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Land use oriented bi-level discrete road network design

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Abstract

Although there is a broad consensus that integrating land use and transport will facilitate sustainable development, land use element is barely considered in network design problem. This paper proposes accessibility to quantitatively describe transport characteristics of a location. With assumptions about the relationship between land use/land cover types and accessibility, this paper introduces a bi-level programming model for land use oriented discrete network design problem (DNDP) and develops a genetic algorithm (GA)-based solution procedure which incorporates Frank-Wolf algorithm for user equilibrium (UE) assignment and Dijkstra algorithm for accessibility measurement. A numerical example is provided to demonstrate the applicability of the model and algorithm. The results indicate that the accessibility of the target traffic zone is improved to meet the demands of commercial areas.

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1. Introduction

Road network outlines urban spatial structure and acts as human circulatory system to facilitate the functioning of our city by transport and movement of goods and people. With unprecedented challenges (e.g. traffic congestion and pollution) posed by urbanization, more sustainability burdens have been placed on transport systems. To address surging transport demand, optimizing the topology of road network is an effective way, which is generalized as network design problem (NDP). NDP principally involves two categories: discrete network design problem (DNDP) which deals with optimal decisions for adding new links to existing road network and continuous network design problem (CNDP) which deals with optimal capacity expansion of existing links. The objective of previous studies of NDP is to minimize the total network cost (Chiou, 2005; Farvaresh and Sepehri, 2011; Gao et al., 2005; Wang et al.,

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2015). With the evolving transport theory, objectives such as improving reliability (Sun et al., 2014), environmental benefits (Haas and Bekhor, 2017) and reserve capacity (Miandoabchi et al., 2013) have extended the study of NDP. In addition to these objectives, this study focuses on DNDP which is land use oriented.

The root causes of many urban problems lie in the ill-matched urban transport systems and land use/land cover pattern. There is widespread acceptance that integrating land use and transport is crucial for establishing more efficient and sustainable urban environments (Geerlings and Stead, 2003; Te Brömmelstroet and Bertolini, 2010). Transport network is supposed to be closely coordinated with spatial development (Arts et al., 2014). However, NDP conventionally concerns transport systems themselves, i.e. how to optimize a given transport system performance measure, and land use is only factored in land use transport interaction (LUTI) model (Li et al., 2016; Szeto et al., 2015). It is notable that though LUTI model yielded significant results (Acheampong and Silva, 2015), on account of a series of challenges such as model transparency, operability, parameter validity, computational performance, LUTI model has not progressed in practice as far as it is expected (Waddell, 2011). This study aims at improving the efficiency of land use/land cover pattern by matching the mobility service provided by road network to the demands of different land use/land cover types. The optimization objective of land use oriented DNDP is drawn from assumptions about the relationship between transport characteristics which are quantified by accessibility and land use/land cover types. Therefore, this study can evade the discussion of the complicated and unfully comprehended mechanism of individual/agent behavior, which restricts the applicability of LUTI models.

Land use and development needs comprehensive support from transport systems including motorized infrastructure, pedestrian infrastructure, bike infrastructure and public transit infrastructure. Motorized network, as the skeleton of urban transport systems, is the focal point of this study, while non-motorized network and public transit network remain to be further explored. The land use oriented DNDP is formulated as a bi-level programming model. The upper level represents the decisions of transport planning department and the lower level describes users’ behavior by the user equilibrium (UE) traffic assignment model. Considering the complexity and non-convexity of bi-level programming model, with a framework of genetic algorithm (GA), a solution procedure incorporating Frank-Wolf algorithm and Dijkstra algorithm is developed.

The reminder of this paper is organized as follows. Next section introduces the basic assumptions for this study and the bi-level programming model for land use oriented DNDP, followed by a GA-based solution procedure in section 3. Section 4 presents a numerical example in a virtual city with Sioux Falls network to illustrate the applicability of the proposed model and algorithm. Section 5 concludes the paper with conclusions and discussion.

2. Problem formulation

Traffic zone is the spatial unit used in this study. The following notes and symbols are used for the problem formulation.

- $R$: set of origins
- $S$: set of destinations
- $A_1$: set of existing links
- $A_2$: set of candidate links
- $A$: set of all links in the network, $A=A_1 \cup A_2$
- $I$: set of traffic zones
- $I'$: set of target traffic zones
- $G$: set of land use/land cover types
- $K_{rs}$: set of path between origin $r$ and destination $s$
- $x_a$: continuous link flow on link $a$, $x=[x_a]$, $a \in A$
- $t_a(x)$: link travel time function, $a \in A$
- $f^r_k$: traffic flow on path $k$ between OD pair $(r, s)$, $r \in R, s \in S, k \in K_{rs}$
- $q_{rs}$: total travel demand between OD pair $(r, s)$, $r \in R, s \in S$
- $\delta^r_a(k)$: link path incidence variable that $\delta^r_a(k) = 1$ if link $a$ is on path $k$ and $\delta^r_a(k) = 0$ otherwise, $r \in R, s \in S, a \in A, k \in K_{rs}$
- $\tau_a$: binary variable that $\tau_a = 1$ if link $a$ is built and $\tau_a = 0$ otherwise
- $\lambda_i$: accessibility of traffic zone $i$, $i \in I'$
gi: land use/land cover type of traffic zone i, i ∈ I, g ∈ G

tij: minimum travel time from traffic zone i to traffic zone j, i, j ∈ I

[A(g)_{min}, A(g)_{max}]: range of accessibility, which is suitable for land use/land cover type g, g ∈ G

c_a: construction cost for link a, a ∈ A_2

M: an large enough arbitrary positive constant

B: total construct budget

2.1. Assumptions

This study builds upon a basic assumption that transport characteristics which are captured by accessibility, have intrinsic links with land use/land cover types. In this study, land use/land cover types contain residential, commercial, industrial, open space and natural area. In this paper, the following assumptions are made based on empirical experience.

Assumption 1. Current road networks and land use/land cover pattern result from long-term mutual adaption process between land use systems and transport systems. It can be convincingly inferred from the proper functioning of a city that the transport conditions of most areas can meet the demands of corresponding land use/land cover type on accessibility. The suitable accessibility of each land use/land cover type can be obtained from rule of thumb.

Assumption 2. The requirements on accessibility for driving, cycling, walking and public transit vary in land use/land cover types. Commercial areas require comprehensively high driving, cycling, walking and public transit accessibility.

Assumption 3. Only driving mode and commercial areas are considered in this study. The cycling, walking and public transit accessibility are all appropriate for the land use/land cover type of each traffic zone.

2.2. Accessibility measure

Accessibility refers to the ease with which anyplace of a certain area can be reached by individuals at a particular location using the mobility service of specific transport systems (e.g. motorized road network for driving). With assumption 3, accessibility is specified to driving accessibility in this study. The intuitive approach to measure accessibility would be travel time because of its operability, interpretability and communicability. The spatial frame of this study necessitates the use of zone-based accessibility measure and the study area needs to be partitioned into a number of traffic zones. Therefore, the accessibility of a traffic zone is measured by the total travel time from that to all the other traffic zones. In accessibility measure, each traffic zone is represented by a point which corresponds to the geometric centroid. The travel time is a function of traffic flow pattern in network and the accessibility can be expressed in the following equation:

$$\hat{\lambda}_i = f(x) = \sum_{j \in I} t_{ij}$$  \hspace{1cm} (1)

2.3. Bi-level land use oriented DNDP

Due to the partition of control over the decision variables between hierarchical levels, DNDP is typically formulated as a bi-level programming problem or a leader-follower problem (Farahani et al., 2013). The lower level is to characterize the UE traffic flow pattern in road network. With fixed demand, the UE problem has the following form (Sheffi, 1985):

$$\text{(L)} \quad \min \quad F = \sum_{a \in A} \int_0^{s_a} t_a(x) \, dx$$  \hspace{1cm} (2)

s.t. \quad \sum_k f_k^{rs} = q_{rs}, \quad \forall r \in R, \quad s \in S  \hspace{1cm} (3)

f_k^{rs} \geq 0, \quad \forall r \in R, \quad s \in S, \quad k \in K_{rs} \hspace{1cm} (4)
The upper-level for land use oriented DNDP, which deals with improving accessibility to cater for specific land use type by adding new links to existing road network, can be formulated as follows:

\[
\max \min \quad (U) \quad Z = \sum_{i \in I} \left[ \lambda_i - \chi(g_i) \right]_{\max} \left[ \lambda_i - \chi(g_i) \right]_{\min} \\
\text{s.t.} \quad \sum_{a \in A_2} c_a \tau_a \leq B \\
\tau_a = 0 \text{ or } 1, \quad \forall a \in A_2
\] (7)

\[
x_a = \sum_r \sum_s \sum_{k} f_{rs} \delta_{a,k}, \quad \forall a \in A
\] (5)

\[
x_a \leq M \tau_a, \quad \forall a \in A_2
\] (6)

3. Solution procedure

The NP-hardness and non-convexity of bi-level programming problem constrain the usage of exact or mathematical methods. In recent years, metaheuristic method is prevalent in solving network design problem for its no requirement for mathematical property and fast speed to obtain a feasible solution (Miandoabchi and Farahani, 2011; Xu et al., 2009). GA is an adaptive heuristic search algorithm which is inspired by natural evolution. The basic mechanism of GA contains crossover, mutation and selection, through which a population of candidate solutions represented by chromosomes evolves towards better solutions. In this study, the construct budget is simplified as maximum amount of added links, i.e., given the cost of each candidate links is equal, added links cannot exceed a predefined amount, $E$. The details of the GA for land use oriented DNDP are given as follows.

Solution encoding and initialization

Discrete decision variables of upper-level problem are coded as genes to constitute a chromosome which represents a possible solution. A chromosome is a vector of discrete variables, which can be given by: $C = (c_1, c_2, \ldots, c_N)$, where $N$ is the total amount of candidate links. Each gene denotes a candidate link. If the candidate link is chosen to be added to road network, the value of the gene is 1, otherwise, the value is 0. Therefore, a possible solution can be represented as Fig. 1.

Consider the maximum allowed added links constraint, the initialization process of a chromosome is given as follows.

Step 1. Generate a random number $L$ between 1 and $E$.
Step 2. Choose $L$ genes randomly.
Step 3. Let the selected $L$ genes be 1, the other genes be 0.

Crossover

In crossover operation, chromosomes are randomly paired. $l_{cross}$ is a random integer between [1, $N$], which points the gene where crossover operates. $p$ is a random number chosen from [0, 1]. If $p < p_c$, where $p_c$ is the possibility of crossover, a parent pair $(C_i, C_j)$ will produce two children $(C_i', C_j')$ by the following crossover operation.
\[ C'_i = C_i [c_i : c_{lcross-i}]^\pm C_j [c_{lcross} : c_N] \] (10)

\[ C'_j = C_j [c_i : c_{lcross-i}]^\pm C_i [c_{lcross} : c_N] \] (11)

where \( C[c_i : c_i] = c_i \), \( C[c_N : c_N] = c_N \), \( C[c_i : c_0] = [ ] \). The operator \( ^\pm \) appends each element of the later part to the end of the former part in sequence. The generated \( C_i \) or \( C_j \) might exceed the maximum amount of added links. If this happens, then the above operation with a newly generated \( lcross \) is repeated until \( C_i \) and \( C_j \) are both feasible. When \( lcross \) is 1, \( C'_i = C_j \) and \( C'_j = C_i \).

**Mutation**

In mutation operation, \( lmutation \) is a random integer between \([1, N]\), which points the gene where mutation operates. \( p \) is a random number chosen from \([0, 1]\). If \( p < p_m \), where \( p_m \) is the possibility of mutation, the mutation operation on a chromosome \( C_i \) will produce a new chromosome \( C'_i \) as follows.

\[ C'_i = C_i [c_i : c_{lmotion-i}]^\pm c_{lmotion}^\pm C_i [c_{lmotion+1} : c_N] \] (12)

where \( C[c_i : c_i] = c_i \), \( C[c_N : c_N] = c_N \), \( C[c_i : c_0] = [ ] \), \( C[c_{N+1} : c_N] = [ ] \). If \( c_{lmotion} = 0 \), \( c_{lmotion}^\prime = 1 \), otherwise \( c_{lmotion}^\prime = 0 \). If \( C'_i \) exceeds the construct budget bound, choose a gene, of which the value is 1, randomly, and turn its value to 0.

**Fitness calculation**

The UE traffic flow pattern would change over different road network design solutions. UE assignment is implemented at each time of fitness calculation and it is solved by Frank-Wolf algorithm. With the updated link travel time, the minimum travel time between traffic zones is searched by Dijkstra algorithm for measuring accessibility.

To summarize, the GA-based solution procedure is outlined as follows.

Step 1. Initialize a population with \( popsize \) chromosomes, each of which represents a possible road network design solution.

Step 2. For each chromosome, implement the UE assignment and calculate accessibility. Then evaluate the fitness which is the upper level objective and find the best solution of current population.

Step 3. If iteration number reaches the pre-specified maximum generation, stop and return the best solution of all generations; otherwise, continue.

Step 4. Select \( popsize \) chromosomes based on roulette wheel selection.

Step 5. Perform crossover operation.

Step 6. Use mutation operator to diversify solutions.

Step 7. Return to Step 2.

**4. Numerical example**

In this section, a numerical example is created in a virtual city (Fig. 2) to illustrate the applicability of the proposed model and algorithm. The Sioux Falls network, which includes 24 nodes and 76 links, is used as the road network of the virtual city. Links of this network are all one-way and the direction is indicated by the arrow. The existing network consists of concrete lines and the six dash lines are candidate links. The 24 nodes are both origins.
and destinations. Besides the free flow travel time, the demand matrix of the test network and capacity of each link are same with Suwansirikul et al. (1987). The first number in the parentheses on the links is the link index and the second number is the free flow travel time. The travel cost function of link \( a \) can be represented as follows.

\[
t_{a} \left( x_{a} \right) = t_{a}^0 \left[ 1 + 0.15 \left( \frac{x_{a}}{s_{a}} \right)^4 \right]
\]

where \( s_{a} \) is the link capacity and \( t_{a}^0 \) is the free flow travel time of link \( a \). The number in inner circles is the node and traffic zone index. The outer circles represent traffic zones surrounding each node. The nodes in road network correspond to the geometric centroids of these traffic zones. With the Sioux Falls network, the example virtual city is composed of 24 traffic zones which are divided into residential traffic zone (RTZ), commercial traffic zone (CTZ), industrial traffic zone (ITZ), open space traffic zone (OSTZ) and natural area traffic zone (NATZ). The land use/land cover types are indicated by different colours shown in Fig. 2.
Urban development is a mutual adaption process between land use systems and transport systems. The transport construction and land use change are durable and very slow (Simmonds et al., 2013), which enables the quasi-equilibrium representation of development for the virtual city. According to assumption 1, the transport characteristics of each land use/land cover type, which are summarized from the majority, can be reference for setting up the objective of land use oriented DNDP. For commercial areas, in current road network, the accessibility of CTZ 8, 9 and 11 are 478.63, 468.51 and 520.03, respectively. Increasing total travel time is associated with decreasing accessibility. The accessibility of CTZ 11 is obviously inferior to CTZ 8’s and CTZ 9’s. Therefore, the suitable accessibility of CTZ was set between 468 and 478. In the bi-level programming model presented in 2.3, the target area of land use oriented DNDP is usually the whole study area, i.e. \( I' = I \). In this numerical example, to simplify matters, only CTZ 11, of which accessibility is unsatisfied, is considered.

As mentioned in section 3, the construct budget is simplified as maximum amount of added links. In this numerical example, \( E = 2 \). Moreover, \( p_c = 0.8, p_m = 0.2 \), the population number was set to 10 and the number of generations was set to 10. Either significant change in transport systems or land use systems can undermine the quasi-equilibrium process of land use/land cover change and transport construction. Landscape alteration would be brought on by transport construction such as new highways, railways and canals. When land use/land cover pattern remains stable, in order to improve the efficiency of current land use/land cover pattern, the upgrade of road network should be within limits without driving land use/land cover change. The final result obtained from the proposed model and algorithm is (0, 0, 0, 0, 1, 1). For the network with link 70 and link 72, the accessibility of CTZ 11 is 472.49, which reaches the necessary level of accessibility for commercial area. Compared with the other solutions such as the combination of link 30 and link 51, or link 50 and link 55, the obtained solution also has minimal impacts on the system performance, which contributes to the stability of transport systems and land use systems. The discussion of the effects of adding links on other traffic zones is beyond the scope of this paper.

5. Conclusions and discussion

In this study, a bi-level programming model for land use oriented DNDP is introduced and a GA-based solution algorithm is proposed. The objective of DNDP presented in this study changes from optimizing a given system performance measure, such as reducing total travel time or improving reliability, to accommodating the demands of land use and development on accessibility. According to empirical experience, the relationship between land use/land cover types and accessibility is built on 3 assumptions. Taking a CTZ as target area, the feasibility and applicability of this road network design method is indicated by a numerical study.

In this study, the appropriate accessibility of target CTZ was set according to the other CTZs. But the transport characteristics of different land use/land cover types need to be validated from empirical evidence. Another thing noted is that the study area partitioning was simplified by 24 traffic zones corresponding to the 24 nodes of road network. In real cases, the most widely used spatial unit is grid cell and the resolution of grid cell can be 200×200m, 100×100m or even finer, besides, the road network would be more complicated than Sioux Falls, though this test work is relatively large scale for NDP. As a classic test network, the system performance of Sioux Falls network is sensitive to any change to the topology, that is, the accessibility of all the 24 traffic zones is bound to be affected by adding links. However, in the numerical example, only the accessibility of one specific CTZ was analyzed. Moreover, since the UE assignment, which is solved by Frank-Wolf algorithm, is conducted many times at each generation for fitness calculation, there is heavy computation burden with the GA-based solution procedure.

There are a few issues can be considered to further develop and improve land use oriented DNDP in future researches. The development of an area needs comprehensive support from motorized infrastructure, pedestrian infrastructure, bike infrastructure and public transit infrastructure. An integrated view encompassing these four modes would extend DNDP and promote the application value of land use oriented DNDP. Secondly, while integrating land use and transport is critical for urban sustainability, the long-standing focuses of NDP, such as reducing total travel time/cost or increasing reliability, are also important criteria for evaluating the city functioning. A multi-objective DNDP, which considers the land use related objective and the performance of transport systems themselves can provide decision makers with efficient options to establish robust transport systems for urban sustainable development. Additionally, a more efficient solution is needed to break the barrier of applying land use oriented network design methods in practice.
References


