

Planning Strategy for Green Transit Oriented Development Using A Multi-objective Planning Model

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Abstract: This study develops a multi-objective planning model for Green transit-oriented development (Green TOD) from the aspect of overall review of urban planning, which aims to generate planning alternatives for land use allocation, bikeway design and water resource allocation. The objectives of the model are maximizing the development density, maximizing the mixed land use, maximizing the biophilic open space, maximizing the bikeway accessibility, minimizing the parking demand, maximizing the benefit of resource allocating and minimizing the rezoning scale of available land. The following constraints are considered in the model including rezoning feasibility of overall review, compatible land use allocation, minimum allocated scale and maximum allocated capacity, budget limit, identification of transit station area and bikeway continuities. The revised minimum deviation method with different weight settings were used to search the non-inferior solutions for a numerical case built by this study to verify the applicability of the proposed model. Finally, scenario analysis was conducted to explore the characteristics of the model. The result found that some of the objectives, which cannot be integrated due to the difference of planning concept and decision making problem, feature of non-trade-off relationship. Approaches of high density development and environmentally friendly development can be applied to pursue the integrated benefit according to this characteristic. Furthermore, Scenario analysis showed that budget amount influences the planning flexibility and trade-off degree significantly. Budgeting should therefore be dealt appropriately base on the current zoning to ensure the achievement of planning preference.

1. INTRODUCTION

Transit-oriented development (TOD), a sustainable urban form features of high density, mix-use and pedestrian-oriented urban design, has become a main concept of urban planning in anticipation of improving transport efficiency and land use function ([J. J. Lin and Gau, 2006](#)). However, excessive density and compact form may deteriorate the traffic condition and accelerate the resource consumption in inner city ([Lehmann, 2010](#); [Nahlik and Chester, 2014](#); [Zhang, 2010](#)), which further influences the living

quality. The concept of Green TOD, which combines TOD and Green Urbanism, has been proposed as an active approach in response to climate change, global warming and energy crisis ([Cervero and Sullivan, 2011](#); [Lehmann, 2010](#)).

Green TOD is an ultra-environmentally friendly urban form, which embeds the ecological planning features in TOD, like reducing energy consumption, improving the efficiency of energy usage, and enhancing the productivity of renewable energy basis on the high density feature, providing chances to integrate energy resources and foster electric vehicles industry through the mix-use pattern, increasing biophilic open space diversely via ecological planning approach, conserving and reusing energy by green techniques, architecture design, etc. Performance of Green TOD can reach the target of sustainable mobility, self-sufficiency in energy and zero-waste living ([Cervero and Sullivan, 2011](#); [Lehmann, 2010](#); [K. Y. Lin, 2009](#); [Wen, 2012](#); [K. L. Wu, 2009](#); [Y. H. Wu, 2009](#))

Nevertheless, studies of Green TOD still focus on defining the planning concept or establishing the evaluation framework and criteria of it ([Cervero and Sullivan, 2011](#); [K. Y. Lin, 2009](#); [Wen, 2012](#); [K. L. Wu, 2009](#); [Y. H. Wu, 2009](#)), it still lacks a planning model for Green TOD to generate planning alternatives objectively for planners, which makes the planning process become intuitional. With regard to the land use planning model, except for [Ridgley and Giambelluca, \(1992\)](#), [Stewart, Janssen, et al., \(2004\)](#), [Ligmann-Zielinska, Church, et al., \(2008\)](#), and [Chen, \(2008\)](#), prior studies seldom took the current zoning and rezoning restriction into consideration during the model formulation phase, which not only made the formulated model fail to represent the real planning problem but also decrease the application value and the correctness of the planning result. This study therefore developed a multi-objective planning model for Green TOD from the aspect of overall review of urban planning according to the contents emphasized by Green TOD, namely land use allocation, bikeway design and water resource allocation to generate the draft plans. In response to model characteristic, the revised minimum deviation method was taken to search non-inferior solutions set for analysis and recommendation.

The remainder of this study is organized as follows. Section 2 describes the modelling concept. Section 3 formulates the model and presents model-solving approach. Section 4 demonstrates the application of the model. Finally, Section 5 gives concludes and recommendations for future research.

2. MODEL CONCEPTS

This section first characterizes the decision-making problem and identifies the key factors of Green TOD planning. The modelling structure is described as the basis of model formulation in ‘‘Model framework’’ section.

2.1 The Decision-making Problem

This study defines the decision-making problem by asking who, when, where, and what. For the question who, four decision making groups, i.e. planner, resident, environmentalist and developer, are considered as the stakeholders for urban planning. Preferences of each groups and decision makers as a whole are surveyed as the basis of model formulation. As for question what, three sections were defined as the decision making problems according to the key factors of Green TOD planning. First, optimal location,

zoning type and size are determined for “land use section” where zoning type is simplified into residential district, commercial district, industrial district, open space, parking lot, and available land. Second, optimal location of bikeway on sidewalk is determined under the given blocks pattern and road networks for “transportation section”. Finally, optimal size of distributed water recycling system (WRS) in each zoning is determined for “energy and resource section” as a practice of green urbanism under the consideration of the stakeholders’ preference. The allocation results mentioned above aims to generate a draft plan as a reference for detail planning afterward rather than a final planning alternative. On the other hand, to formulate a planning model for reviewing, question when is therefore defined as the overall review phase of urban planning which is static planning work. Following the question when, question where is thus suitable for urban area with given transportation network and land use zonings. Furthermore, block is defined as the decision unit to enhance the application value of the proposed model under the given configuration. However, to simplify the formulated complexity of the proposed model, bikeway allocation problem is determined on the “block topology graph” where nodes are derived from block center, and links are constituted by the adjacent nodes rather than “network graph” (see [Figure 1](#)).

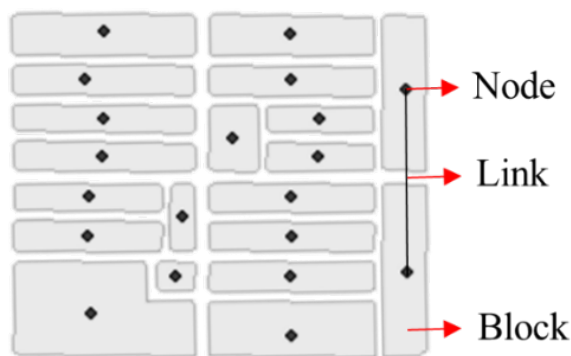


Figure 1. Definition of Planning Space

2.2 Problem Analysis

A literature review was performed to identify the planning factors of Green TOD (e.g., [Beatley, 2000](#); [Calthorpe, 1993](#); [Cervero and Kockelman, 1997](#); [Cervero and Sullivan, 2011](#); [Ewing and Cervero, 2010](#); [Freilich, 1998](#); [Hess and Lombardi, 2004](#); [Jabareen, 2006](#); [Lehmann, 2010](#); [Loukaitou-Sideris, 2001](#); [Newman, 2010](#); [Newman and Matan, 2013](#); [Wen, 2012](#)) and come out to be nineteen ones with their content. Representatives of the stakeholders, 2 persons per group which includes official planner, consulting planner, expert and scholar of environmentalism, village chief, chief member of community committee and developers, were selected. Questionnaires of fuzzy Delphi method ([Jeng, 2001](#)) were conducted to screen the key factors for Green TOD planning. For the detail, please refer to [Liu, \(2015\)](#). The factors that concerned by each stakeholder groups and the ranking of those are shown in [Figure 2](#). Factors of the top five ranking, except for factor 14, focus on TOD strategies of regional scale like transportation system planning and growth management, etc. While factors that ranked from six to ten, factor 17 excluding, emphasize on TOD strategies of station area (SA) scope. In contrast, the importance of the

factors that features of green urbanism are relatively lower than others, but the point of the least important one still reaches 5.5 within 10 point interval and is thus important in general. The aforementioned analysis shows that Green TOD still lays stress on TOD but tend to incorporate the strategies of green urbanism in it. Furthermore, strategies of Green TOD should be taken from regional scale to SA scope gradually. Since some factors in [Figure 2](#). are not suitable for mathematical programming model, factors were classified into three group, i.e. pre-modeling, in-modeling, and post-modeling. The pre-modeling factors include factor 1 and 8 in response to make the model be applied in developable urban area with given transportation network. Factors 9 and 15, which feature of energy policy and construction phase, respectively, are post-modeling factors and should be handled after modeling analysis. Factors that belong to in-modeling are discussed in the next sub-section where factor 10 merely deals with the bikeway allocation between trip ends without detail design for bikeway type, factor 14 only tackles the open space designated for biophilic use without the discussion of ecological engineering, and factor 17 simply discusses the allocated location and size of WRS instead of the selection of system types.

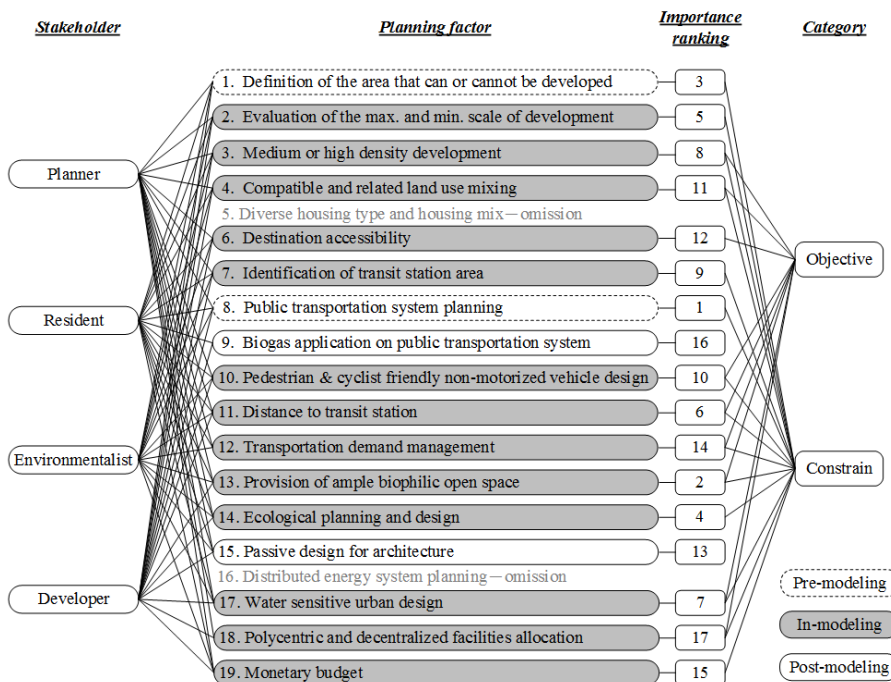


Figure 2. Planning Factors Tackled in The Planning Model for Green TOD

2.3 Model Framework

Base on the analysis of last sub-section, factors that do not have clear threshold but induce clear expectation are categorized into objectives. Seven objectives were draft for modeling; however, some factors are integrated due to the correlation ship between one other ensuring the trade-off relationship of multi-objective programming.

The first objective, derived from factor 3, is maximizing the ridership of metro system in TOD area after referring to the prior studies ([Feng and Chang, 1993](#); [Kaneko, Hanzawa, et al., 1999](#); [J.-J. Lin and Li, 2008](#); [J. J. Lin and Gau, 2006](#)). High density development can not only increase transport

efficiency, land use function, management ability of energy and resource usage, but also prevent from the drawback of urban sprawl.

The second objective, derived from factor 4, is maximizing the mixed land use degree in TOD area by using entropy index rather than mixing type only in prior studies ([Huang, 2008](#); [J.-J. Lin and Li, 2008](#)) to decide the optimal mixing type and size simultaneously. A vibrant street with multiple functions is expected to be shaped under the mix use pattern by shortening the travel distance of trip, which further enhance activities convenience and urge people communicating face by face.

The third objective, derived from factor 13 and 14, is maximizing the biophilic open space per floor area in TOD area where open space includes that designated by both urban plan and zoning regulation. City that embraces nature as integral and bring nature into life can relief the stress of high density development of TOD, enhance amenity and living quality, conserve biological diversity, and adjust microclimate.

The fourth objective, derived from factor 6, 10 and 11 that are tightly connected with accessibility, is maximizing the trip ends served by bikeway and travel demand of them in TOD area. The allocation of bikeway can enhance the accessibility of non-motorized vehicle and urge trips shift from cars to green modes, which further reduce carbon emission and reach the vision of carbon neutral.

The fifth objective, derived from factor 12, is minimizing the allocated size of parking lot in TOD area where parking lot designated by urban plan was discussed only for the sake of the definition of decision-making problem. The management of parking demand curb the automobile use, which results in fewer usage of fuel and prevents the water resource and runoff from being polluted.

The sixth objective, derived from factor 17 and 18, is maximizing the allocated benefit of distributed WRS. To simplify the difficulty of model formulation, optimal volume that should be allocated in residential, commercial and industrial district was discussed only rather than the discussion of the diverse WRSs, which feature of different allocated characteristics. Furthermore, since the application of WRS mainly focuses on building scale, floor area that can be built in zoning is taken as the allocated basis via transforming the land area of zonings by floor area ratio (FAR). With the practice of water sensitive design, a water saving society can be expected to relief the pressure of water supply and enhance the efficiency of water usage by recycling.

The seventh objective is minimizing the rezoning scale of available land under the assumption that the available land can be used for rezoning. The available land mentioned above is the zonings that does not be discussed in model but exist before the overall review and make certain function. The purpose of this objective is to retain land for other functional usage and to ensure the urban developing soundly.

It's noteworthy that objectives, though, cannot correspond to that concerned by each stakeholder one by one for the sake of factor screening and integration, preference of each stakeholders is still involved in it. In further, since content of the TOD, green urbanism and the characteristics of overall review were involved in the objectives of proposed model, corresponding scope is thus designated for different objectives. The first five objectives, which tightly related to the concept of TOD, is designated for the scope in TOD area. While planning area as a whole is design for the last two objectives, which reflect the planning concern of green urbanism and overall review planning, respectively.

On the other hand, following constrains were proposed on the basis of the prior studies experience and the factors with clear regulation or thresholds in [Figure 2](#).

The rezoning feasibility of overall review defines the allowable rezoning condition in [Table 1](#) under the consideration of the land rent of zonings in Taiwan. The constrain may prevent from the dispute of justice and ensure the property right of landlord. Nevertheless, to ensure the service quality of public facility, the allocated public facility land before overall review is forbidden to be rezoned despite the lower land rent versus other zonings.

Table 1. Table of Allowable Rezoning Condition

Origin zoning	Allowable rezoning condition				
	Commercial district	Residential district	Industrial district	Public facility land	Available land
Commercial district	-	×	×	×	×
Residential district	○	-	×	×	×
Industrial district	○	○	-	×	×
Public facility land	×	×	×	-	×
Available land	○	○	○	○	-

Note: ○ is allowable rezoning condition; × is unallowable rezoning condition.

The restriction of allocated location firstly prohibit to allocate the residential district and industrial district adjacently to prevent from external cost caused by incompatible land use mixing. Furthermore, minimum width of sidewalk that allowable for bikeway allocation, namely 2 meter, is defined after referring to the Institute of Transportation (Su, Cheng, et al., 2013) in Taiwan and is taken as the screening basis for candidate bikeway definition.

As for the restriction of allocated scale and capacity, restrictions for the land use section ensure the allocated result comply with the regulation of the economic scale of each zoning, the carrying capacity of each units, and the relationship between the specific zonings allocated totally. Restrictions for the transportation section, on the other hand, regulate the metro trip derived from land use allocation not to exceed the limited capacity of metro system and the reasonability of tridistribution. Finally, restrictions for the WRS ensure the efficiency and safety of the allocated system by designating the minimum floor area scale for allocating WRS, the lower bound of the utilization standard and the upper bound of that.

Continuity restriction among the important nodes of bikeway network was revised from that proposed by ([J.-J. Lin and Liao, 2014](#)) to tackle land use and network design problem simultaneously and ensures the convenience of cyclists. The origin and destination of important nodes pairs is consisted of the nodes where the metro stations located in and the remaining ones respectively according to the TOD planning concept. Each o-d pairs is determined one by one if it's necessary to paved bikeway between them.

Budget limitation ensures that cost for expropriating the public facility land and bikeway constructing are less than the government investment. Identification of transit station ensures the sense of place of different SAs according to their texture by the evaluation of Job-Housing ratio (JHR) after referring to the index used by ([J.-J. Lin and Li, 2008](#)). Finally, value range of decision and ancillary variable, non-negative real number, binary integer

number and real number between 0-1 included, ensure the reasonable allocation result of the proposed model.

3. MODEL FORMULATION

In terms of model application, the proposed model was generated based on the following assumption. First, zonings that doesn't be discussed in the proposed model are simplified into "available land" which can be used for rezoning. The parameters of it, zoning regulation and transportation demand for instance, are negligible. Second, each zoning was allocated for its main usage without considering the permitted usage of it. Third, TOD area of metro stations, determined by Thiessen's polygon method, doesn't overlap with each other. Besides, travelers are supposed to use the nearest metro stations and choose the shortest travel path base on rationality. Forth, the capacity of metro system in morning peak hour and that in afternoon are not only equal but also greater than that in off-peak hour. Finally, the limitation of bikeway capacity, which is determined by the bikeway types, is negligible as the bikeway type is absent in the decision-making problem of the proposed model.

The first objective, maximizing the ridership of metro system in TOD area. The second objective, maximizing the mixed land use degree in TOD area. The third objective, maximizing the biophilic open space per floor area in TOD area. The forth objective, maximizing the trip ends served by bikeway and travel demand of them in TOD area. The fifth objective, minimizing the allocated size of parking lot in TOD area. The sixth objective, maximizing the allocated benefit of distributed WRS. The seventh objective, minimizing the rezoning scale of available land. To deal with the rezoning problem of overall review, each block is taken as the basis unit for the confirmation of the rezoning feasibility.

The decision-making problems of the propose model include three sections, which cannot be involved in modeling of each objectives simultaneously, the revised minimum deviation method (RMDM) is therefore used for problem solving to prevent from the solving bias caused by different measurement of the objectives via normalization approach. Following by this, the establishment of the trade-off table thus differs from the traditional way in response to the RMDM. The solving process of RMDM is presented as [Figure 3](#).

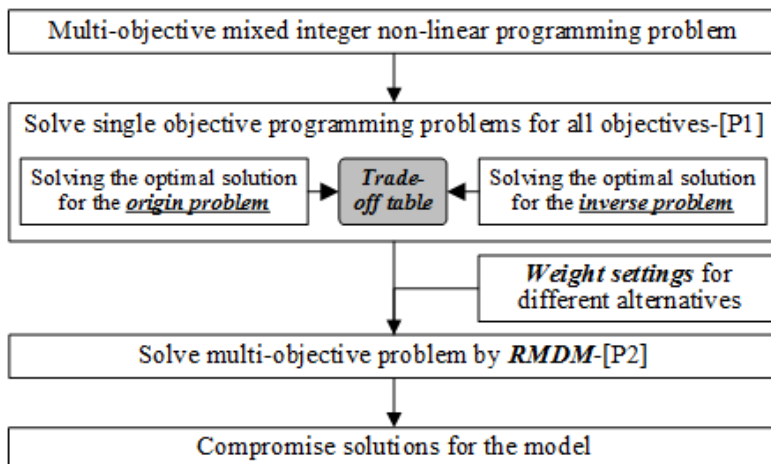


Figure 3. Solving process of RMDM

4. NUMERICAL CASE STUDY

This section first describes the numerical case. The parameter used in model are stated followed by planning result. Finally, scenario analysis of increasing the budget limit are presented.

4.1 Numerical Case and parameter

To ensure that the proposed model is applicable for reviewing, this study proposes the numerical case and parameter used after referring to the condition of Danhai new town (DNT), whose main purpose for the second overall review plan is suitable for the Green TOD planning. The total planning area is 140.8 ha where area for review is 111.3 ha (land use for road is excluded) and 24 blocks with current zonings are included in. As for the transportation system, road system with grid pattern is set as well as a metro system consisted of two stations whose development orientation are residential one and commercial one, respectively. The SA of TOD within a radius of one-quarter mile from a transit station is defined by Thiessen's polygon to prevent from overlapping. On the other hand, the allocated bikeway before overall review and candidate bikeway network in TOD area are also categorized. However, the destination nodes of important pairs which has been discussed in “model framework” are defined as the nodes that neither contain the metro stations nor be served by the bikeway before overall review since the continuity constrain on nodes that are served by bikeway before overall review has been satisfied already. The technique mentioned above can significantly relief the computing burden of model meanwhile ensure the same planning result. Attributes mentioned above are presented in [Figure 4](#).

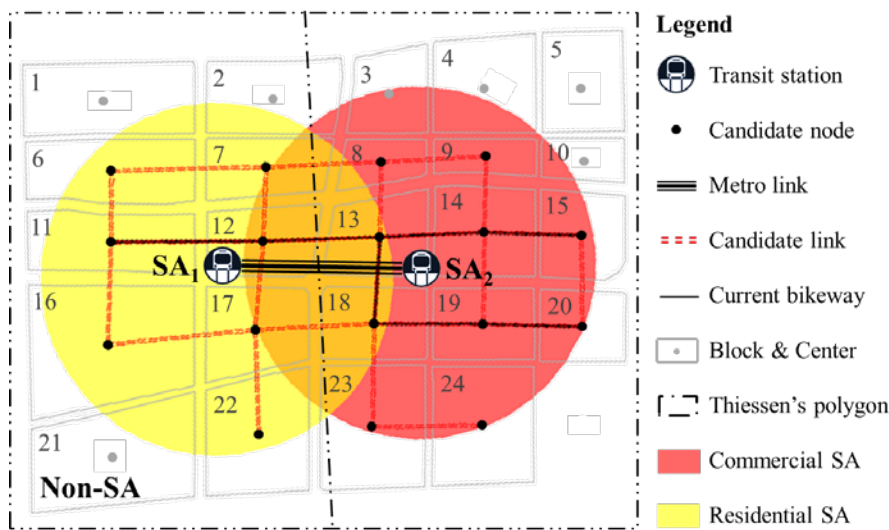


Figure 4. Scenario of the numerical case

In terms of parameters, estimations and sources are list only to control the article space; for detail, please refer to [Liu, \(2015\)](#). For the attributes of each zonings, floor area ratio (FAR_k), building coverage ratio (BCR_k), green coverage ratio (GCR_k) and economic scale (L_k) were derived from zoning regulation of DNT and overall review of urban plan; generation rate (G_k), production rate (O_k) and attraction rate (D_k) of trips were proposed according to the Institute of Transportation ([Chiu, Chen, et al., 1995](#)); modal

split rate of metro system (M_k) and bike (B_k) were derived from the public transit survey in Taiwan; yearly water consumption (WC_k), baseline proportion for utilizing the reclaimed water (BP_k) and proportion of the total water consumption that can be substituted by reclaimed water (SP_k) were estimated from design guideline of rainwater harvesting at construction sites (DGRHCS), building technical regulations, regulation for environmental impact assessment on industrial district development, industrial water consumption report, and technology for water saving in public places. Euclidean distance of candidate links (d_{ij}) were measured by Arc GIS. Attributes of metro system, i.e. ratio of passenger capacity in morning peak hour to that of whole day (u) and two-way passenger capacity of links (C_a) were derived from the construction contract of Danhai LRT system; cost saving derived from WRS allocation (CS) was obtained from statistical data of Taiwan water corporation; unit cost of expropriating public facility land (UCP) was estimated by average market price of real estate of DNT and floor area conversion rate to obtain the compensation fee for land per unit; unit cost of type A bikeway of bikeway construction plan drawn by Executive Yuan in Taiwan was used as the parameter of UCB ; budget limit for public facilities construction (BPF) was proposed after referring to the project cost of the first overall review plan of DNT.

In terms of the upper bound (L_k^u) and lower bound (L_k^l) of the totally allocated size of specific zonings in planning area, parameters were estimated base on “the regulations for the periodical overall review of urban planning”. The parameter of L_k^u for commercial district (191,000m²) was set according to the planning area scale and population plan. In contrast, the parameters of L_k^l were set for parking lot and open space. The former ones were estimated by commercial district scale and planned vehicle number which were represented as $0.1 \times \sum_i (F_{i2}/FAR_2)$ m² and 1,964 m², respectively. The later one was limited not to be allocated lower than 140,805m² (10% of the planning area) if the rezoning scale achieves 1 ha, which are reformulated as [eq. 1](#) to [eq. 3](#) in response to if-then relation.

$$\sum_i \sum_k \frac{|F_{ik} - F_{ik}^b|}{2FAR_{ik}} - 10000 < MCondition \quad (1)$$

$$\sum_i \sum_k \frac{|F_{ik} - F_{ik}^b|}{2FAR_{ik}} - 10000 \geq (Condition - 1)M \quad (2)$$

$$\sum_i F_{i5} \geq 140,805 \times Condition \quad (3)$$

As for the economic scale for allocating WRS (WF_{ik}), regulation of DGRHCS was referred and $F_{ik}/(FAR_k \cdot \beta_k)$ was used as an adjustment ratio to transfer the regulation from building scale to zoning scale. Yet, parameter of WF_{ik} should not be minified if the adjustment ratio is lower than 1 since the allocated floor area doesn't achieve the scale (10,000 m²) regulated by DGRHCS originally. Constrains of [eq. 4](#) to [eq. 6](#) are therefore added in response to the if-then relations where $Ratio_{ik}$ is 1 if the adjustment ratio of allocated zoning k in unit i is greater than 1; otherwise, 0. However, since the ordinance regulates that WRS should be allocated in

industrial district no matter what the zoning scale is, WF_{i3} is set as 0 as [eq. 7](#).

$$F_{ik} - FAR_k \times \beta_k \leq MRatio_{ik}, \forall i, k = 1, 2 \tag{4}$$

$$F_{ik} - FAR_k \times \beta_k > (Ratio_{ik} - 1)M, \forall i, k = 1, 2 \tag{5}$$

$$WF_{ik} = \frac{10000 \times F_{ik}}{FAR_k \times \beta_k} \times Ratio_{ik} + (1 - Ratio_{ik}) \times 10000, \forall i, k = 1, 2 \tag{6}$$

$$WF_{i3} = 0, \forall i \tag{7}$$

4.2 Planning Result

Since the propose model features of many non-linear functions, the global solver and multithreading computing (LINGO) software package were used for mixed integer non-linear programming problems solving. Scenarios with different budget amount, i.e. S_1 and S_2 were conducted for the comparison analysis (see section 4.3 for further explanation). Trade-off table of [P1] of two scenarios is presented in [Table 2](#). Weight sets of differential alternatives, i.e. $A_1(70,5,5,5,5,5,5), A_2(5,70,5,5,5,5,5), A_3(5,5,70,5,5,5,5), A_4(5,5,5,70,5,5,5), A_5(5,5,5,5,70,5,5), A_6(5,5,5,5,5,70,5)$ and $A_7(5,5,5,5,5,5,70)$ for each objectives, were set for [P2] to discuss the preferential differences of objectives between alternatives. Planning results of the allocated zonings and bikeway network are spatially represented in [Figure 5](#) and [Figure 6](#) where the former one is represented by the SA scope to control the article space. The planning result of water resources, in contrast, is represented by objective value only for the sake of less stress on the allocated location of the decision-making problem. [Table 3](#) lists the objective and performance values of these alternatives where the performance values are derived from [*] in eq. 51 and ranges between 0% (worst) to 100% (best). Planning results of S_1 are discussed as following first versus that of S_2 in section 4.3.

Table 2. Trade-off table of the RMDM

Ideal solution Objectives	S ₁		S ₂		Unit
	*Z _q	Z _q	*Z _q	Z _q	
Z ₁	128.484	99.772	130.06	99.304	10 ³ trip person
Z ₂	1.599751	1.121364	1.811551	1.102918	-
Z ₃	0.274952	0.205526	0.309788	0.175059	-
Z ₄	31.577	9.631*	31.97	9.572*	10 ³ trip person
Z ₅	0*	6.84726*	0*	21.54726*	hectare
Z ₆	60.69211	0*	65.46739	0*	Million NT\$
Z ₇	7.132183	27.0586*	7.132183	27.0586*	hectare

Note: global solutions are signed with * versus local solution of others in finite solving time.

In general, different planning results are yielded to reflect the preference of alternatives. To maximize the ridership of metro system in TOD area (1,284,560 trip person), A₁ tends to transfer the zonings toward residential and commercial district which feature of higher FAR and trip generation rate. To enhance the mixed land use degree (the summation value of the entropy is 1.598942), A₂ tends to decrease the residential district but

increase commercial one and open space in TOD area. To maximize the biophilic open space per floor area in TOD area (the summation value of the ratio is 0.27495), A_3 tends to transfer the zonings toward open space and residential district, which features of lower FAR and higher GCR versus that of commercial district. To maximize the bikeway usage (31,543 trip person), A_4 ensures that all the candidate nodes in TOD area are able to be served by allocated bikeway and zonings of them tend to be rezoned as residential and commercial district for the same reason of A_1 . To minimize the allocated size of parking lot in TOD area (0 ha), A_5 tends to rezone the current parking lot to others and allocate the land use demand of it (1.6302 ha) in non-TOD area. To maximize the allocated benefit of WRS (60.27446 million NT\$), A_6 tends to transfer the zonings toward to commercial and residential district instead of industrial one that features of high FAR and the slackest upper bound for allocating the WRS due to the limitation of allocated location (eq. 19). Finally, A_7 , though, tends to retain the allocated size of available land, 7.31915 ha of it still be transferred to satisfy the allocated lower bound of open space and the preference of other objectives.

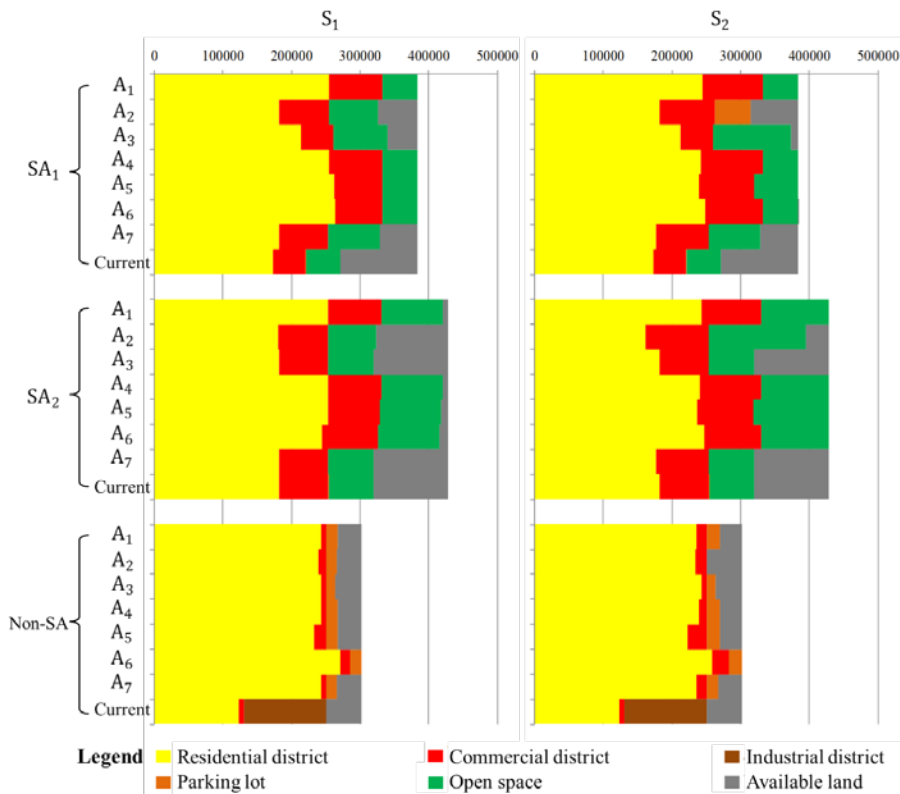


Figure 5. Planning result of zonings in different scope of alternatives

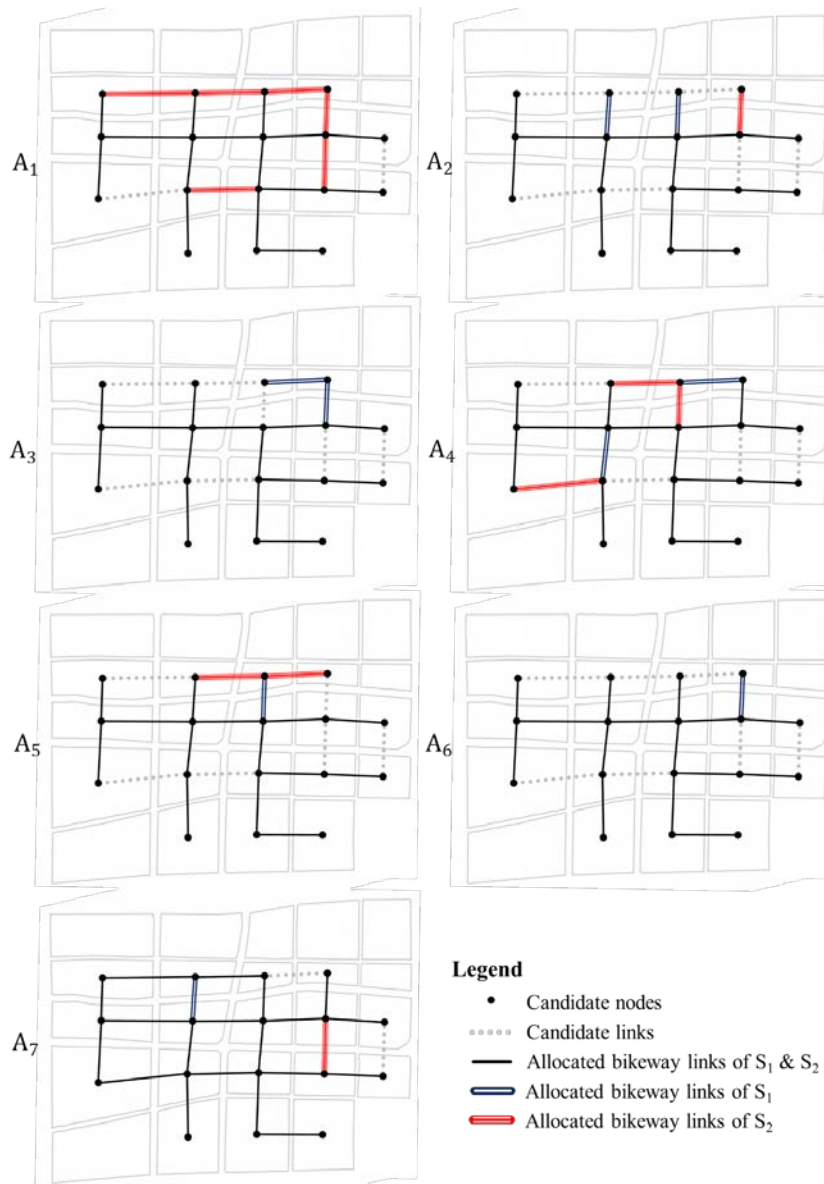


Figure 6. Bikeway network of alternatives

The trade-off relationship between objectives can be observed by the performance of objectives in [Figure 7](#). Generally speaking, the preferential objective of each alternatives (with the highest weight) performs best. Improvement on the performance of the specific objective will sacrifice the performance of others. Nevertheless, there are no trade-off relationship between some objectives as following.

Table 3. Objective and performance value of the compromise solution of alternatives

Objectives		Z_1	Z_2	Z_3	Z_4	Z_5	Z_6	Z_7
Alternatives								
A_1	S_1	1284.56 (100%)	1.519488 (83%)	0.239331 (49%)	30.953 (97%)	0 (100%)	59.27223 (98%)	22.8635 (21%)
	S_2	1295.84 (98%)	1.545650 (62%)	0.235743 (45%)	31.79185 (99%)	0 (100%)	64.13519 (98%)	23.93250 (16%)
A_2	S_1	1002.60 (2%)	1.598942 (100%)	0.253671 (69%)	23.886 (65%)	0 (100%)	48.14336 (79%)	7.421682 (99%)
	S_2	1033.68 (13%)	1.796984 (98%)	0.229151 (40%)	23.24079 (61%)	21.5468 (0%)	49.65224 (76%)	11.78403 (77%)
A_3	S_1	999.92 (1%)	1.559334 (92%)	0.274950 (100%)	24.437 (67%)	0 (100%)	47.87495 (79%)	8.114755 (95%)
	S_2	999.92 (2%)	1.606130 (71%)	0.309787 (100%)	23.00114 (60%)	0 (100%)	46.32837 (71%)	11.48354 (78%)
A_4	S_1	1284.24 (100%)	1.518836 (83%)	0.239609 (49%)	31.543 (100%)	0 (100%)	59.27189 (98%)	22.86345 (21%)
	S_2	1298.08 (99%)	1.547547 (63%)	0.233881 (44%)	31.87585 (100%)	0 (100%)	64.13528 (98%)	23.93250 (16%)
A_5	S_1	1275.20 (97%)	1.506121 (80%)	0.244336 (56%)	30.666 (96%)	0 (100%)	58.82715 (97%)	22.66298 (22%)
	S_2	1247.28 (83%)	1.580486 (67%)	0.260933 (64%)	30.57785 (94%)	0 (100%)	63.32287 (97%)	23.93250 (16%)
A_6	S_1	1273.36 (96%)	1.510293 (81%)	0.242115 (53%)	31.245 (98%)	0 (100%)	60.27446 (99%)	25.83007 (6%)
	S_2	1291.36 (97%)	1.540574 (62%)	0.239519 (48%)	31.08150 (96%)	0 (100%)	65.19106 (100%)	27.05816 (0%)
A_7	S_1	1002.16 (2%)	1.598326 (100%)	0.252468 (68%)	24.493 (68%)	0 (100%)	53.28291 (88%)	7.319150 (99%)
	S_2	1006.64 (4%)	1.597890 (70%)	0.247525 (54%)	24.60486 (67%)	0 (100%)	55.04227 (84%)	7.439245 (98%)

First, the preferential objectives of A_1 , A_4 , and A_6 , i.e. Z_1 , Z_4 , and Z_6 , respectively, all perform well in these three alternatives. The phenomenon may result from the promotion of green modes usage (Z_1 and Z_4) and resources saving approach (Z_6), all of which make the zonings transfer toward commercial and residential district that feature of higher FAR, trip generation rate, and slacker upper bound for allocating the WRS. Second, though pursuit of Z_2 and Z_3 are expected to restrain Z_7 from pursuing via transferring the available land in SA to open space/commercial district and open space, respectively, the preferential objectives of A_2 and A_7 , i.e. Z_2 and Z_7 of each, both performed well in these two alternatives, and the performance of Z_7 in A_3 is also high. The expected trade-off relationships are offset by synergetic effect of budget limitation and allocated lower bound of open space. In other words, the finite budget limits the allocated scale of open space, which not only curbs Z_2 , making it easier to be achieved, and restrains Z_3 from pursuing, but also fail to curb Z_7 via differentiating the allocated scale of open space to the lower bound of it designated by regulation. Third, the preferential objectives of A_5 , namely Z_5 , reaches its positive ideal solution in all alternatives, which may result from the transferable condition between public facility lands and the little demand of parking lot versus others in zoning plan. The planning result of A_5 thus tends to search the compromise solution among the remaining objectives. However, since the finite budget limits the ability of Z_3 to compromise with other objectives, the planning result tends to transfer toward the objectives that feature of high density development and make Z_1 , Z_4 , and Z_6 perform higher. Finally, though the transferable condition

between open space and parking lot is expected to present win-win relationship between Z_3 and Z_5 , trade-off relationship of these two objectives, which may be pseudo, is presented in A_5 due to the attribute of parking lot mentioned above. In other words, transformation from parking lot to open space does little contribution to Z_3 for the sake of little demand of parking lot.

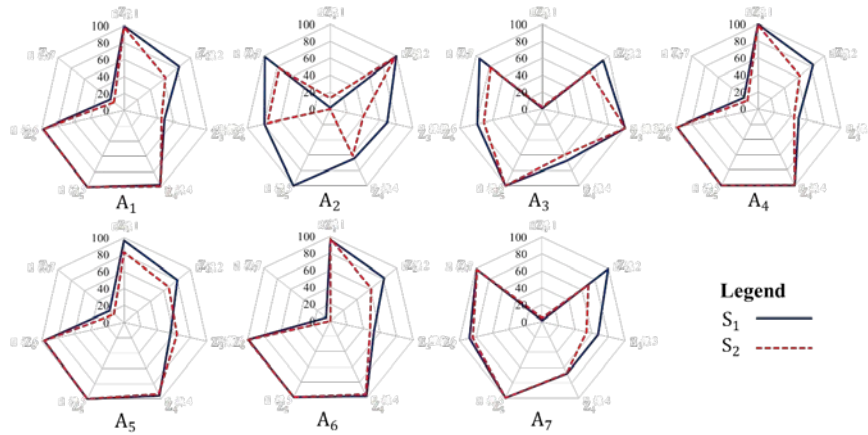


Figure 7. Trade-off relationship between objectives of alternatives

4.3 Scenario Analysis

The planning result stated in section 4.2 reveals that budget amount significantly influences the planning flexibility. S_2 with higher budget amount (15 billion) is therefore conducted to figure out the influence of the adjustment on planning result. [Table 2](#) reveals that except for Z_5 and Z_7 , whose positive ideal solution have already been reached, the remaining objectives can seek a better Z_a in S_2 . Furthermore, trade-off effects between objectives in S_2 are also clarified as following versus those in S_1 . First, trade-off relationships between Z_2 & Z_7 and Z_3 & Z_7 are clearly represented by A_2 , A_3 and A_7 in S_2 (see [Figure 7](#)). Since the allocation of public facility land, parking lot and open space included, is less limited by budget amount, the allocated scale of it of A_2 and A_3 in S_2 (around 19.2 ha) are able to excess to that in S_1 (around 15.7 ha), which curbs the performance of Z_7 in further. Meanwhile, as the value of Z_2 enhances from 1.59 to 1.81 (see [Table 2](#)), the compromise solution of A_7 in S_2 thus fails to reach Z_2 and makes the Z_2 perform worse than that in S_1 . Second, since the pursuit of Z_3 is less limited by the budget amount, the objective of A_5 in S_2 thus performs well versus that in S_1 via allocating more open space and less residential use. Meanwhile, though Z_2 of A_5 in S_2 performs worse than that in S_1 due to the widening of the normalization interval of entropy, the objective value of it (1.580486) still higher than that in S_1 (1.506121). Namely, budget adjustment still contributes to the pursuit of Z_2 . However, it's noteworthy that though A_2 in S_2 tends to transfer the open space to parking lot in SA_1 to prevent Z_2 from being curbed by the normalization operator of entropy, Z_3 and Z_5 with bad performances were yield. The result may be triggered by the multiple non-linear functions of proposed model, which makes it difficult to seek a global optimal solution in finite solving tim.

This study also uses floor to land area ratio (FLR) as an index to discuss the density pattern of the alternatives spatially for both scenarios (see [Figure 8](#)). In general, the development density of the alternatives, the SA of A_3 excluded, increase after the overall review; however, growth condition of each alternatives differs from each other according to their preferential objectives. The growth trend of A_1 , A_4 , and A_6 are relatively high under the preference of high density development; growth trend of A_2 , A_3 , and A_7 , on the other hand, are relatively low under the preference of mixed land use, biophilic planning and conservative planning, respectively; growth trend of A_5 is middling represented, which reflects the compromise effect between objectives since the preferential objective of A_5 can be easily achieved. Furthermore, patterns of the FLR in and out of the SAs of each alternative reveal that, alternatives that allocated with high density pattern along TOD area are A_1 and A_4 only. Since the preferences of A_2 and A_3 tend to transfer the zonings in SA toward open space to ease the impact caused by heterogeneous allocation and high density development respectively, the development density in SAs of A_2 and A_3 are relatively low especially for A_3 . As for the A_5 , since the open space allocated in SA in S_2 is higher than that in S_1 , which further crowds out the allocated space for residential use, the density pattern thus transfers outward the TOD area from S_1 to S_2 . Regarding the A_6 , though the alternative tends to pursue high density development, the allocated location doesn't been stress on for the decision-making problem, which result in the higher density pattern of non-SA versus that of SA_2 . Finally, different growth trend of A_7 would be represented depending on the allocated zoning condition before overall review.

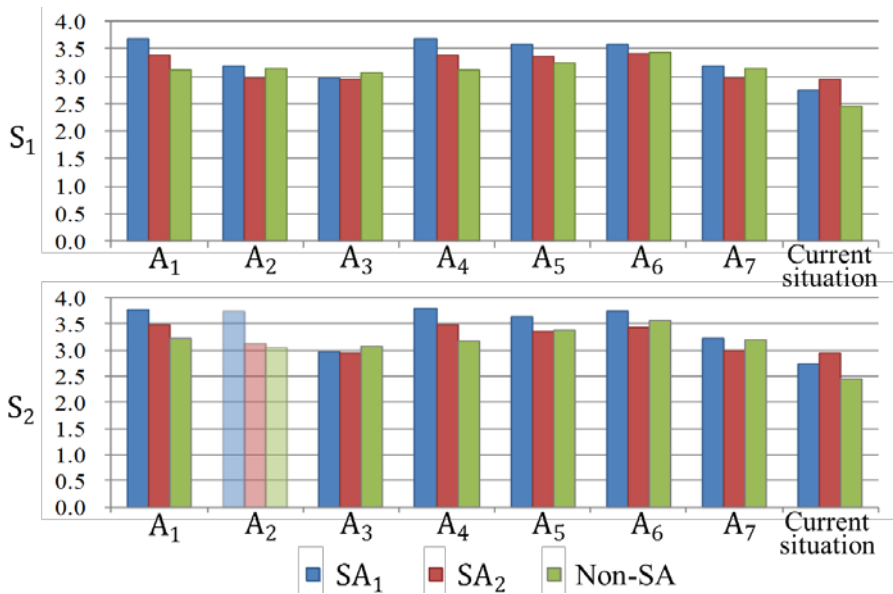


Figure 8. Patterns of the FLR of each alternative

5. CONCLUSIONS

This study develops a multi-objective planning model for Green TOD planning from the aspect of overall review of urban planning, which further assists planning authorities for land use allocation, bikeway design and water resource allocation. The planning result reveals that the propose model is applicable and features of the following characteristics. First, Local optimal solutions are derived in finite solving time due to the multiple non-

linear functions design, which makes the preferential objective of some alternatives fail to perform best (for instance, Z_7 of A_7 in S_1 performs worse than Z_2 of A_7 in S_1 , Z_1 of A_1 in S_2 performs worse than Z_4 of A_1 in S_2 , and Z_1 of A_1 in S_2 performs worse than Z_1 of A_4 in S_2). Yet, the proposed model aims to generate draft plans for detail planning afterward, planning results are still referable despite being unable to find the global optimal solution. Second, there are no trade-off relationships between the objectives of Z_1 , Z_4 , and Z_6 in pair as well as Z_3 and Z_5 . The aforementioned result, though, seems against the theory of multi-objective programming, it's necessary to retain these objectives whose planning concepts and decision making problem are different but tightly connects to Green TOD planning. The corresponding application, i.e. high density development and environmentally friendly development approaches, can be taken to achieve synergetic benefit via satisfying more objectives simultaneously according to this characteristic. Third, since budget limitation is a bounded constrain which directly influence the achievement of the ideal solutions of each single objectives and the trade-off degree between objectives, budgeting should be dealt appropriately before overall review base on the current scale and quality of public facility to ensure the planning flexibility. Last, different type of urban forms, compact one (A_1 , A_4 , A_6), biophilic one (A_3) and functional one (A_2 and A_7) included, are shaped spatially according to the preference of alternatives. Planning preference of the decision making group should therefore be well integrated into objectives weight to make the urban form develop toward the preferential one.

Based on the planning results mentioned above, the following recommendations are made when applying the model. First, the proposed model is established for static planning work and deterministic parameter value was used for the model. The planning results are therefore not able to reflect the uncertainty and dynamic change of urban development. Future study may involve grey programming or fuzzy theory in and adopt dynamic programming for model formulation to handle these problems. Second, the proposed model is design for the overall review phase of urban plan, which should be applied in the planning area with given transportation network only. Planning model that brings the network planning problem in should be studies further to deal with the decision making problem that suitable for the newly constituted urban plan. Third, since the proposed model merely yields the draft plan, the decision making problem of each sections can be discussed further as following. For the land use section, different types of the same zonings, the first type residential district and the second type of that for instance, could be subdivided and zoning types that are not included in the proposed model could be added in to fit the real planning problem. As for the transportation section, the entering and departure route of each units, bikeway types, and the limitation of bikeway capacity could be taken into consideration. The definition of the important nodes pairs could also be revised to discuss the linkage between all nodes rather than that defined in the model framework merely. In respect to the energy and resource section, the distributed energy system could be involved in the decision making problem to extend the content of green urbanism. Formulation of the objective function could also be revised after considering the allocating cost of the distributed energy and resource systems. Regarding the model constrains, gravity model and maximum likelihood method could be applied to estimate the tridistribution to reflect the travel behavior more appropriately. Finally, since the proposed model contains multiple non-linear

functions design, heuristic algorithm may be designed according to the characteristics of the proposed model to approximate the near optimum solution globally in future study.

REFERENCES

- Beatley, T. (2000). *Green urbanism: learning from European cities*, Island Press, Washington, DC.
- Calthorpe, P. (1993). *The next American metropolis: ecology, community, and the American dream*, Princeton Architectural Press, New York.
- Cervero, R., and Kockelman, K. (1997). "Travel demand and the 3Ds: Density, diversity, and design", *Transportation Research Part D: Transport and Environment*, 2(3) 199–219. Retrieved from [https://doi.org/10.1016/S1361-9209\(97\)00009-6](https://doi.org/10.1016/S1361-9209(97)00009-6)
- Cervero, R., and Sullivan, C. (2011). "Green TODs: marrying transit-oriented development and green urbanism", *International Journal of Sustainable Development & World Ecology*, 18(3) 210–218. Retrieved from <https://doi.org/10.1080/13504509.2011.570801>
- Chen, S. C. (2008). *Applying Genetic Algorithms for Solving the Multi-objective and-Use Planning Problem*, Master Thesis, Department of Urban Planning and Spatial Information, Taiwan (In Chinese).
- Chiu, K., Chen, C. H., Wu, H. L., and Lo, H. K. (1995). *The User's Manual of the Characters of Trip Generation of Urban-land in Taiwan Area- The Trip Generation Rate of Mixed Land-use in Taipei Metropolis*, Institute of Transportation Ministry of Transportation and Communications, Taipei (In Chinese).
- Ewing, R., and Cervero, R. (2010). "Travel and the Built Environment", *Journal of the American Planning Association*, 76(3) 265–294. Retrieved from <https://doi.org/10.1080/01944361003766766>
- Feng, C. M., and Chang, C. Y. (1993). "A transit-oriented land use model", *Transportation Planning Journal*, 22(4) 429–444.
- Freilich, R. H. (1998). "The Land-Use Implications of Transit-Oriented Development: Controlling the Demand Side of Transportation Congestion and Urban Sprawl", *The Urban Lawyer*, 30(3) 547–572. Retrieved from <https://doi.org/10.2307/27895129>
- Hess, D., and Lombardi, P. (2004). "Policy Support for and Barriers to Transit-Oriented Development in the Inner City: Literature Review", *Transportation Research Record: Journal of the Transportation Research Board*, 1887 26–33. Retrieved from <https://doi.org/10.3141/1887-04>
- Huang, S. F. (2008). *The Design and Application of Land Use Planning Model for Healthy City*, Master Thesis, Department of Land Economics in National Chengchi University, Taiwan (In Chinese).
- Jabareen, Y. R. (2006). "Sustainable Urban Forms: Their Typologies, Models, and Concepts", *Journal of Planning Education and Research*, 26(1) 38–52. Retrieved from <https://doi.org/10.1177/0739456X05285119>
- Jeng, T. B. (2001). *Fuzzy Assessment Model for Maturity of Software Organization in Improving Its Staff's Capability*, Master Thesis, National Taiwan University of Science and Technology, Taiwan (In Chinese).
- Kaneko, Y., Hanzawa, Y., and Fukuda, A. (1999). "A Study on Location Control Model for Transit Oriented Development", *INFRASTRUCTURE PLANNING REVIEW*, 16 769–777. Retrieved from <https://doi.org/10.2208/journalip.16.769>
- Lehmann, S. (2010). "Green Urbanism: Formulating a Series of Holistic Principles", *SAPI EN. S. Surveys and Perspectives Integrating Environment & Society*, 3(2) 1–10. Retrieved from <https://journals.openedition.org/sapiens/1057>
- Ligmann-Zielinska, A., Church, R. L., and Jankowski, P. (2008). "Spatial optimization as a generative technique for sustainable multiobjective land-use allocation", *International Journal of Geographical Information Science*, 22(6) 601–622. Retrieved from <https://doi.org/10.1080/13658810701587495>
- Lin, J.-J., and Li, C.-N. (2008). "A grey programming model for regional transit-oriented development planning", *Papers in Regional Science*, 87(1) 119–138. Retrieved from

<https://doi.org/10.1111/j.1435-5957.2007.00146.x>

- Lin, J.-J., and Liao, R.-Y. (2014). "Sustainability SI: Bikeway Network Design Model for Recreational Bicycling in Scenic Areas", *Networks and Spatial Economics*, 16(1) 9–31. Retrieved from <https://doi.org/10.1007/s11067-014-9245-7>
- Lin, J. J., and Gau, C. C. (2006). "A TOD planning model to review the regulation of allowable development densities around subway stations", *Land Use Policy*, 23(3) 353–360. Retrieved from <https://doi.org/10.1016/J.LANDUSEPOL.2004.11.003>
- Lin, K. Y. (2009). *Developing a land use assessment model for the station area from the viewpoint of Green TOD-An Empirical study of the KRT R13 Stations Area*, Master Thesis, Department of Urban Planning in National Cheng Kung University, Taiwan (In Chinese).
- Liu, J. H. (2015). *A Land Use Planning Model for Green TOD*, Master Thesis, Department of Land Economics in National Chengchi University, Taiwan (In Chinese).
- Loukaitou-Sideris, A. (2001). "Transit-Oriented Development in the Inner City: A Delphi Survey", *Journal of Public Transportation*, 3(2) 75–98. Retrieved from <https://doi.org/10.5038/2375-0901.3.2.5>
- Nahlik, M. J., and Chester, M. V. (2014). "Transit-oriented smart growth can reduce life-cycle environmental impacts and household costs in Los Angeles", *Transport Policy*, 35 21–30. Retrieved from <https://doi.org/10.1016/J.TRANPOL.2014.05.004>
- Newman, P. (2010). "Green Urbanism and its Application to Singapore", *Environment and Urbanization ASIA*, 1(2) 149–170. Retrieved from <https://doi.org/10.1177/097542531000100204>
- Newman, P., and Matan, A. (2013). *Green urbanism in Asia: the emerging green tigers*, World Scientific, Singapore.
- Ridgley, M. A., and Giambelluca, T. W. (1992). "Linking water-balance simulation and multiobjective programming: land-use plan design in Hawaii", *Environment and Planning B: Planning and Design*, 19(3) 317–336. Retrieved from <https://doi.org/10.1068/b190317>
- Stewart, T. J., Janssen, R., and van Herwijnen, M. (2004). "A genetic algorithm approach to multiobjective land use planning", *Computers & Operations Research*, 31(14) 2293–2313. Retrieved from [https://doi.org/10.1016/S0305-0548\(03\)00188-6](https://doi.org/10.1016/S0305-0548(03)00188-6)
- Su, C. W., Cheng, C. Y., Kao, H. C., Huang, C. C., and Tien, J. C. (2013). *A Study of Integration and Evaluation of the Bicycle Lane Network System in the Eastern Region Plan*, Institute of Transportation Ministry of Transportation and Communications, Taipei (In Chinese).
- Wen, Y. H. (2012). *A Study of The Built Environment Planning and Designing Under the Green TOD*, Master Thesis, Graduate Institute of Urban Planning in National Taipei University, Taiwan (In Chinese).
- Wu, K. L. (2009). "Developing a Framework of Green Transit Village", In: *Paper presented at the Forum on Land Use and Planning*, Tainan (In Chinese).
- Wu, Y. H. (2009). *Developing Evaluation Framework of Green-TOD Site Selection: an Empirical Study of the Rail Corridor in Kaohsiung City*, Taiwan (In Chinese).
- Zhang, M. (2010). "Can Transit-Oriented Development Reduce Peak-Hour Congestion?", *Transportation Research Record: Journal of the Transportation Research Board*, 2174 148–155. Retrieved from <https://doi.org/10.3141/2174-19>