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Smart Growth Principles Combined with Fuzzy AHP and DEA Approach to the Transit-oriented Development (TOD) Planning in Urban Transportation Systems

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ABSTRACT

The research for a land use and transportation planning has always been an important study area among the urban planning field. Since the 20th century, automobiles had become the main media as the transportation vehicle. However, the automobile-oriented development (AOD) also caused the sever urban sprawl problem during the past years. In order to reduce the problems of urban sprawl, the Smart Growth concepts have been proposed and applied to transportation planning process. In recent years, with the up to date sustainable development concept, the transit-oriented development (TOD) model has become one of the novel transport planning strategies utilized to improve the urban environment by means of Smart Growth principles. This study tries to integrate smart growth principles into the urban transportation planning development strategies and utilize objective scientific method to the empirical study. This study will include the following sections. First of all, we try to study and classify the category of smart growth principles based on literature review. Followed by applying fuzzy Delphi technique (FDT) to obtain individual expert's opinions and to screen the most important criteria of proposed principles in our research. And then the empirical study of Taipei Metro Transit System will be demonstrated to show the application of our proposed methodology. Finally, the utilization of data envelopment analysis (DEA) model combined with assurance region analysis will be applied to select the most suitable MRT stations as the suggested strategies for public sectors.

Keywords: Smart Growth, Transit-oriented Development (TOD), Fuzzy Delphi Technique (FDT), Data Envelopment Analysis (DEA)

1. Introduction

The concept of Smart Growth concentrates growth in compact walkable urban centers to avoid sprawl. It thus emphasizes on compact, transit-oriented, walkable, bicycle-friendly land use, including neighborhood schools, complete streets, and mixed-use development with a range of housing choices. The movement leads to the formation of the Smart Growth Network. The Network is formed by the U.S. Environmental Protection Agency and joined with over 40 organizations from a diverse array of interests. It is operated by a group of people including planning experts, architects, private development companies, and local citizens.

The concept of transit-oriented development (TOD) planning mode in an urban area was proposed based on the principles of smart growth and sustainable development in recent years. Meanwhile, the development of appropriate design techniques for the surrounded built environment of TOD has become important increasingly as the TOD applied in an urban district. The available evidence lends itself to the argument that a combination of urban design strategies and TOD patterns that promotes the quality of urban built environment will help create active, healthier, and more livable communities and it is an essential element of this research. This paper presents a study on a decision-making problem integrating smart growth principles into the urban transportation planning development strategies. A case of Taipei metro transit system will be taken as an empirical example to illustrate the application of our proposed methodology for assessing the comparative performance of TOD planning multicriteria analysis.

This study will try to study and classify the category of smart growth principles based on literature review. And then the empirical study of Taipei Metro Transit System will be demonstrated to show the application of our proposed methodology. Finally, the utilization of Fuzzy Analytic Hierarchy Process (FAHP) method and Data Envelopment Analysis (DEA) model combined with assurance region analysis will be applied to select the most suitable MRT stations as the suggested strategies for public sectors.

Our research is an attempt to illustrate the complexity of such comparisons and integration. The evaluators determined that the performance evaluation framework for TOD planning in Taipei Metro Transit System must be rational, open to the public, and easy to understand. To meet these requirements, we propose a consensus decision-making method that integrates the advantages of two well-known and often used methods, DEA and FAHP. The new hybrid FAHP/DEA developed here suffers from the limitations of neither of the two methods used alone. The literature contains some prior limited attempts to merge traditional AHP and DEA. For example, Shang and Sueyoshi (1995) used the subjective AHP results in DEA to select a flexible manufacturing system. Yoshiharu and Kaoru (2003) developed an integrated DEA and AHP model for relocating the Diet and other Japanese government organizations outside Tokyo. We try to propose a newly integrated FAHP/DEA methodology, consisting of combined data envelopment and fuzzy hierarchy analysis that seems suitable for a candidate-TOD station selection problem.

2. Literature review

Smart growth is an urban planning and transportation theory that concentrates growth in compact walkable urban centers to avoid sprawl. The theory can be applied to solve urban planning design problems (e.g., mixed-use infill development), to accelerate land use efficiency, and to manage urban growth (e.g., human population control). It also advocates compact, transit-oriented, walkable, and bicycle-friendly land use—e.g., neighborhood schools, complete streets—and mixed-use development with a range of housing choices. To implement this idea of smart growth, it requires a public-private partnership. By doing so, we will be able to achieve economic growth without having the ugliness, congestion, and environmental degradation. We will also be able to reduce wasteful public subsidies of sprawling development (Glendening, 1997).

So far, there is no one single definition of smart growth that satisfies everyone and many people have their own (Miller and Hoel, 2002). For example, Barbara McCann, the executive director of Smart Growth America, states that "smart growth is so many different things. It's not just transportation. it's a mindset towards creating a more holistic community. We've talked about quality of life. And what has been more fundamental to quality of life than physical health?" Another example, the National Association of Home Builders explains smart growth from a developers' perspective. The organization defines smart growth as "development that provides a wide range of different housing choices." That is, smart growth is defined as the development that provides: (1) a firm, comprehensive, open, and locally-based planning, (2) a more effective, innovative, and market-sensitive way of utilizing land areas, and (3) housing units according to economic and population projections. Though no two organizations define smart growth in precisely the same terms, the design principles of smart growth which are promulgated by the Smart Growth Network have gained widespread recognition. These principles are listed and described in Table 1.

Smart growth has rapidly raised its popularity in the past two decades because it is a type of development that has the following characteristics (Duany and Plater-Zyberk, 1992; Song, 2005):

(1) a street network circulation design that utilizes shorter street lengths in a grid-like pattern to promote better traffic flow

(2) higher density residential uses surrounding retail, recreational, and governmental uses

(3) more mixture of land uses that reduce the number of vehicle trips

(4) better accessibility to retail and transit that improves quality of life

(5) pedestrian-friendly neighborhoods

Many researchers highlight the relationship between DEA and Multi-Criteria Decision Analysis (MCDA): "Indeed in common with many approaches to multiple criteria analysis, DEA incorporates a process of assigning weights to criteria" (Belton and Vickers, 1993; see also Belton, 1992; Cook et al., 1990, 1992; Doyle and Green, 1993; Stewart, 1994, 1996). Ranking is very common in MCDA literature, especially when there is a discrete list of elements or alternatives with a single criterion or multiple criteria to evaluate and compare or select. Various approaches are suggested in the literature for fully ranking elements, ranging from the utility theory approach (see Keeney and Raiffa, 1976; Keeney, 1982; Sinuany-Stern and Mehrez, 1987; Fishburn, 1988) to AHP.

Further insights can be gained about DEA from the weights used. DEA assumes equally proportional improvements of all inputs or all outputs. This assumption becomes invalid when a preference structure over the improvement of inputs (or outputs) is present in evaluating inefficient DMUs. The unrestricted weight means that some of the inputs or outputs may be assigned a weight of zero, especially if the DMU is doing poorly in a particular dimension. This assumption is definitely not true in the present study, in which all the variables contribute in some way to the overall efficiency. To address this problem, in the integrated model, AHP was used to restrict the weights by using the management input, so that the weights assigned are more realistic.

However, the study shows that the AHP method when used alone involves only intuitive decision making. Because human bias is possible, the validity and stability of the AHP result can be questioned. Realizing the problems that each of these methods caused, we looked at a decision-weight framework that integrates objective and subjective information complementing each other's weaknesses. Charnes et al. (1979) also pointed out that the weights in a traditional DEA model might need some improvements to increase the efficiency of the model. Other researchers have proposed CCR (Charnes, Cooper, and Rhodes)/AR and BCC/AR to improve the DEA model (Thompson et al., 1986; Cooper et al., 2000; Dyson and Thanassoulis, 1988).

Table 1. Design Principles of Smart Growth

Principle	**Description**
Mix Land Uses (SGP1)	-Supporting the integration of mixed land uses in communities as a critical component of achieving better place to live.
Compact Building (SGP2)	-Providing a means for communities to incorporate more compact building design as an alternative to conventional, land-consumptive development.
Variety of Housing Choices (SGP3)	-Providing a range of housing types, sizes, and prices.
Walkable Neighborhoods (SGP4)	-Creating walkable communities to live, work, learn, worship, and play.
Community with Strong Sense of Space (SGP5)	-Fostering communities with a strong sense of place to craft a vision and set standards for development that respect community values of architectural beauty and distinctiveness, as well as expand choices in housing and transportation.
Preserve Open Space and Critical Environmental Areas (SGP6)	-Open space preservation supports smart growth goals by bolstering local economies, preserving critical environmental areas, improving our community's quality of life, and guiding new growth into existing communities.
Infill Development of Existing Communities (SGP7)	-Directing development towards existing communities already served by infrastructure, seeking to utilize resources that existing neighborhoods offer, and conserving open space and irreplaceable natural resources on the urban fringe.
Variety of Transportation Choices (SGP8)	-Providing a wider range of transportation options in an effort to improve beleaguered current systems.
Cost Effective Development (SGP9)	-Embracing the private sector to help make development decisions to be predictable, fair, and cost effective.
Community-stakeholder partnership (SGP10)	-Encouraging community and stakeholder to jointly making development decisions.

Source: The official website of Smart Growth Network, http://www.smartgrowth.org/network.php

3. Research design and methodology

We propose a consensus-making method based on a combination of FAHP and the AR model of DEA. As with other typical urban problems, there are multiple criteria, both quantitative and qualitative, for comparing candidate stations. The nine main criteria derived from smart growth principles for the candidate-TOD station selection were: (C1) Mix Land Uses, (C2) Fill-in Redevelopment, (C3) Open Space, (C4) Compact Building Design, (C5) Housing Opportunities and Choices, (C6) Walkable Neighborhoods, (C7) Variety of Transportation Choices, (C8) Community Participation, and (C9) Public Policy. The evaluators individually and independently, reported their rating of each station by assigning each a cardinal number score. The higher the score, the better the evaluation. The result was a score matrix with seven columns (candidate stations) and nine rows (criteria).

The second-stage problem was how to synthesize these seven evaluations in order to reach consensus. There are several possible ways for reaching such a consensus. In this study, we used a methodology suitable for candidate-station selection. It consisted of a combination of DEA (Cooper et al., 1999) and Fuzzy AHP (Saaty, 1980). Taking into account all these factors, a reasonable conclusion was sought for the group decision-making process.

There are several practical issues associated with using the proposed methods for candidate-TOD station selection. These include a multi-stage procedure for applying an FAHP-like method to analyze the weights each evaluator allocated to the criteria, and the combined use of strength and weakness scores using the DEA method to characterize the candidate stations. These issues are addressed below.

In applying Fuzzy AHP (FAHP), it should be kept in mind that the number of paired comparisons grows rapidly with the number of alternatives. Some evaluators may regard this number as too large or unnecessary, since it is usually their first experience with FAHP. In an effort to lessen this stress, a multi-stage process was used. At the first stage, the evaluators assigned their weights to criteria using either FAHP or their own subjective judgments. In the former case, incomplete paired comparisons were allowed so that members could skip the comparison if they had little or no confidence in comparing the criteria. At the end of the first stage, seven sets of weights on nine criteria were gathered. At the second stage, the distribution of weighted scores was shown to the evaluators. Each member thus knew where they were in the distribution and had the chance to alter their decisions. Note that this is a form of Delphi. This process continued until convergence was obtained.

We then consider the sensitivity analysis required to generate a final decision. First, the sensitivities of selected criteria scores are analyzed. Some criteria, e.g., the ease of transferring to other forms of local transportation, will have a degree of uncertainty in their scores, even if evaluators rate them. Thus, the sensitivity of results *vis-à-vis* these scores should be examined, and the robustness of any solutions verified. Secondly, the sensitivity of the criteria weights should be analyzed later. The assurance region model used to evaluate the efficiency measures is sensitive to the values of the lower and upper bounds, L_{ij} and U_{ij}, which restrict the ratio of weights u_i and u_j as follows: $L_{ij} \le u_i/u_j \le U_{ij}$. These values are derived from the minimum and maximum ratios estimated by the six evaluators. If someone's estimate of the ratio differs substantially from that of the others, thus yielding "too small an L_{ij}" or "too large a U_{ij}", we might neglect such extreme lower or upper bounds. This reduces the interval that the ratio can accept as allowable. Note that this rule is similar to one used for scoring a gymnast in the Olympic Games in order to avoid a "home-town decision".

A straightforward application of this formula indicates that we are severely disadvantaged with regard to discrimination. Thompson et al. (1990) introduced their AR model for obtaining sharper discrimination in the station-selection process for the Super Collider project. Although the assurance region constraints contribute to narrowing the production possibility set and strengthening the discrimination power of this problem, there may still remain cases where we cannot discern significant differences in efficiency. For such cases, we are obliged to tighten the upper and lower bounds of the assurance region.

DEA is a method for estimating the efficiency of units, normally called DMUs, where it is difficult to identify absolute measures of efficiency (Charnes et al., 1978). A typical application might be comparing different distribution centers in a wholesale network in which the mixture of products distributed by different DMUs varies widely. If we consider a case with only one input but two heterogeneous outputs, the method can be relatively easily visualized. If we calculate the output for each unit of input, the outputs for each DMU can then be plotted on a two-dimensional graph. The envelope enclosing the data points represents something like an optimum mix of outputs, which is achieved by using the most efficient DMUs in the system.

The literature on DEA includes examples of benchmarking in health care (hospitals, doctors), education (schools, universities), banks, manufacturing, management evaluation, fast food restaurants, and retail stores (Anderson, 2002). The method is used to deal with systems with multiple inputs and multiple outputs, although these are very difficult to visualize. The main advantage of DEA is that, by comparing each unit to all other similar units, the need to unify inputs and outputs to a single scale, or to weight the relative importance of inputs and outputs, is avoided. The present study is another attempt to fully rank scale units in the DEA context, using one of the more popular MCDM methods, the AHP (see Saaty, 1980). AHP makes pairwise comparisons between criteria and between units, assessed subjectively by the decision maker, to rank the units overall. The eigenvector of the maximal eigenvalue of each pairwise comparison matrix is used for ranking. Based on the hierarchy structure we describe, the experts made judgments about the elements in the hierarchy on a pairwise basis with respect to their parent element. Because the model consists of more than one level, hierarchical composition was used to weight the eigenvectors based on the weights of the criteria. The sum was taken from all weighted eigenvector entries corresponding to those in the lower level, and so on, which resulted in a global priority vector for the lowest level of the hierarchy. The global priorities are essentially the result of distributing the weights of the hierarchy from one level to the level immediately below.

A recent paper by Wang et al. (2007) shows and proposes an LP method for Generating the most Favorable Weights (LP-GFW) from pairwise-comparison matrices; the method incorporates the variable weight concept of DEA into the AHP priority scheme to generate the most favorable weights for the underlying criteria and alternatives based on a crisp pairwise-comparison matrix. The LP-GFW method differs from the LP-based approach presented by Chandran et al. (2005): the former uses variable weights for each criterion or alternative and consists of n LP models, while the latter uses fixed weights and is comprised of a two-stage-goal programming model.

Given the score matrix $S = (S_{ij})$, we evaluate the total score of station $j = j_0$ using a weighted sum of S_{ij_0} as

$$\theta_{j_0} = \sum_i u_i S_{ij_0} \tag{1}$$

with a nonnegative weight set (u_i).

To evaluate the positives of station j_0, the weights (u_i) in Equation 1 are chosen so that they maximize θ_{j_0} under the conditions that the same weights are applied when evaluating all other stations and that the objective station is compared relative to these. This principle can be formulated as follows (Charnes et al., 1978; Cooper et al., 1999). The above statements also explain how AHP is incorporated into the DEA/AR model.

$$Max \quad \theta_{j_0} = \sum_i u_i S_{ij_0}, \tag{2}$$

subject to

$$\sum_i u_i S_{ij_0} \le 1 \ (\forall j), \tag{3}$$

$$u_i \ge 0 \ (\forall j). \tag{4}$$

4. Empirical study

In this section, the suggested method is applied to select the candidate TOD station. The candidate stations, criteria, and evaluators are explained in detail.

To simplify matters, let the seven candidate TOD stations be L01, L02, L03, L04, L05, L06, L07, and L07 shown as Fig. 1. We also choose the nine criteria, C1, C2, C3, C4, C5, C6, C7, C8, and C9 for the sake of comparison.

In this study, we propose a linear programming (LP) method that integrates the DEA variable-weight concept with AHP to generate the most favorable weights for criteria or alternatives based on a matrix of pairwise comparisons. The variable weights imply preference structures derived from different decision makers, which allows the interpersonal comparison of utilities to be addressed as follows.

Unlike MCDA models, which usually rank elements on multiple criteria (inputs and outputs) and usually provide common weights, DEA does not use common weights. In DEA, the weights vary among the units: this variability is the essence of DEA. The values of the weights differ from unit to unit, and it is this flexibility in the choice of weights that characterizes the DEA model. This variability of weights is the strength of DEA, because DEA is directed to frontiers rather than central tendencies. Instead of trying to fit a regression plane through the center of the data, DEA floats a piecewise linear surface, the efficient frontier, to rest on top of the observations. In other words, DEA chooses the set of weights that assigns the highest possible efficiency score for each unit being evaluated (Sinuany-Stern et al., 2000). It is assumed that the weights can vary from station to station in accordance with the principle we choose for characterizing the stations.

It should be noted that the DEA is here directed towards "effectiveness" rather than "efficiency" since it is not a matter of resource utilization, as required for evaluating efficiency. Achieving the already stated (or prescribed) goals is the aim. The initial goals, stated broadly, are made sufficiently precise with accompanying criteria for evaluation so that (a) proposed actions can be evaluated more accurately and that (b), once the proposals are implemented, any accomplishments (or lack thereof) can be subsequently identified and evaluated (see Cooper et al., 1999, p. 66, for additional discussion).

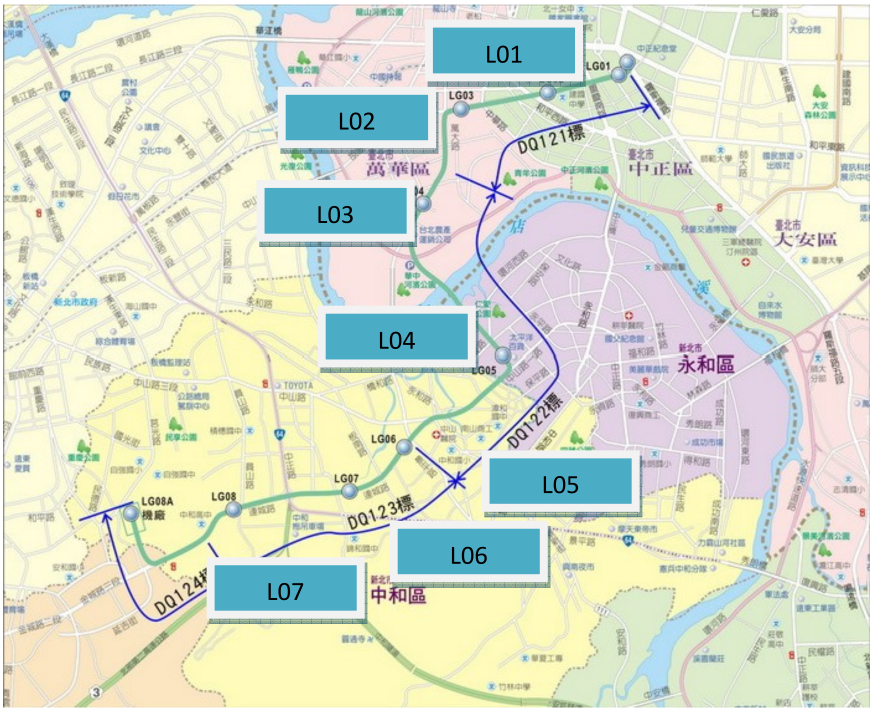

Figure 1. An Empirical Study of TOD Stations in Taipei City

Furthermore, the weights given each criterion should reflect the preferences of all evaluators. This can be represented by a version of the AR model. For every pair of criteria i_1, i_2, the ratio u_{i_1}/u_{i_2} must be bounded by $L_{i_1 i_2}$ and $U_{i_1 i_2}$ as

$$L_{i_1 i_2} \leq u_{i_1}/u_{i_2} \leq U_{i_1 i_2} \tag{5}$$

where the bounds are calculated by using the evaluator's weights (W_{ki}) as

$$L_{i_1 i_2} = \min_k \frac{W_{ki_1}}{W_{ki_2}}, \; U_{i_1 i_2} = \max_k \frac{W_{ki_1}}{W_{ki_2}}. \tag{6}$$

Thus, Equation 2 is maximized subject to the constraints expressed by Equations 3-5. The most preferable weight set, therefore, is assigned to the target station within allowable ranges so that the "positives" of the station are evaluated. However, the same weight is used to evaluate all other stations, and the target station is compared to them. If the optimal objective value $\theta^*_{j_0}$ satisfies $\theta^*_{j_0} = 1$, then the station j_0 can be judged to be the best. If, on the other hand, $\theta^*_{j_0} < 1$, the station is inferior to others with respect to some (or all) criteria.

The proposed empirical process is explained in detail below. We have the lower/upper bounds of ratios for every pair of criteria. Using these bounds as the assurance region constraints, the variable weight problem was solved.

In the paragraph that follows, we verify that the optimal weights for all other stations shown in Table 2 also satisfied these weight constraints.

Station L02 could not attain a full score of 1 even when assigned the best allowable weights. As can be verified, the weights gave a full score of 1 to L03 and L06, which are called "reference" to L01 and are on the efficient frontier of the current problem. Table 1 shows that Stations L03 and L06 were the best performers. The scores in Table 1 indicate the relative distances from the efficient frontier. The lower a score, the weaker the "positives" of the station. Thus, the stations can be ranked as in Table 2.

We now use the AR model of DEA to evaluate candidate stations. First, the lower (L_{ij}) and upper (U_{ij}) bounds were estimated on the ratio of criteria i and j in (1) by

$$L_{ij} = \min_{k=1,\dots,5} \frac{W_{ki}}{W_{kj}}, \; U_{ij} = \max_{k=1,\dots,5} \frac{W_{ki}}{W_{kj}}. \tag{7}$$

Table 2. Optimal "positives" scores and weights.

TOD station	L01	L02	L03	L04	L05	L06	L07
Score $\theta_{j_0}^*$	0.87	0.91	1.00	0.96	0.98	1.00	0.96
Rank	7	6	1	5	3	1	4

These bounds were used for the AR model.

Two stations, L07 and L04 (both have positive = 1.00) are excellent. The other stations lag significantly behind stations L07 and L04. From the results obtained using the DEA model, we found that although station L07 was beyond the CBD of Taipei City, it had higher scores than L04, which is in near the center of downtown. All of this shows that the overall performance for each candidate station was influenced primarily by the specific factors of smart growth principles considered in our study.

Using both of the above traditional weighting method and the AR/DEA method, each TOD station was first evaluated numerically with respect to the set of chosen criteria. These evaluations may be made objectively (quantitatively) or subjectively (using expert knowledge). Second, each evaluator used their own judgment on the relative importance of the criteria. For this purpose, either FAHP or direct subjective judgments may be used. When these conditions are satisfied, the proposed methods rank the candidate stations to bring consensus within the evaluator group. Results obtained using the AR model have, in particular, several merits for both candidates and evaluators. For candidate stations, the results are acceptable in the sense that the most preferable weights for the station are assigned within the allowable bounds of the evaluators. The optimal weights vary from station to station in that the best set of weights is assigned to the station. In a similar way, the relative weaknesses of each station can also be evaluated. These two measures are then used to characterize the candidate stations. For evaluators, each can be assured that their judgments on the criteria are taken into account and that the ratios of every pair of weights fall within the allowable range. Despite the exclusion of several evaluators' ratios for discrimination purposes, this approach is more reasonable and acceptable than using the average weights of all evaluators, especially when there is a relatively high degree of scatter to consider.

5. Conclusion

Urban sprawl and the congestion of cities have become the inevitable development trend in the process of economic growth. At the early stage of urban development, there lacks of design and control strategy towards urban planning and development. The pursuit of the auto-oriented development has led to urban sprawl and leapfrog developments.

A wide array of methods and approaches to uncertainty, optimization, and interactions between human and biophysical domains in decision-making have been developed (Hill et al., 2005). There has, however, been a frustrating deficiency in the implementation of these methods within practical frameworks for decision-making and in forms that make them accessible to the lay policy analyst or regional planner. Because the AHP/MCDA approach has many advantages, including simplicity and flexibility, it has been highly successful. However, MCDA would be greatly improved by having a suite of different methods and approaches that allow the user to explicitly propagate uncertainty and to apply various fuzzy and probabilistic approaches as shown in this study.

We have presented a method-oriented study on the evaluation process for locating a TOD planning in Taipei metro transit system, Taiwan. We believe that the proposed method can be used to execute this critical portion of the project. The key characteristics of the proposed method can be summarized as follows. Each station has been numerically evaluated with respect to the set of chosen criteria. These evaluations can be made objectively (quantitatively) or subjectively (using expert knowledge). However, each evaluator can make their own judgments about the relative importance of the criteria using FAHP.

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