against customers' preference and requirement; 4) allocating total landuse forecast to small areas. In the wake of geographic information system, spatial data collection is no longer a major problem. In the second stage, expert knowledge and linguistic descriptions are often used by planners to set up landuse classes' preference on spatial attributes. We are often heard of such kind of expressions as: if a small area is moderately close to highway and urban pole, then it is very suitable for a residential site. Most of these linguistic descriptions such as *close* and *suitable* are fuzzy in nature [3, 4, 6].

In this paper, fuzzy logic technology and transshipment model are applied to address the landuse simulation process. Firstly, we use fuzzy expert systems to simulate each kind of customers' preferences on spatial attributes, which are best to be represented by fuzzy rules. Then fuzzification, inference and defuzzification methods are introduced to produce a "score", which reflects how suitable a small area is for the growth of some kind of landuse. After suitability evaluation process, transshipment model is employed to produce an optimal scheme to allocate total landuse forecast to small areas, so that all small areas make the best uses. The second part of this paper shows landuse simulation process fits well into an application of transshipment model.

The proposed method was tested on a real distribution system in north China, and advantages over traditional ones were demonstrated.

2. MATHEMATICAL FORMULATION OF LANDUSE SIMULATION PROCESS

In order to find other alternatives to deal with landuse simulation process, this section presents a mathematical formulation for spatial load forecasting.

Spatial load forecasting involves a lot of spatial information collected from Geographic information system. Let $\bigcup Layer$ represents a collection of attribute layers in a landuse map *Map*. A rasterization process creates a grid of uniform small areas while collecting spatial attributes $F_{(x,y)}$ with respect to small area *(x, y)*.

$$R(Map(\bigcup Layer)) = F_{(x,y)} \tag{1}$$

From the mathematical point of view, spatial load forecasting problem can be represented as three mappings:

$$F_{(x,y)} \xrightarrow{f_1} L_{(x,y)} \xrightarrow{f_2} S_{(x,y)} \xrightarrow{f_3} S_t \tag{2}$$

Where, f_1 maps spatial attribute $F_{(x,y)}$ to landuses $L_{(x,y)}$, f_2 converts landuses to electric load $S_{(x,y)}$. In SLF, f_2 can be further represented as:

$$f_2 : S_{(x,y)} = \sum_{i=1}^{m} L^i_{(x,y)} \times LC_i = \sum_{i=1}^{m} S^i_{(x,y)} \tag{3}$$

where, *m* is the number of landuse classes, LC_i is the load density of class *i*, $L^i_{(x,y)}$ and $S^i_{(x,y)}$ represents class *i* 's landuses and electric load respectively.

After all small areas' loads are obtained, system load S_t can be calculated by a simple aggregation operator f_3:

$$S_t = f_3(S_{(x,y)}) = \sum_{(x,y)} S_{(x,y)} \tag{4}$$

In equations (3) and (4), f_2 and f_3 are two simple mappings, whose purpose is to convert landuses to electric load. However, f_1 is highly nonlinear, stochastic, spatial and time dependent, and too complicate for us to find an accurate mathematical expression. In fact, f_1 is the landuse simulation process, which can be further formulated as a composition of two other mappings: $f_1 = f_1^{'} \circ f_1^{''}$. Where, $f_1^{'} : F_{(x,y)} \longrightarrow P_{(x,y)}$ maps spatial attributes to preference score $P_{(x,y)}$, and $f_1^{''} : P_{(x,y)} \longrightarrow L_{(x,y)}$ converts preference scores into landuses. It's obvious that $f_1^{'}$ and $f_1^{''}$ correspond to the suitability evaluation and landuse allocation stage, as shown in fig.1, respectively. The key to landuse simulation process is to find these two mappings.

In making landuse decisions, we have to determine which kind of customer will be developed in each small area, and how many. This procedure can be simulated by an optimization model, which seeks an optimal landuse allocation scheme, while subjecting to two major constraints: 1) for each small area, the total landuses summed by landuse classes couldn't exceed the available landuses $L^d_{(x,y)}$; (2) for each landuse class, the total landuses summed by small areas should equal to the previously forecasted total landuses of this class L^i. Thus, landuse allocation stage can be formulated as:

$$\max_{L_{(x,y)}} \sum_{i=1}^{m} \sum_{(x,y)} P^i_{(x,y)} L^i_{(x,y)} \tag{5}$$

Subject to:

$$\sum_{(x,y)} L^i_{(x,y)} = L^i \tag{6}$$

$$\sum_{i=1}^{m} L^i_{(x,y)} \le L^d_{(x,y)} \tag{7}$$

$$P_{(x,y)} = f_1^{'}(F_{(x,y)}) \tag{8}$$

If $f_1^{'}$ is known, substituting $P^i_{(x,y)}$ in equation (5) with (8), the landuse allocation problem will become a transshipment model. Therefore, we can use transshipment model to simulate the allocation stage in landuse simulation process. With $f_1^{''}$ in hand, the only problem remained is to find the mapping $f_1^{'}$, i.e. how to evaluate the suitability of small areas for landuse classes.

Fuzzy logic technology has been widely used as function simulators to deal with problems which are hard to be solved by traditional methods. Here, fuzzy logic is used to simulate $f_1^{'}$, which can be reformulated as:

$$f_1^{'} : F_{(x,y)} \xrightarrow{FuzzyLogic} P_{(x,y)} \tag{9}$$

Through procedures of fuzzification, inference and defuzzification, $f_1^{'}$ produces scores by matching spatial attributes with preference rules, one score for each class.

3. FLOW DIAGRAM OF SPATIAL LOAD FORECASTING

This section presents a flow diagram for spatial load forecasting. As shown in Figure 2, SLF consists of four interrelated modules. In the first module, rasterization divides utility's service territory into a grid of uniform small areas, and categorization distinguishes one landuse class from another according to both landuse and load characteristics. In the second module, end-use load forecast is to provide the future typical load curves of landuse classes, which plays an important role in converting system load forecast to each class's landuse forecast, and in translating landuse decisions to load distribution. As to system load forecast, a variety of forecasting methods can be used. Although all these steps mentioned above are very important in producing correct distribution load forecast, the following sections will concentrate on applications of fuzzy logic technology and transshipment model to landuse simulation process.

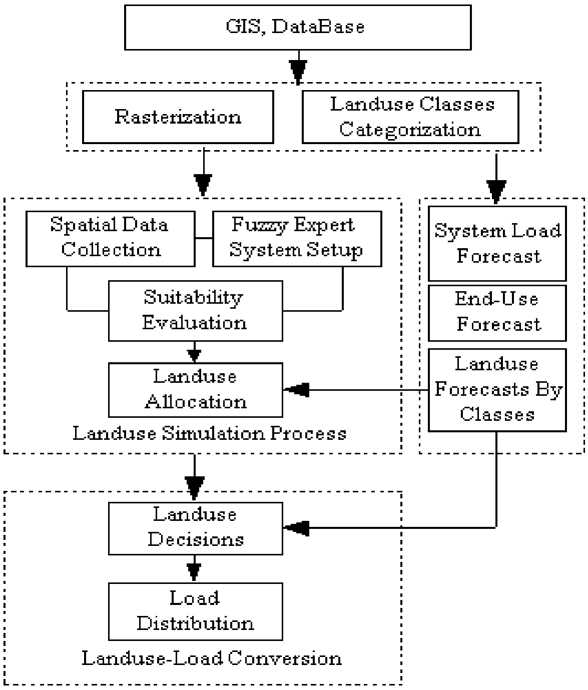

Fig.2 Flow Diagram of SLF

3.1 Example System and Data Preparation

In order to help reading, a real distribution system, located near Beijing, China, is given as an example. At the present time, the system's service area is about 20km^2. The planning area is about 30km^2, including a high-tech zone in the south and another development area in the east. There are no developable areas in the west and north due to geographical, governmental and environmental restrictions. As shown in Figure 5, the service area is divided into 108 small areas, each 0.5km long and 0.5km wide. For simplicity, we classify electric customers into four landuse classes: industrial, commercial, residential and institutional. Spatial attributes are collected from GIS platform for each small area, and grouped into three factors, as shown in Table 1. Local factors are attributes of the small area itself, mostly related to the land's suitability to be built upon in any manner. To have any possibility of development, a small area must have terrain that can be built upon. It must not be precluded from development by law and other factors. Proximity factors measure influences that are mainly a function of distance. Surrounding factor indicates the residential and commercial activities around certain small area. If commerce around a community is over developed and saturated, no business would like to enter.

Table 1. Spatial attributes of small areas

Factor	Spatial Attributes
Local Attributes	Undevelopable areas due to geographic, governmental and environmental restrictions, etc.
Proximity Factor	Distance to highway, road, school, urban pole, district center, etc.
Surrounding Factor	Residential areas within 0.5km and 1.5km, commercial areas within 1.5km, etc.

3.2 Preference Fuzzy Expert System

After spatial data collection, we have to set up preference expert system for each landuse class. In spatial load forecasting, linguistic descriptions are often used to express landuse requirements and preferences. For example, residential customers in Beijing prefer to live near urban, to be close but not too close to road and subway in order for easy traffic but avoiding noise, to be in vicinity of school and marketplace, and in beautiful surroundings. From this example, we can see that suitability evaluation is multi-objective. A community in good surroundings may be far from urban. A compromise is needed to make a final decision.

Table 2 Preference Fuzzy Expert System for Residential Customers

Evaluation Criterion	Weighting Factor	Fuzzy Rules for Evaluation
Distance to urban pole	0.9	VH-SP; H-MP; N-NT; L-MA; VL-SA
Distance to district centers	0.8	VH-SP; H-MP; N-NT; L-MA; VL-SA
Distance to nearest road	0.8	VH-SP; H-MP; N-NT; L-MA; VL-SA
Distance to nearest school	0.8	VH-SP; H-MP; N-NT; L-MA; VL-SA
Residential areas within 0.5km	0.7	VH-SP; H-MP; N-NT; L-MA; VL-SA
Commercial areas within 1.5km	0.7	VH-SP; H-MP; N-NT; L-MA; VL-SA

Notes: VH very high, H high, N Normal, L low, VL very low, SP strongly prefer, P preferred, NT normal, A against, SA Strongly against. Actual meaning depends on which spatial attribute it is being applied to.

In order to make multi-objective decisions, weighting factors with respect to evaluation criteria are set based on the decision-maker's preference. For example, weighting factor 0.9 for "distance to urban" means it is a very important criterion in deciding whether a small area is suitable for residence. Table 2 lists the residential customer's preference rules we used in the example system. The last column of this table presents a set of fuzzy rules used by each criterion. VH-SP is a rule, which means if VH then SP. VH and SP are fuzzy sets, which will be described in the next section.

3.3 Fuzzy Logic Techniques Applied to Landuse Simulation Process

In order to use fuzzy logic technology to solve landuse simulation problem, there are several issues needed to be addressed:

1. How to implement linguistic descriptions such as “close” and “far”?
2. How to evaluate a small area’s spatial attributes against each criterion using fuzzy rules extracted from distribution planner’s knowledge and experience, such as those listed in table 2?
3. How to judge the suitability of small areas by compromising all evaluation criteria, and produce a final preference score?

In this paper, three popular fuzzy logic techniques are used to answer these questions. Membership functions will be used to convert the input values (crisp spatial data) to the linguistic descriptions and membership values. The Mamdani inference is used to aggregate inputs and fuzzy rules. Centroid rule, which is the popular method to perform defuzzification in fuzzy logic, will be used to evaluate the fuzzy output into a crisp one. Fuzzy multi-criteria analysis is employed to give a compromise suitability evaluation. The suitability evaluation process, where fuzzy logic techniques are applied, is shown in Fig.3. For each small area, suitability evaluation is accomplished by judging spatial attributes against each criterion using the min fuzzy inference method, and then doing fuzzy multi-attribute analysis.

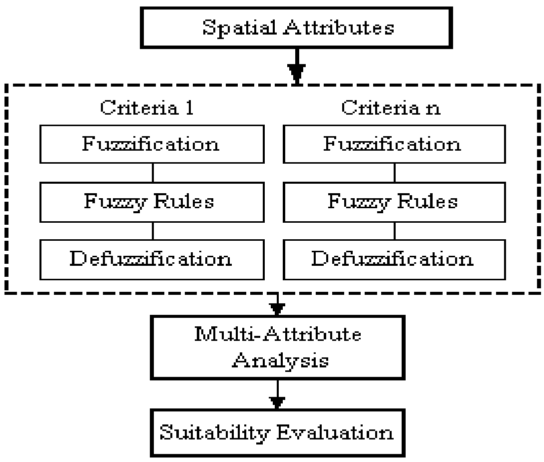

Fig.2 Suitability Evaluation Process

3.3.1 Membership Functions, Fuzzification and Defuzzification

A fuzzy set is a set containing elements that have varying degree of membership in the set. Elements of a fuzzy set are mapped to a universe of *membership values*, usually [0, 1], and is termed *membership function* [3, 4, 7]. In this section, we define five trapezoid fuzzy sets, and use them as a template. As shown in fig.4, not only membership values of fuzzy sets but also universe of discourse are normalized to interval [0, 1]. Using this technique, we don’t have to define as much fuzzy sets as the number of spatial attributes previously defined, five is enough. For example, for “distance to urban”, suppose the universe of discourse is between 0 and 10km, we can still use the fuzzy set template mentioned above to describe fuzzy variables “very close”, “close”, “Normal”, “Far”, “Very Far”, by normalizing [0, 10] to [0, 1].

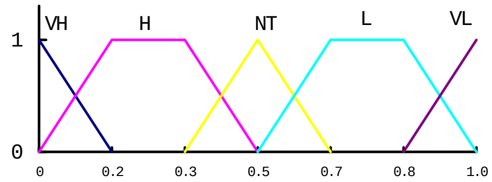

Figure 4 Membership function

Fuzzification process converts actual numerical value (in this case spatial data) to its membership value (fuzzy). For “distance to urban”, a relative value of 0.3 has a membership value 1 for “close to urban”. After the fuzzy inference process, the results should be converted back to actual crisp output (in this case, suitability score) by a process called defuzzification. In this paper, the most prevalent centroid rule approach is adopted.

3.3.2 Min Fuzzy Inference

Min fuzzy inference is a popular approximate reasoning technique, whose purpose is to aggregate fuzzy information and fuzzy rules. Suppose there are 2 rules in a knowledge base, which are described as [8]:

R_1: If x is A_1 and y is B_1, then z is C_1;

R_2: If x is A_2 and y is B_2, then z is C_2;

Where, A_i, B_i and C_i are fuzzy sets, whose meanings depend on where they are applied. Given $x = x_0$ and $y = y_0$, the fuzzy output C' of z can be written in membership form as:

$$\mu_{c'}(w) = \max_i [\min\{\mu_{A_i}(x_0), \mu_{B_i}(y_0), \mu_{Ci}(w)\}] \tag{10}$$

Applying this technique to each criterion’s knowledge base illustrated in table 2, we can obtain a fuzzy suitability evaluation with respect to that criterion. The defuzzification process described in section 3.3.1 will output a crisp suitability value.

3.3.3 Fuzzy Multi-Attribute Analysis

It has become more and more obvious that comparing different ways of action as to their desirability, judging the suitability of products, determining “optimal” solutions in decision problems can in many cases not be done by using a single criterion or a single objective function [7]. As to the landuse simulation process, whether or not a small area is suitable as a residential or commercial sites should be judged by a number of criteria, such as proximity and surrounding factors. Fuzzy multi-attribute analysis, which concentrates on decision making with several criteria, is applied in this paper to aggregate single-criterion evaluation results obtained by fuzzy inference technique described in 3.3.1 and 3.3.2.

Recalling the fuzzy expert system illustrated in table 2, let w_i denote the weighting factor with respect to criterion i, o_i denote the single-criteria judgement with respect to criterion i. The multi-criteria evaluation can be written as:

$$\mathrm{E} = min[\underset{\mathrm{i}}{max}\{1 - \mathrm{w_i}, \mathrm{o_i}\}] \qquad (11)$$

Where, E is the final multi-criteria evaluation, w_i acts as a threshold to let unimportant criteria have less effect on judgement.

Using table 2 as an example, there are six criteria in judging small area's suitability for residence. We use small area 55 in our example system to illustrate the process of multi-attribute analysis, as shown in Table 3.

Table 3. Example for Fuzzy Multi-Attribute Analysis

Criteria	Weight Factor	Spatial Data	o_i	$max(1-\mathrm{w_i}, \mathrm{o_i})$
1	0.9	0.27	0.75	0.75
2	0.8	0.10	0.77	0.77
3	0.8	0.30	0.75	0.74
4	0.8	0.40	0.65	0.75
5	0.7	0.65	0.70	0.70
6	0.7	0.94	0.81	0.81
Multi-criteria suitability				0.70

3.4 Landuse Allocation Decision Using Transshipment Model

The last step of landuse simulation process is the landuse allocation stage. This stage involves the allocation of previously forecasted landuses to small areas according to scores obtained at the suitability evaluation stage. In order to illustrate how well transshipment model fits into a landuse allocation decision, we make the following list (table 4), where r_{ij} is the suitability score of small area i with respect to landuse class j. From table 4, we can easily see that the following optimization model [9] is applicable to the landuse allocation stage.

$$Max \sum \sum x_{ij} r_{ij} \qquad (12)$$

Subject to:

$$\sum_j x_{ij} \le a_i \quad \sum_i x_{ij} = b_i \quad x_{ij} \ge 0 \qquad (13)$$

Where x_{ij} is the landuse allocated to small area i with respect to landuse j, and is a decision variable.

The proposed model is exactly an imbalance transshipment model. Using suitability score as "prices", developable areas as "capacity" and landuse forecast as "requirement", the optimal landuse allocation problem can be easily solved.

By contrast, the traditional methods in literature [1, 2, 5] solve this problem by allocating landuses to high-scored areas for each class until all the forecasted landuses are allocated. Study shows that the allocation scheme given by this kind of allocation methods is equivalent to the initial solution obtained by *northwest corner rule* in transshipment model [9]. Obviously, transshipment model gives more reasonable results.

Table 4 Transshipment model applied to optimal landuse allocation stage

Class / Site	IND	COM	INS	RES	DA
1	r_{11}	r_{12}	r_{13}	r_{14}	a_1
2	r_{21}	r_{22}	r_{23}	r_{24}	a_2
3	r_{31}	r_{32}	r_{33}	r_{34}	a_3
4	r_{41}	r_{42}	r_{43}	r_{44}	a_4
LF	b_1	b_2	b_3	b_4	

Notes: IND industrial; COM commercial; INS institutional; RES residential; DA developable areas; LF landuse forecast by classes

3.5 Load forecasts for the example system

The proposed method has been applied to the example system to predict the load distribution of future 13 years. In order to do multi-stage distribution planning, the forecast is done in three stages, i.e. year of 2000, 2005 and 2010. Besides, the authors believe that this stage-by-stage forecasting style is more suitable for spatial load forecasting. The load distributions, as shown in Figure 5, clearly demonstrate the load growth process, both spatially and temporally.

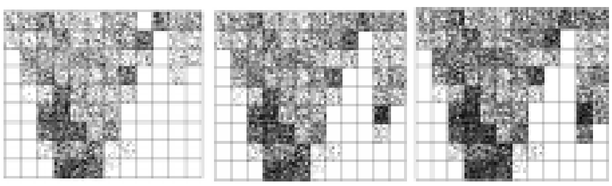

Figure 5. Load distribution for year of 2000, 2005 and 2010

4. CONCLUSIONS

Spatial load forecasting is a fundamental part of distribution system planning. Incorrect forecasts, either wrong magnitudes or wrong locations, will make new substations and right-of-ways acquired at wrong locations, leading to much higher costs.

This paper presents a novel landuse based spatial load forecasting method. Two major improvements have been made for the landuse simulation process, which is the core of spatial load forecasting. Fuzzy logic technology is applied to address the suitability evaluation problem, and transshipment model is used to produce an optimal landuse allocation scheme. The proposed method has been applied to a real distribution system in Beijing, and reasonable results have been achieved.

This paper also have put forward a mathematical formulation for spatial load forecasting, which will help SLF researchers find other alternatives to deal with the landuse simulation process. As described in section 2, the key to solve the landuse simulation problem is to find two mappings, which correspond to the suitability evaluation and landuse allocation stage.

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6. BIOGRAPHY

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