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Dear Editor,

Greetings!

Thank you very much for your time and efforts spent in the paper inspection process and we also express our great appreciation to the reviewers for the time they has taken in reviewing our paper as well as the valuable suggestions they offered. The manuscript **“LOCATING URBAN TRANSIT HUBS: A MULTI-CRITERIA MODEL AND CASE STUDY IN CHINA”** (Manuscript No. TEENG-688) has been revised in response to the review comments.

The files attached in this submission include:

- (1) Revised Manuscript;
- (2) Response to Reviewer Comments;
- (3) Copyright Transfer Agreement form signed by the authors;

Regarding to Copyright Transfer Agreement form, I will mail it to ASCE if the original form is required.

Please contact me using the email yueliu1980@gmail.com should you have any problems.

Best Regards.

Yours sincerely,

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LOCATING URBAN TRANSIT HUBS: A MULTI-CRITERIA MODEL AND CASE STUDY IN CHINA

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ABSTRACT: This paper presents a comprehensive model for ranking candidate location plans of multiple urban transit hubs, which can effectively capture various aspects of concerns in the transit hub location planning process, including the overall efficiency of the transit network, the transfer intensity, the proximity to major passenger generators/attractors, the effectiveness of hub service coverage, the compatibility with land use restrictions, and the adaptability to future developable transit concepts. Grounded on an Analytical Hierarchy Process (AHP)-based framework integrated with the fuzzy logic, the proposed model offers the strengths to effectively determine the weights for multiple evaluation criteria, and to synthesize the final score of each candidate plan for comparison. Results from a case study in Suzhou Industrial Park, China reveal that the proposed model offers some promising properties for transportation planners to use in planning of transit hub locations. Comparative studies with respect to different evaluation criteria has further demonstrated the effectiveness of the proposed model in capturing the impacts of different criteria on the decision making process.

CE Database Subject Headings: Transit hub location selection; Multi-criteria decision making; Analytical Hierarchy Process; Fuzzy logic.

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INTRODUCTION

Over the past several decades, contending with traffic congestion has emerged as one of the imperative issues during the process of urbanization in developing countries such as China. Development of a transit-oriented urban transport system has been realized by an increasing number of researchers as one of the most effective and environment-friendly strategies for mitigating congestion. As the essential facility for urban transit systems, the transfer hub functions to provide the switching points for inter-modal flows and to provide seamless pedestrian connections. Properly located transit hubs can significantly improve the effectiveness of the limited transportation resources and the quality of transit services. Therefore, location planning of hubs in transit network has always been the foremost priority and one of the challenging tasks for transportation planners. Despite the tremendous resources invested on the hub network in many mega cities in China, the critical issue of properly selecting those transit hub location plans has not been sufficiently addressed yet.

Locating urban transit hubs

In view of the literature, most previous studies on this subject have focused on selecting the location of a single inter-modal passenger transfer facility with the pioneering works dated back to the 1970's (Demetsky et al., 1976; Demetsky et al., 1977; TRB, 1974). Since then, key issues, technologies, experiences and priorities on developing selection criteria have been shifted and evolved. For instance, Horowitz and Thompson (1995) constructed a list of 70 generic objectives for evaluation of an intermodal passenger transfer facility after extensive literature review and interviews with users. They found that safety, security, and ease of transferring were among the highest-ranked transit agency objectives. On the other hand, Seneviratne (1995) proposed a set of quantitative criteria, including availability, reliability, accessibility and productivity to measure the efficiency of intermodal terminal performance. Nevertheless, one still needs to properly determine the weighting factors attached to each of those evaluation criteria.

In contending with this critical issue, Rosenberg and Esnard (2008) applied a hybrid scoring method to evaluate six candidate transfer station sites, and a recent study by Wey and Chang (2009) developed a hybrid analytical hierarchy process (AHP) - data envelopment analysis (DEA) method to conduct comparative location study for the joint development station of a mass rapid transit system. In addition, Smart et al. (2009) examined the performance of transit stops and stations from a transit agency's perspective. In their research, a sophisticated nonparametric

ranking method was employed through an online survey of U.S. transit systems to estimate the magnitudes viewed by managers regarding to importance of an array of attributes associated with the stop/station.

Despite the significant progress in the location selection of a single intermodal passenger transfer facility, few efforts have been devoted to selecting option plans of multiple urban transit hubs in the network-wide context based on multi-criteria. In the real-world applications, planners and engineers usually need to take into account a number of critical factors associated with urban transit hub location planning (e.g. how efficient are those hubs to produce high-quality transfer services, how convenient are other types of transportation modes to access those hubs, how adaptable are those hubs to future developable transit concepts, and etc) to ensure that they can successfully achieve an efficient utilization of the limited transportation resources. However, there lacks an effective tool in practice that can assist planners to capture all above contributory factors and assess their comprehensive impacts.

The AHP

AHP, a subjective method for multi-criteria decision-making process introduced by Saaty (1980), has been commonly used in facility location studies (Min, 1994; Wey and Chang, 2009; Yang et al., 2000). However, the following critical issues deserved further investigation during the application of AHP, which are: 1) how to handle the very unbalanced scale of judgment, 2) how to properly construct the pair-wise comparison matrix subject to the biased impacts from the subjective judgment, selection and preference of decision-makers. In view of the literature, the most commonly used approach for constructing the pair-wise comparison matrix in the AHP is to rely on the knowledge of specialists, which may sometimes result in arbitrary and biased decisions. In estimating the weights for all criteria, eigenvalue method (Saaty, 1980; Golden et al., 1989), logarithmic least squares method (Bryson, 1995; Yu, 2002), the geometric mean method (Sudhakar and Shrestha, 2003), and linear programming methods (Chandran et al., 2005; Wang et al., 2008) have all been widely used. However, due to the vagueness and uncertainty on judgments of the decision-maker(s), the crisp pair wise comparison by the aforementioned methods in the conventional AHP still remains insufficient and imprecise to capture the right judgments of decision-maker(s). In order to model such uncertainty in human preference, fuzzy sets could be integrated with the pair-wise comparison which enables a more accurate description of the decision making process. Recent studies (Jin et al., 2004; Ayağ and Özdemir, 2006) have yielded promising results by integrating the fuzzy logic with the AHP to conduct pair-wise comparisons. Along the line of previous research, this study aims to enhance the fuzzy-AHP

model by developing a non-linear optimization formulation to maximize the consistency in pair-wise comparison and weight estimation.

The research objective

The proposed approach has the potential to capture all the contributory factors for planning of the urban transit hub locations, and offer the basis for planners to assess and refine the planning results. The paper will focus on the following critical research tasks:

- Construct a set of comprehensive evaluation criteria related to a broad range of transit hub location planning concerns, including 1) the overall efficiency of the transit network, 2) the transfer intensity in the transit network, 3) the proximity to the major passenger generators/attractors, 4) the effectiveness of hub service coverage, 5) the compatibility with land use restrictions, and 6) the adaptability to future developable transit concepts;
- Propose a robust model to tackle the multi-criteria decision problem, which features the integration of the fuzzy logic with a hierarchical AHP structure to: 1) normalize the scales of different evaluation indicators, 2) construct the matrix of pair-wise comparisons with fuzzy set, 3) optimize the weight of each criterion with a non-linear programming model, and 4) synthesize the final score for evaluating each of the candidate transit hub location plans; and
- Illustrate the proposed model through an example case to assist planners in best understanding and applying the proposed model.

DEVELOPMENT OF LOCATION SELECTION CRITERIA

In planning of urban transit hub locations, one needs to take into account the concerns of all potential stakeholders, including transportation planners, system users, federal/state department policy makers, public transportation associations, and local level implementing agencies. As the priority may vary with different stakeholders, such a decision-making problem generally has no solution to concurrently satisfy all criteria. Thus, the multi-attribute decision process employed in this paper shall be a desirable method.

After extensive literature review and collecting feedback from different stakeholders in China, this study has constructed a list of evaluation criteria associated with various aspects of the planning for urban transit hub locations. A detailed description for each of these criteria is given below.

Criterion-1: Efficiency C_E

The overall efficiency of a transit hub network is one of the most critical factors to be taken into account during the hub location planning process. In this study, the demand-weighted average travel time is employed as the criterion for evaluating the overall transport efficiency of a transit hub network with the following equation:

$$C_E = \sum_{i \in N} \sum_{j \in N} (t_{ij} * w_{ij}) / \sum_{i \in N} \sum_{j \in N} w_{ij} \quad (1)$$

Where, C_E = the transport efficiency criterion (unit: min); N = the set of demand origins or destinations; i, j = index of the origins/destinations; t_{ij} = travel time from i to j (either directly or via hubs, unit: min), and w_{ij} = transit flows from i to j (unit: trips). Note that, the lower C_E is, the more efficient the transit hub network is.

Criterion-2: Transfer Intensity C_T

From the perspective of system planners, passenger transfer activity shall be encouraged since it helps maximize the economies of network scale and utilize the corresponding transportation resources efficiently. However, passengers usually prefer non-stop paths between the origins and destinations due to the transfer inconvenience (e.g., extra transfer walking time and unreliable waiting time). In this study, an index of transfer intensity by the Urban Road Transportation Planning and Design Standard (1995), given by Eq. (2a), is employed to measure the intensity of transfer activities within the given transit network. Depending on the travelers' behavioral patterns and the network structure, there usually exists an ideal level of transfer intensity at which the interests between the system planners and passengers can be best balanced.

Therefore, the discrepancy between the actual and ideal transfer intensity level of a transit hub network is designated as the criterion for evaluating the location planning, as is given by Eq. (2b).

$$TI = \sum_{i \in N} \sum_{j \in N} (w_{ij} + w_{ij}^T) / w_{ij} \quad (2a)$$

$$C_T = |TI - TI_o| \quad (2b)$$

Where, C_T = the transfer intensity criterion; w_{ij}^T = transfer transit flows from i to j (unit: trips); w_{ij} = transit flows from i to j (unit: trips); and TI_o = the ideal value of transfer intensity. Note that, the lower C_T is, the more desirable transfer intensity a transit hub network has.

Criterion-3: Proximity C_p

Proximity, in this study, refers to the closeness of transit transfer hubs to different types of major passenger generators/attractors, including: (1) multi-modal connection facilities (e.g., public parking garages, train/airport/harbor terminals); (2) business districts (e.g., high-rise business buildings, government buildings, and courthouse districts); (3) entertainment areas (e.g., entertainment plazas, shopping malls, and public parks); and (4) residential areas (e.g., high-density residential apartments). According to the guidelines by American Planning Association (2006), a 0.4km radial ring surrounding the transit hub is considered as proximity since it is within a reasonable walking distance. Therefore, this study has developed the following criterion to evaluate the proximity attribute of the transit hub network:

$$C_p = \sum_{k \in K} w_k * n_k^a / \sum_{k \in K} w_k \quad (3)$$

Eq. (3) represents the flow-weighted average number of generators/attractors within the proximity of a transit hub, where C_p = the proximity criterion (unit: # of generators/attractors); k = index of the transit transfer hubs; K = the set of transit transfer hubs; w_k = the total passenger flows accessing hub k (unit: trips); and n_k^a = the number of passenger generators/attractors within the 0.4km radial ring surrounding hub k . Note that, the higher the C_p is, the more convenient for passengers to access the hubs.

Criterion-4: Homogeneity C_H

It is desirable for a transit network to have homogeneously distributed transfer hubs so as to avoid duplicate coverage of the service areas. The study by Fradd and Duff (1989) has indicated that a radial ring of 6.4~8km is considered as the suitable service coverage area for a transfer facility. Therefore, two or more hubs located within

the 6.4~8km radius of one another may cause mutually negative competition of the system serviced, and thus shall be prevented from the planning process. Grounded on the above analysis, the criterion of homogeneity developed in this study can be represented by the percentage of non-duplicate service area coverage in the study network, given by:

$$C_H = (\sum_{k \in K} A_k^s - \sum_{k \in K} A_k^d) / \sum_{k \in K} A_k^s \quad (4)$$

Where, C_H = the homogeneity criterion; A_k^s = the total service area covered by hub k (unit: m^2), and A_k^d = the duplicate service area at hub k caused by nearby hub competition (unit: m^2). Note that, the higher C_H is, the more properly the hubs are distributed.

Criterion-5: Compatibility C_C

To minimize the cost and delay in construction, transit transfer hubs should be located in accordance with local ordinances and land use restrictions. Obviously, government-owned vacant land is the most easily attainable area for use in locating transit transfer hubs, as it can be available immediately and its land use cost is much less expensive than the private land. Therefore, the criterion of compatibility in this study is estimated by calculating the percentage of government-owned vacant land, is given by:

$$C_C = \sum_{k \in K} A_k^p \cap A_k^g / \sum_{k \in K} A_k^p \quad (5)$$

Where, C_C = the compatibility criterion; A_k^p = the planning land to locate hub k (unit: m^2); and A_k^g = the government-owned vacant land to located hub k (unit: m^2). Note that, the higher C_C is, the more compatible the planned hub locations will be.

Criterion-6: Developability C_D

The developability of a site refers to its cost, availability, ownership, size, and land use (Rosenberg and Esnard, 2008). Expanding existing hubs is usually much less expensive than building new hubs. Hence, the expansion potential for existing hubs is also a critical factor to be considered during the planning process. In this study, the

criterion of developability is defined as the potential for the transit hubs to expand spaces so as to adapt to future needs, which can be estimated by the following equation:

$$C_D = \sum_{k \in K} w_k * (A_k^e / A_k^p) / \sum_{k \in K} w_k \quad (6)$$

Eq. (6) represents the average level of expansion capability for a hub network, where, C_D = the developability criterion; w_k = the total passenger flows accessing hub k (unit: trips); A_k^e = the available extra land to expand hub k (unit: m^2); and A_k^p = the current planning land to locate hub k (unit: m^2). Note that, the higher C_D is, the more developable the planned hub locations will be.

THE PROPOSED FUZZY AHP MODEL

In the previous section, this study has proposed a set of 6 critical criteria for evaluating the location planning of urban transit hubs. In order to perform a comprehensive evaluation, this study proposes a fuzzy AHP model to integrate those criteria effectively into a single performance index. Different from the conventional AHP which features a three-level hierarchical structure (i.e., the goal, criteria, and alternatives), the proposed model added a fuzzy scale level between the criteria level and the alternative level to facilitate the normalization of different criteria scales. Fig. 1 outlines a graphical illustration of the proposed hierarchical AHP structure that includes four levels:

- Goal: As the first level of the hierarchy, the goal initially established by decision makers is to determine the most suitable urban transit hub location plan from a predefined set of alternatives;
- Criteria: A comprehensive list of evaluation criteria constitutes the second level of the hierarchy. Detailed descriptions for these criteria can be found in Section 2;
- Fuzzy scale: The fuzzy membership functions are employed to normalize the scales of different indicator so as to represent the satisfaction of each criterion with respect to each alternative; and
- Alternatives: The last level of the hierarchy represents a series of predefined transit hub location plans to be evaluated.

Insert Figure 1 here

Notation

To facilitate the presentation, all definitions and notations used hereafter are summarized in Table 1.

[Insert Table 1 here](#)

Model formulation

The proposed fuzzy-AHP model can be stated as the following four steps:

Step 1: Fuzzy Scaling

In view of the difficulty in comparing the indicators with different types of units, this step has employed a set of fuzzy membership functions to normalize the scales of different indicators, based on the characteristics of each evaluation criterion. Two types of indicators, i.e. “the-lower-the-better” and “the-higher-the-better” are identified to normalize x_{ik} with their fuzzy sets, given by:

For the-lower-the-better indicators:

$$\mu_{ik} = [x_{i(\max)} + x_{i(\min)} - x_{ik}] / [x_{i(\max)} + x_{i(\min)}] \quad (7)$$

For the-higher-the-better indicators:

$$\mu_{ik} = x_{ik} / [x_{i(\max)} + x_{i(\min)}] \quad (8)$$

Step 2: Pair-wise Comparisons

After normalization of all the indicators by fuzzy sets, it is noticeable that, if the variation of one data set $\{\mu_{ik} | k=1 \cdots m, \forall i\}$ is larger than that of the other data set $\{\mu_{jk} | k=1 \cdots m, j \neq i\}$, criterion i is expected to be more influential than criterion j when calculating the priority score of alternative k . Such observation enables us to employ the standard deviation of indicators to determine which criterion is more important and to what extent. The calculation of standard deviation, S_i , is given by Eq. (9).

$$S_i = \sqrt{\sum_{k=1}^m (\mu_{ik} - \bar{\mu}_i)^2 / (m-1)} \quad (9)$$

Then, a pair-wise comparison matrix $A = (a_{ij})_{n \times n}$ is created to measure the relative importance of criterion i over criterion j , as shown in Eq. (10).

$$a_{ij} = \begin{cases} \frac{s_i - s_j}{s_{\max} - s_{\min}} (a_m - 1) + 1, & s(i) \geq s(j) \\ 1 / \left[\frac{s_j - s_i}{s_{\max} - s_{\min}} (a_m - 1) + 1 \right], & s(i) < s(j) \end{cases} \quad (10)$$

Here, $a_m = \min \{9, \text{int}[s_{\max} / s_{\min} + 0.5]\}$ is a comparison scale for all criteria recommended by Jin et al. (2004).

Step 3: Weights Determination

According to theory of AHP analysis, if a_{ij} can consistently or correctly reflect the importance of criterion i over criterion j , we will have $a_{ij} = w_i / w_j$. Then, the following three laws can be deduced: (a) $a_{ii} = w_i / w_i = 1$; (b) $a_{ij} = w_i / w_j = 1 / a_{ji}$; and (c) $a_{ij} a_{jk} = (w_i / w_j) \cdot (w_j / w_k) = w_i / w_k = a_{ik}$. Therefore, one can obtain the weight for each criterion by solving the following linear equations:

$$\sum_{i=1}^n \sum_{j=1}^n |a_{ij} w_j - w_i| = 0 \quad (11-a)$$

$$w_i > 0 \quad i = 1, \dots, n \quad (11-b)$$

$$\sum_{i=1}^n w_i = 1 \quad (11-c)$$

However, as mentioned in many previous studies (Bryson, 1995; Jin et al., 2004; Saaty, 1980; Sudhakar and Shrestha, 2003; Yu, 2002), it is usually difficult in practice to obtain a completely consistent pair-wise comparison matrix that satisfies the aforementioned three laws. Thus, this study has proposed the following non-linear optimization model to estimate the weights $\{w_i | i = 1, \dots, n\}$ from the inconsistent a_{ij} :

$$\min C.I.C.(n) = \sum_{i=1}^n \sum_{j=1}^n |y_{ij} - a_{ij}| / n^2 + \sum_{k=1}^m \sum_{l=1}^m |y_{ij} w_j - w_i| / n^2 \quad (12)$$

s.t.

$$y_{ii} = 1 \quad i = 1, \dots, n \quad (13)$$

$$1 / y_{ji} = y_{ij} \in [a_{ij} - da_{ij}, a_{ij} + da_{ij}] \quad i = 1, \dots, n; j = i + 1, \dots, n \quad (14)$$

$$w_i > 0 \quad i = 1, \dots, n \quad (15)$$

$$\sum_{i=1}^n w_i = 1 \quad (16)$$

In the above equations, $Y = (y_{ij})_{n \times n}$ is defined as the consistency judgment matrix, which is adjusted based on $A = (a_{ij})_{n \times n}$ during the minimizing process of the consistency index coefficient, denoted by $C.I.C.(n)$. It consists of the following two parts:

- Minimization of $\sum_{i=1}^n \sum_{j=1}^n |y_{ij} - a_{ij}| / n^2$ to match the judgment matrix $Y = (y_{ij})_{n \times n}$ with the original comparison matrix $A = (a_{ij})_{n \times n}$ as closely as possible so that $Y = (y_{ij})_{n \times n}$ can reflect the original comparison information to the maximum extent; and
- Minimization of $\sum_{k=1}^m \sum_{l=1}^m |y_{ij} w_j - w_i| / n^2$, functions to ensure that $Y = (y_{ij})_{n \times n}$ be as consistent as possible to satisfy Eq. (11a-c).

Constraints (13) and (14) limit that all the elements in $A = (a_{ij})_{n \times n}$ should satisfy the first two aforementioned laws. Note that the third law is not included in the constraints since it is considered by the second part of the objective function. In addition, constraint (14) introduces a non-negative parameter d to measure the deviation degree between $Y = (y_{ij})_{n \times n}$ and $A = (a_{ij})_{n \times n}$. Constraint (15) ensures the non-negative weights, and constraint (16) limits the sum of all weights equal to 1.

Solving the proposed optimization model yields two types of information: 1) the judgment matrix $Y = (y_{ij})_{n \times n}$, and 2) the vector of weights for different criteria $\{w_i | i = 1, \dots, n\}$. However, the global optimal solutions are not assured for the proposed optimization model due to its non-convexity attribute. Thus, this study has employed the convergence criterion of $C.I.C.(n) \leq 0.1$ to ensure that the obtained judgment matrix $Y = (y_{ij})_{n \times n}$ is consistent, as recommended by Jin et al. (2004), based on extensive numerical experiments.

Step 4: Synthesis

After obtaining the weights for all criteria from the optimization model, the final evaluation score of each alternative k will be synthesized by Eq. (17), and be stated as:

$$S_k = \sum_{i=1}^n \mu_{ik} \cdot w_i \quad (17)$$

The synthesis results will reflect the overall preference for all the alternatives with respect to the goal. A diagram of the evaluation process is shown in Fig. 2.

Insert Figure 2 here

CASE STUDY

To illustrate the applicability of the proposed multi-criteria approach in location planning for multiple transit hubs, this study has employed the transit network in Suzhou Industrial Park (SIP), China for case study. The SIP was initiated in 1994 as a Sino-Singapore joint development project in the area of a 70km² farmland. Since then, it has experienced an amazing growth (averaging 30% per annum) and expansion to 288km², which brings increasing challenges to the transportation authorities in tackling the magnified traffic congestion problems. As one of the most effective strategies to relieve the traffic congestion, development of an effective transit-oriented urban transport system has recently emerged as the foremost priority task for the SIP Council.

In response to the above critical need from the SIP Council, the research team has collected ample field data in the target area for conducting a comprehensive location planning for transit hubs, which serves as the basis and first step for the subsequent development of an urban transit system.

Candidate hub location plans

Constrained by the budget limit, the SIP Council has planned to construct five transit transfer hubs within the study area consisting of 58 TAZs (see Fig. 3). Considering the geographical, political, and administrative restrictions, the research team has divided the entire SIP into 5 clusters, and located exactly one hub within each of them (Yu et al., 2008, 2009). Since different clustering rules yield different decompositions of the study area, it will also generate different transit hub location plans. After distillation of opinions from a large number of transit system

users, transportation planners and engineers, it has yielded four candidate location plans (see Fig. 4) for final selection, with the corresponding clustering results listed in Table 2.

[Insert Figure 3 here](#)

[Insert Figure 4 here](#)

[Insert Table 2 here](#)

Application of the proposed model

In order to apply the proposed model for selecting the best location plan from the four candidates, the research team has collected the following information for model inputs:

- The O-D matrix of the study area;
- The average travel time by transit between each O-D pair;
- The transfer flow via hubs between each O-D pair;
- The total passenger flow accessing each candidate hub;
- The detailed land use map of the study area;
- The ideal level of transfer intensity for the study area is set at 1.3, as recommended by the Urban Road Transportation Planning and Design Standard (1995) depending on the size, population and land use of the study area;
- The radius of hub service coverage (here we use 6.5km considering the relatively compact study area);

With the above input information, this study has computed the value of each evaluation criterion, based on their definitions in Section 2 (see Table 3). The proposed fuzzy AHP model is then employed to obtain the final evaluation scores for all the four candidate plans. As illustrated in Fig. 2, the evaluation procedure is presented below:

Step 1: Fuzzy scaling

This step employs the fuzzy membership functions to normalize the scales of all crisp values of evaluation criteria, $\{x_{ik} | i = 1 \cdots 6\}$, shown in Table 3. According to the definitions in Section 2, the criteria of “efficiency” and “transfer intensity” are considered as the-lower-the-better indicators, which will be processed with Eq. (7). While the remaining four indices, i.e. “proximity”, “homogeneity”, “compatibility”, and “developability” are taken

as the-higher-the-better ones, and thus computed by Eq. (8). All of the fuzzified values, denoted as $\{\mu_{ik} | i = 1 \cdots 6\}$, are listed in Table 3.

Insert Table 3 here

Step 2: Pair-wise comparisons

After normalization of all indicators with the fuzzy sets, the standard deviation of indicators $\{s_i | i = 1 \cdots 6\}$ were calculated with Eq. (9), and are shown in the second last column of Table 3. Then, the pair-wise comparison matrix $A = (a_{ij})_{n \times n}$ was constructed as follows with Eq. (10), where a_m is 5 by $\min \{9, \text{int}[s_{\max} / s_{\min} + 0.5]\}$:

$$A = \begin{bmatrix} 1.000 & 0.491 & 0.284 & 1.643 & 1.543 & 1.241 \\ 2.036 & 1.000 & 0.403 & 2.678 & 2.579 & 2.276 \\ 3.518 & 2.482 & 1.000 & 4.161 & 4.062 & 3.759 \\ 0.609 & 0.373 & 0.240 & 1.000 & 0.910 & 0.713 \\ 0.648 & 0.388 & 0.246 & 1.099 & 1.000 & 0.768 \\ 0.806 & 0.439 & 0.266 & 1.402 & 1.303 & 1.0000 \end{bmatrix}$$

Step 3: Weights Determination

The proposed non-linear programming model was implemented in the LINGO 9.0 Solver with systematic variation of parameter d , and the judgment matrix $Y = (y_{ij})_{n \times n}$ reached consistency as shown below with $C.I.C(n) = 0.035$ and $d = 0.04$.

$$Y = \begin{bmatrix} 1.000 & 0.511 & 0.296 & 1.708 & 1.605 & 1.290 \\ 1.958 & 1.000 & 0.419 & 2.786 & 2.682 & 2.367 \\ 3.383 & 2.387 & 1.000 & 4.327 & 4.224 & 3.909 \\ 0.585 & 0.359 & 0.231 & 1.000 & 0.946 & 0.742 \\ 0.623 & 0.373 & 0.237 & 1.057 & 1.000 & 0.798 \\ 0.775 & 0.422 & 0.256 & 1.348 & 1.253 & 1.000 \end{bmatrix}$$

The corresponding weights for all criteria, $\{w_i | i = 1 \cdots 6\}$, are also obtained, as shown in the last column of Table 3.

Step 4: Synthesis

The evaluation scores are synthesized by aggregating the products of the fuzzified values and their corresponding criteria weights, as shown in the second last row of Table 3. It is noticeable that Candidate Plan I

seems to be the most suitable transit hub location plan since it outperforms all the other three plans in terms of the final evaluation score. The final ranking results of all candidate plans are also listed in Table 3.

Comparative analysis of different criteria

To further investigate the impacts of different criteria on the final ranking results, this study has also compared the evaluation scores of all candidate plans with respect to different criteria, as shown in Fig. 5.

[Insert Figure 5 here](#)

It can be observed in Fig. 5 that there exist significant discrepancies in the evaluation scores of different candidate plans with respect to different criteria. For example, the candidate Plan I outperforms all other plans with respect to the criteria of efficiency, transfer intensity, and proximity. However, in terms of homogeneity, compatibility, and developability, the candidate Plan IV shows the highest score. In real-world planning process, such discrepancies may result in a dilemma in transportation planner's decision making process. The proposed approach in this study, which features an objective multi-criteria method to integrate all six criteria into one index, can assist transportation planners in effectively tackling such a dilemma. As shown in Fig. 5, the proposed model gives the highest rank to the candidate Plan I, but the lowest rank to the candidate Plan IV, which clearly indicates that the criteria of efficiency, transfer intensity, and proximity have more significant impacts on the final decision making than with other three criteria do. This is probably due to the fact that the relatively low variation of evaluation scores among candidate plans with respect to the other three criteria has slipped their weights down when constructing the pair-wise comparison matrix in the AHP.

Also indicated in Fig. 5 is the capability of the proposed model in selecting pretty similar candidate plans. For example, the candidate Plan II and III exhibit very close evaluation scores with respect to each of the six evaluation criteria. However, Plan III is given a higher final rank than the candidate Plan II because the proposed model could capture the intrinsic differences of those similar plans, and reflect them into the synthesized final evaluation scores.

CONCLUSIONS

This paper presents a comprehensive evaluation model for selecting candidate location plans of multiple urban transit hubs. A set of evaluation criteria including efficiency, transfer intensity, proximity, homogeneity, compatibility, and developability has been proposed to effectively capture various aspects of concerns in the transit

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4 hub location planning process. Grounded on an AHP-based framework integrated with the fuzzy logic, the proposed
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6 model offers the advantage of effectively preventing the arbitrariness in determination of the weights for multiple
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8 evaluation criteria, and easily synthesizing the final score of each candidate plan for comparison. Moreover, the
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10 clarity of model inputs and its ease of interpreting of the results with respect to different evaluation criteria offer the
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12 best potential for use in hub location planning process. The model was successfully applied to assist transportation
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14 planners in selecting proper transit hub location plans in Suzhou Industrial Park, China. Comparative studies with
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16 respect to different evaluation criteria has further demonstrated the effectiveness of the proposed model in capturing
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18 the impacts of different criteria on the decision making process as well as its potential to be applied to developing a
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20 cost-effective decision support tool to assist planners to design and evaluate various hub location planning strategies.
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22 Note that this paper has presented preliminary evaluation and comparative analysis results for the proposed
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24 model through a case study. More extensive tests or evaluations will be essential to assess the effectiveness of the
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26 proposed model with more data samples and to account for additional critical impact indicators.
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Fig. 5 Evaluation scores for different alternatives with respect to different criteria

Table 1. Notation of key parameters used in the proposed model

i	Index corresponding to criterion ($i = 1 \cdots n$)
k	Index corresponding to alternative ($k = 1 \cdots m$)
x_{ik}	Indicator representing the alternative k being evaluated by criterion i
μ_{ik}	Fuzzy membership value corresponding to indicator x_{ik}
$\bar{\mu}_i$	Average fuzzy membership value for criterion i
$x_{i(\min)}$	The minimal crisp value for criterion i
$x_{i(\text{mid})}$	The medium crisp value for criterion i
$x_{i(\max)}$	The maximal crisp value for criterion i
s_i	Standard deviation of indicator values corresponding to criterion i
$s_{\min}$	$\min\{s_i i = 1, \cdots, n\}$
$s_{\max}$	$\max\{s_i i = 1, \cdots, n\}$
$A = (a_{ij})_{n \times n}$	Pair-wise comparison matrix
a_m	Comparison scale for the pair-wise comparison matrix
w_i	Weight for criterion i
$Y = (y_{ij})_{n \times n}$	Consistency judgment matrix
$C.I.C.(n)$	Consistency index coefficient
S_k	The synthesized ranking score of alternative k

Table 2. Clustering of TAZs in the study network

Candidate Plan No.	Clustering (TAZ IDs)
1	{1-9,12,37-39}, {10-11, 13-28}, {40-46}, {32-36}, {29-31, 47-58}
2	{1-9,12, 47-51}, {10-11, 13-28}, {37-39, 40-46}, {29-30, 32-36}, {31, 52-58}
3	{1-9,12, 37-38,46-51}, {10-11, 13-28}, {39, 40-46}, {32-36}, {29-31, 52-58}
4	{1-9,12, 37-38}, {10-11, 13-21, 40-46}, {47-55}, {22-28, 32-36}, {29-31, 47-58}

Table 3. Results obtained by applying the proposed AHP model

Evaluation	Candidate Plan I		Candidate Plan II		Candidate Plan III		Candidate Plan IV		S_i	w_i
Criteria	x_{i1}	μ_{i1}	x_{i2}	μ_{i2}	x_{i3}	μ_{i3}	x_{i4}	μ_{i4}		
Efficiency	37	0.580	46	0.477	43	0.511	51	0.420	0.067	0.126
Transferability	0.140	0.632	0.190	0.500	0.170	0.553	0.240	0.368	0.111	0.231
Proximity	27	0.711	17	0.447	18	0.474	11	0.289	0.174	0.376
Homogeneity	0.720	0.456	0.770	0.487	0.740	0.468	0.860	0.544	0.039	0.083
Compatibility	0.430	0.448	0.470	0.490	0.490	0.510	0.530	0.552	0.043	0.086
Developability	0.160	0.432	0.180	0.486	0.190	0.514	0.210	0.568	0.056	0.098
Evaluation Score	0.605		0.474		0.503		0.395		--	--
Rank	1		3		2		4		--	--

Figure 1
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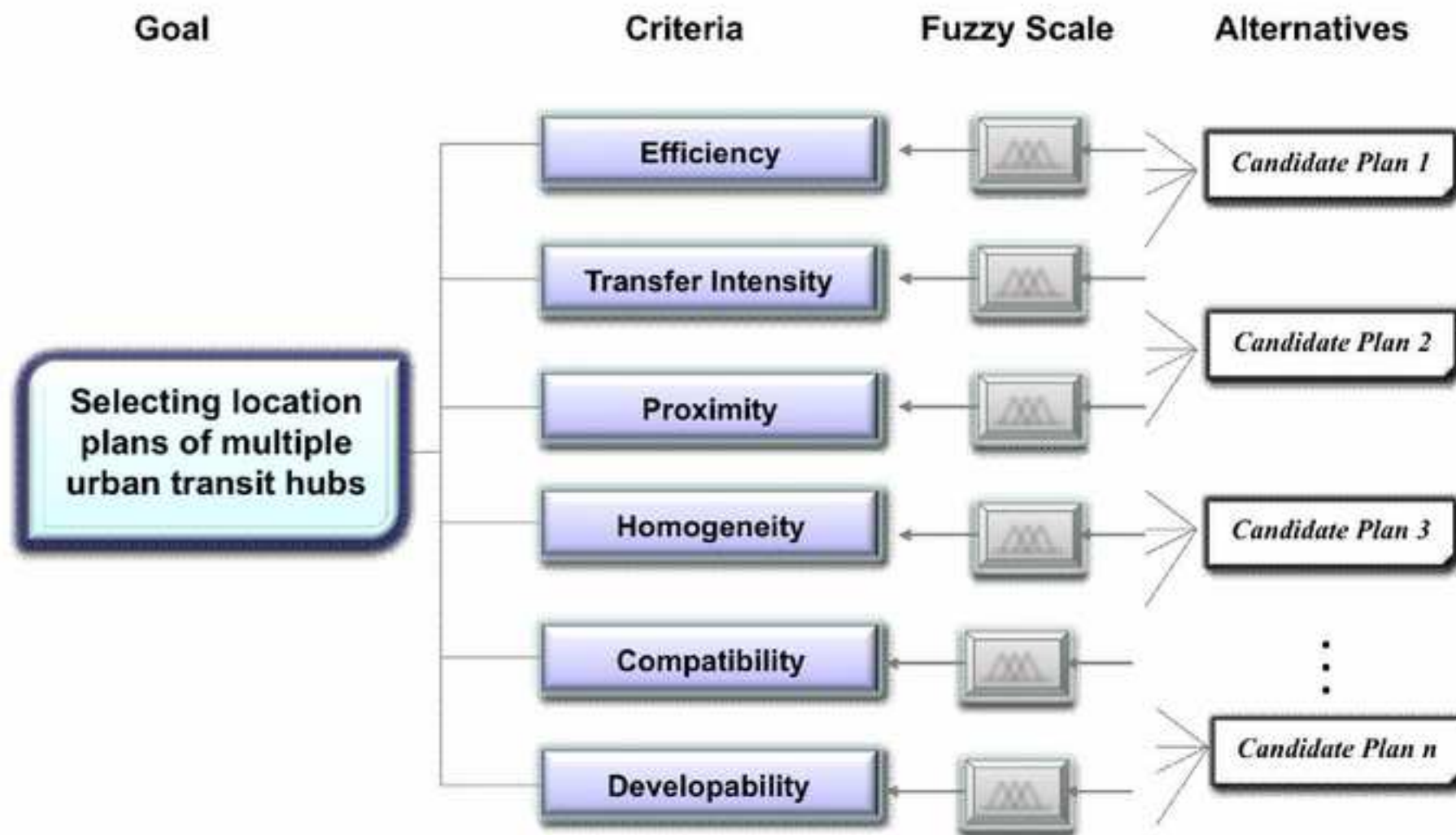


Fig. 1.The proposed hierarchical AHP structure

Figure 2
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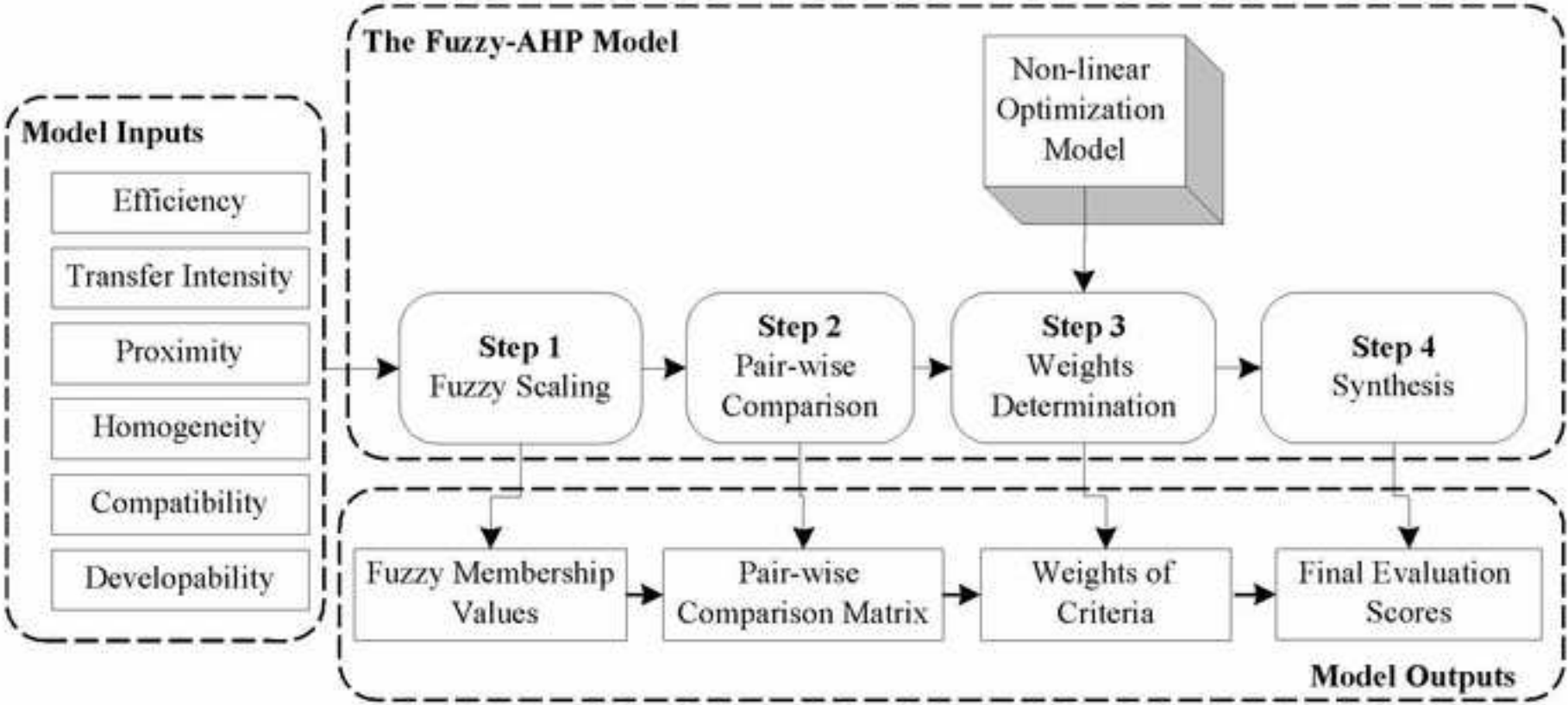


Fig. 2. The evaluation process with the fuzzy-AHP model

Figure 3
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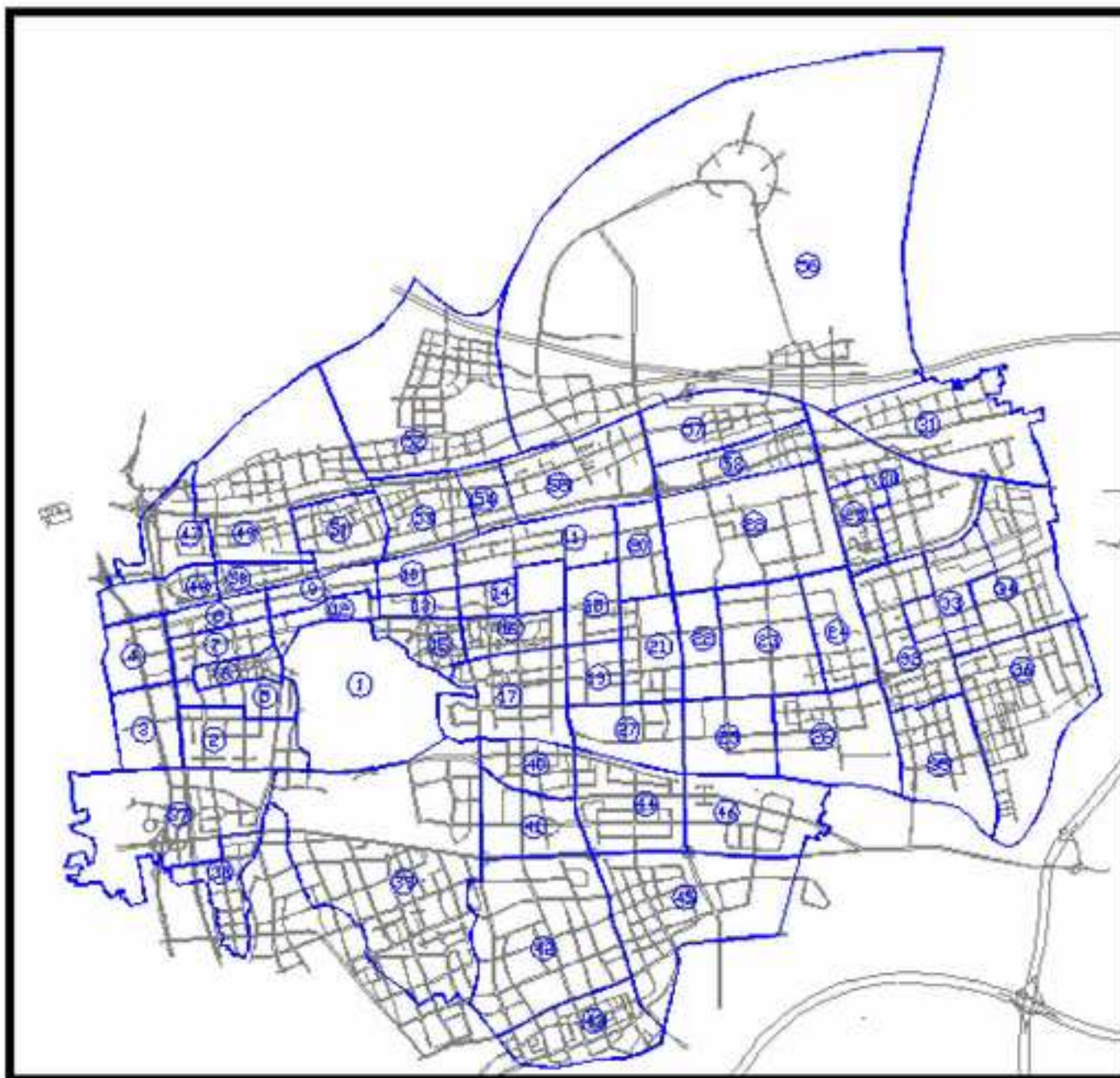


Fig. 3. Distribution of 58 TAZs on the study area

Figure 4
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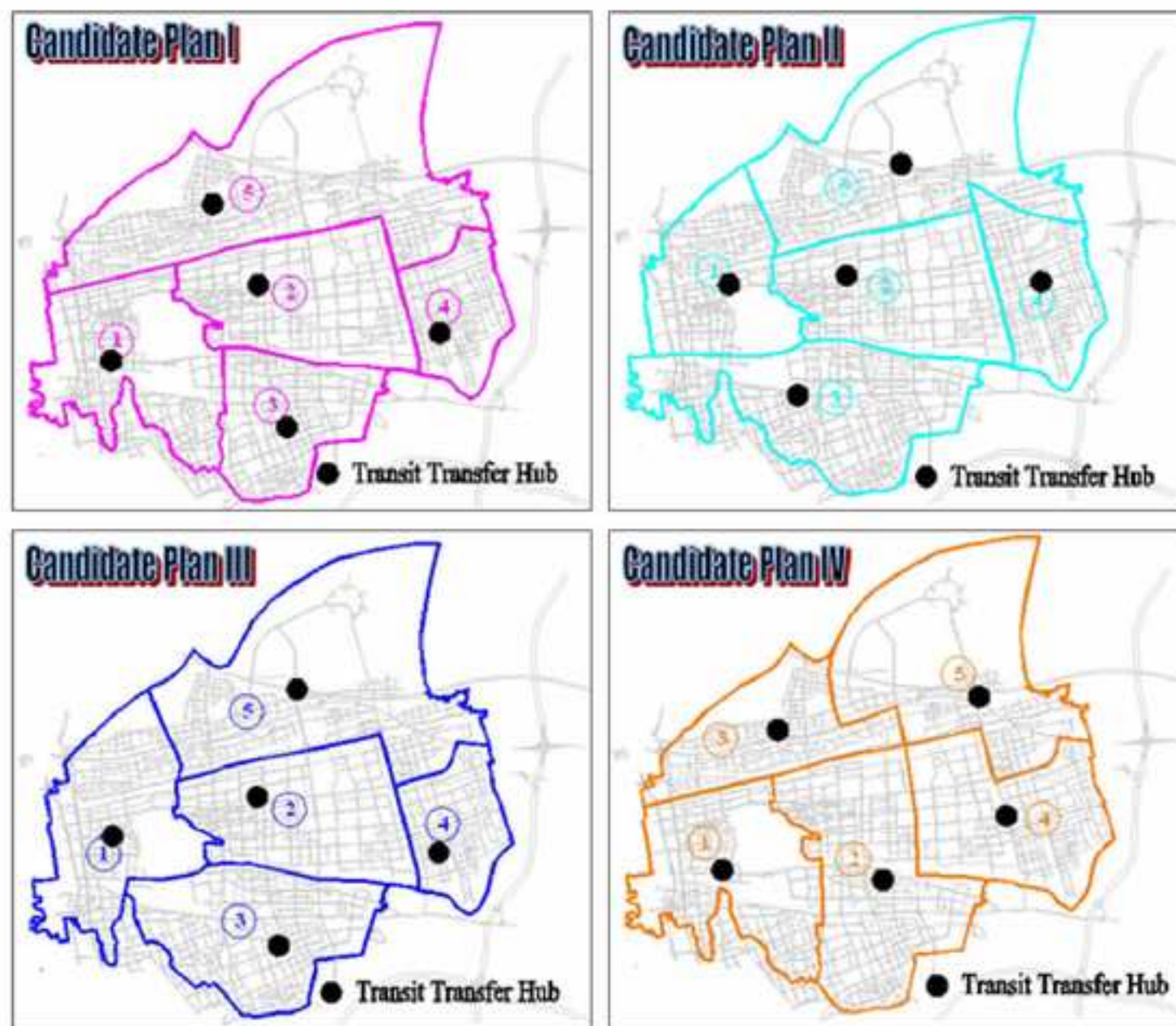


Fig. 4. Candidate location plans for transit transfer hubs in the study network

Figure 5
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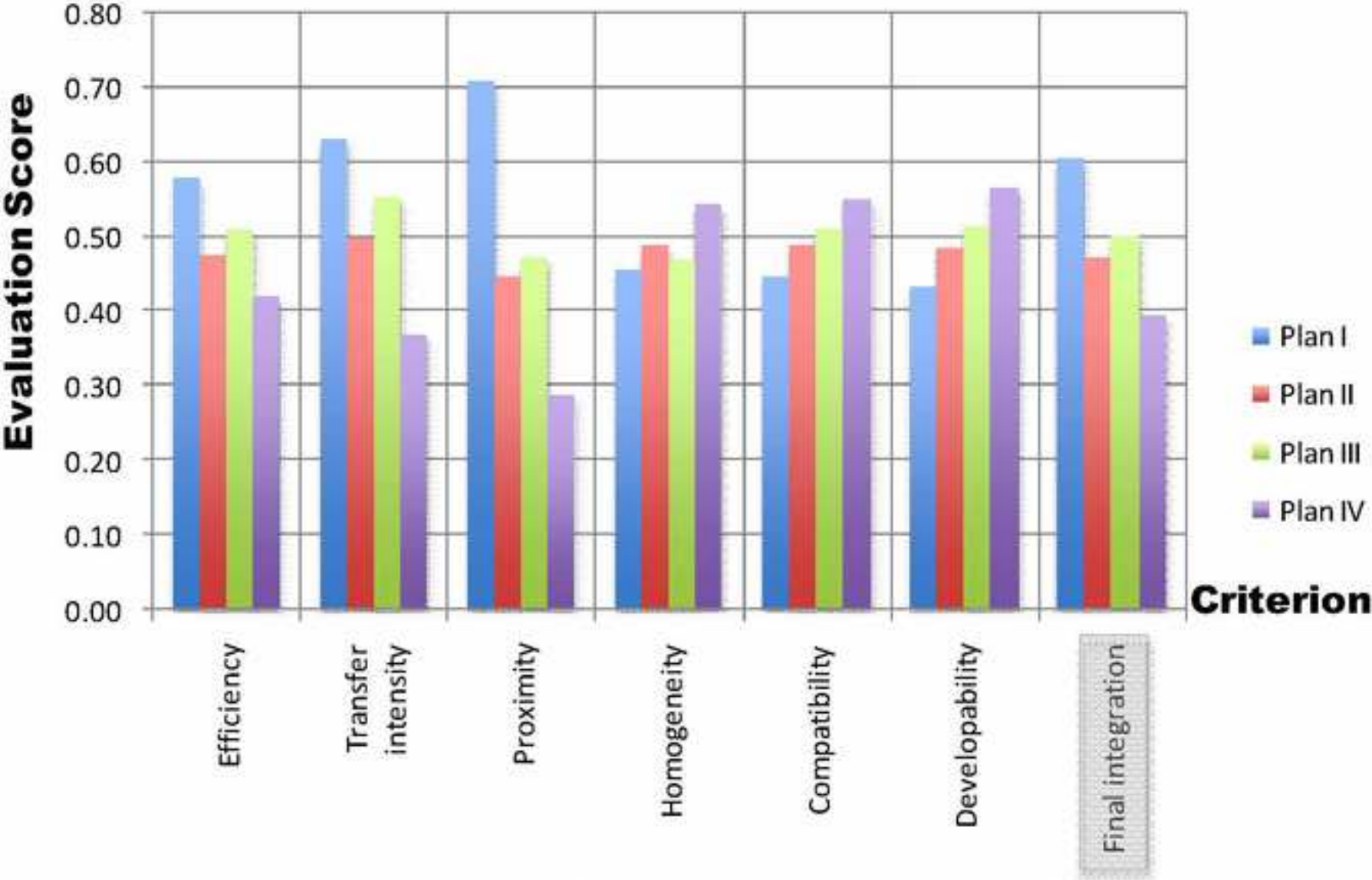


Fig. 5. Evaluation scores for different alternatives with respect to different criteria



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Authors' Response to the Review Comments

Journal: ASCE Journal of Transportation Engineering

Manuscript #: TEENG-688

Title of Paper: LOCATING URBAN TRANSIT HUBS: A MULTI-CRITERIA MODEL AND CASE STUDY IN CHINA

Authors: Jie Yu; Yue Liu; Gang-Len Chang; Wanjing Ma; Xiaoguang Yang

Date Sent: Aug 30, 2010

We appreciate the time and efforts by the editor and referees in reviewing this manuscript. We have addressed all issues indicated in the review report, and believed that the revised version can meet the journal publication requirements.

Response to Comments from Reviewer 1

Comment 1:

In this paper the authors present a model that uses an AHP based framework, interfaced with fuzzy logic to establish the weights for multiple evaluation criteria to determine scores for different alternative plans. These scores can then be used as means of ranking the alternatives. The authors also demonstrate the application of the model for ranking/selecting plans for locating transit hubs in Suzhou Industrial Park in China.

The authors present a set of six criteria that they consider to be related to transit hub location. With the exception of criteria 3 and 4, they offer very little justification for selecting them, relative to the literature or state of practice. In their present form, the remaining four criteria appear to have been chosen somewhat arbitrarily, or as found convenient to the authors. The authors should address this issue in their final draft.

Response:

We greatly appreciate the reviewer's efforts to carefully review the paper and the valuable suggestions offered. As suggested by the reviewer, we have added references

correspondingly to justify the selection of some criteria used in this study. Please refer to page 5-7 in the revised manuscript. In this study, we have proposed the evaluation criteria framework to our best knowledge to capture various aspects of concerns in the transit hub location planning process. We admit that some criteria, for example the transfer intensity and developability deserve further rigorous research. In addition, the definitions of criteria may vary depending on different project objectives and decision maker preferences. Since this research focuses on developing a multi-criteria ranking model rather than selecting and comparing different evaluation criteria, we will leave the investigation of the impact of different evaluation criteria on the model performance in our next-step research definitely. Please note that the proposed ranking model is generic and has the flexibility to accommodate any new sets of criteria.

Comment 2:

Further, all the six criteria are in the "higher the better" or "the lower the better category". In Model Formulation, (Step1), the authors describe three types of indicators. Equation (8), that addresses "the medium the better" indicators, needs explanations, relative to its logic, and its applicability in the case study. This reviewer is not sure if this premise was used in the case study. The authors should describe situations where such premise may be relevant, even though it may not have been used in the case study.

Response:

Thanks for the comments. In the case study, “the medium the better” indicators are not used. To avoid the confusion, we have eliminated the “the medium the better” indicator in the revised manuscript.

Comment 3:

In steps 2 and 3, the authors present the framework for determining a_{ij} , w_i and w_j , and in step 4, the show how the weights are utilized in determining the final scores. But they do not discuss what information they needed to compute these weights for the case study. They should clarify this.

Response:

Thanks for the comments. Please note that the information needed to compute the weights can be obtained by solving the proposed non-linear optimization model (Eq. 12-16). On page 14, step 3 shows the results of the model solution, and all relevant information is listed in Table 3. In the revised manuscript, we have also added a diagram (Fig. 2) to show the data flow in the entire model application process.

Comment 4:

It is not clear what clustering rules were used in developing the four plans. Even though, the second column in Table 2 is entitled Clustering Rules, they indeed are not. They are actually the effect of some unknown rules. The authors should clearly state the "what" and "why" of these rules in setting up the plans for the purpose of completeness, even though that is not the focus of this paper.

Response:

We appreciate the reviewer's insightful comment. Table 2 actually shows the clustering results. The clustering rules of TAZs are based on geographical, political, and administrative restrictions in the study area. A more detailed description of clustering rules can be found in the following two papers, and we have supplemented the two references accordingly on page 12 in the revised manuscript.

Yu, J., Liu Y., Yang, X., 2008, "Cluster-based Optimization of Urban Transit Hub Locations: Methodology and Case Study in China," Transportation Research Record 2042, 109-116.

Yu J., Liu, Y., Chang, G. L., Ma, W., Yang, X., 2009, "A Cluster-Based Hierarchical Model for Urban Transit Hub Location Planning: Formulation, Solution, and Case Study," Transportation Research Record 2112, 8-16.

Comment 5:

For the sake of brevity, this reviewer suggests that Table 3 can be completely eliminated, because Table 3 does not have any information that is not there in Table 4.

While none of the above flaws are fatal, this reviewer feels that the authors should address the issues raised above to improve the quality of the paper.

Response:

Thanks for the suggestion. We have eliminated table 3 in the revised manuscript.

Response to Comments from Reviewer 2

Overall Comment:

The manuscript presents a very straight forward description of a method for locating a system of transit hubs and provides an example for considering a new system. You might state at the end how it might be applied to improve/expand an existing system.

Response:

We appreciate the comments by reviewer-2 and have supplemented information as for the application of the proposed model in the conclusion section.

Comment 1:

Break the Introduction into subsections

Response:

Thanks for the suggestion. We have formatted the introduction part as suggested.

Comment 2:

Under "Transfer Intensity" explain how the base intensity is obtained

Response:

Thanks for the insightful comment. The base intensity is suggested by the China Urban Road Transportation Planning and Design Standard (1995). One can determine its value depending on the size, population, and land use of the study area.

Comment 3:

Is criteria 5 widely applicable? Maybe in China but not in most western countries

Response:

We appreciate the reviewer's comment. We agree with the reviewer that criterion 5 is applicable in China but not in most western countries. It does affect the decision maker's choice in location selection in China, so we have included as one criterion in the case study.

Comment 4:

On page 12 - a diagram of the process that included input, computational steps and output would help. You could then refer to the process for the application on P. 13.

Response:

We much appreciate the reviewer's suggestion. We have added a diagram of the evaluation process (Fig. 2 in the revised manuscript).

Comment 5:

Explain clustering rules shown in table 2, i.e. indicate that these reflect the TAZs in the clusters.

Response:

We much appreciate the reviewer's careful review. Table 2 actually shows the clustering results. The clustering rules of TAZs are based on geographical, political, and administrative restrictions in the study area. A more detailed description of clustering rules can be found in the following two papers, and we have supplemented the two references accordingly on page 12 in the revised in the manuscript.

Yu, J., Liu Y., Yang, X., 2008, "Cluster-based Optimization of Urban Transit Hub Locations: Methodology and Case Study in China," Transportation Research Record 2042, 109-116.

Yu J., Liu, Y., Chang, G. L., Ma, W., Yang, X., 2009, "A Cluster-Based Hierarchical Model for Urban Transit Hub Location Planning: Formulation, Solution, and Case Study," Transportation Research Record 2112, 8-16.

Response to Comments from Reviewer 3

Overall Comment:

This paper proposes a method to locate transit hubs in a transportation network. The paper identifies six criteria with which potential locations should be evaluated; the research then proposes an AHP-based technique employing fuzzy logic to identify the importance of each criterion and an OR method to ensure consistency in results. A final recommendation is made amongst four candidate hub locations.

The paper's goals and objectives are very clearly stated and the logic of the paper is very good. The quantitative techniques proposed are logical, well-explained and are well-grounded in actual techniques applied in practice. The case study appropriately demonstrates the paper's techniques.

I would recommend that the authors proofread the paper to correct several awkward expressions; these are largely contained to the first section of the paper (pages 2 - 4).

Response:

We greatly appreciate the reviewer's efforts and have performed a careful editing work.

Comment 1:

When generating evaluation criteria, the authors propose to use a flow-weighted metric for efficiency, intensity and proximity. For the land criteria - homogeneity, compatibility, and developability (which are awkward titles), the authors choose not to weight these criteria

by flow. It seems that these criteria should be equally sensitive to passenger volumes as the previous three. Some explanation of why the flow weightings are used in some cases, but not in others would be helpful.

Response:

Thanks for the suggestion. Please note that his study is not the first to design those land criteria. The definitions of homogeneity and developability can be referred to the following paper and are not sensitive to passenger volumes.

Rosenberg J R, Esnard A M, 2008, "Applying a hybrid scoring methodology to transit site selection" ASCE Journal of Urban Planning and Development 134(4) 180-186.

The criterion "compatibility" is kind of special to China but not applicable in most western countries. Since it does affect the decision maker's choice in location selection in China, we have included as one criterion. It is related to the land cost but not the passenger flows.

Comment 2:

The Transfer intensity metric relies heavily on an ideal transfer intensity (Io). This is presented in the case study as 1.3 with a somewhat obscure reference to a 1995 paper. I think more discussion of the Io value is necessary - there are many references that deal with the tradeoff between operators' desires for transfers and passengers' preferences for "single-seat" trips.

Response:

Thanks for valuable comments. We fully agree with the reviewer that the ideal transfer intensity is a critical parameter whose value has a significant impact on the evaluation criterion. We have provided the factors that may affect the determination of its value on page 13 (the 6th bullet) of the revised manuscript. In this study, we assume the planner has the best knowledge about the study area and can provide reliable estimates of parameters to compute each criterion as the model input. But, we will leave the investigation and sensitivity analysis of the impact of different intensity values on the model performance in

our next-step research definitely.

Comment 3:

The paper would be greatly improved by some sensitivity analysis; how do the results vary if the access distance increases from 400 m to 600 m or 800m? How do the results change as a function of the hub service area limits (6.8km)? How scaleable is the work - as the authors note, the study area of 288 km² is relatively small.

Response:

Thanks for valuable suggestion. Please note that a 0.4km radial ring surrounding the transit hub is considered as proximity according to the guidelines by American Planning Association (2006), since it is within a reasonable walking distance. We expect the ranking results could slightly vary if the access distance increases or the hub service area changes. Depending on the scales of the study area, those parameters could be different. However, it will not affect the validity of the proposed model. In this study, we assume the planner has the best knowledge about the study area and can provide reliable inputs for the proposed model to generate ranking results.

Comment 4:

An interesting extension to the paper would be to use a more traditional means of having stakeholders rate the importance of each criterion and compare the results to the fuzzy, non-linear solution method developed in the paper.

Response:

Thanks for the suggestion. We will include the comparison in the future study as suggested. We expect the proposed model will outperform the traditional way due to its capability to capture uncertainty in human preference and enable a more accurate description of the decision making process.