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A bi-level programming model for the land use – network design problem

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Abstract. A sketch map in urban planning roughly lays out a physical plan. However, the process of generating sketches has long been viewed as a "black box". The *sketch layout model* (SLM) was developed in 1999 to improve the efficiency and quality of layout tasks. This model is a nonlinear and multi-objective programming, for analyzing the integrated layouts of land uses, transport network and public facilities. Although the SLM had been developed for three phases and can be applied to real cases, the method still does not distinguish the types of roads in the transport network. This study develops the SLM-IV, a bi-level programming, by integrating the SLM-III and the combined trip distribution/assignment model, to generate a hierarchical network. This improved model can analyze travel demands, and then decide the link type of the network in SLM. A numerical example with relevant sensitivity analysis is presented to verify the operational feasibility and identify the model's characteristics.

JEL classification: C61, R42, R53

1. Introduction

Creating a layout is an important part of developing a physical plan. The layout is presented on a development map, which provides the rules for urban development and serves as a guideline for the public.

The layout task usually begins with generating alternatives, from which a favorable sketch will be chosen and modified to yield a detailed and clear development map. Generating alternatives has long been considered to be a "black box" inside which planners work subjectively with few alternatives, such that the development map is always biased and inappropriate. Consequently, an efficient and systematic process by which the real optimal layout can be attained has become essential.

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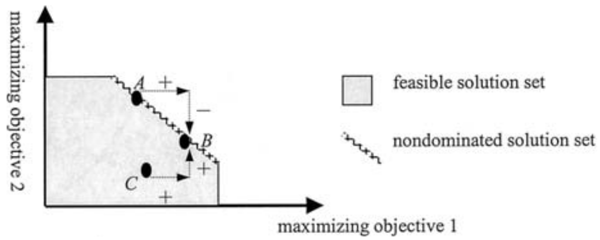

Fig. 1. Example of nondominated solution

A physical plan basically consists of two elements – land use and transport network. However, most studies regarding layout problems merely concentrate on one with the other fixed. For example, Bammi et al. (1976), Bammi and Bammi (1979), Barber (1976), Brotchie (1978), Brotchie et al. (1980), Dokmeci et al. (1993), Gordon and MacReynolds (1974), and Ridgley and Giambelluca (1992) studied the *land use design problem* (LDP), under a given transport system. Janson and Husaini (1987), LeBlanc (1975), Mackinnon and Hodgson (1970), Maganti and Wong (1984), Poorzahedy and Turnquist (1982), and Xiong and Schneider (1995) investigated the *network design problem* (NDP) under a given land use distribution. A few further studies, for example, those of Los (1978, 1979) and Lundqvist (1973) dealt simultaneously with the optimal layout of both land use and the network. Those studies address so called *land use-network design problem* (LNDP).

The *Sketch Layout Model* (SLM) developed by Feng and Lin (1999a,b, 2000) is an LNDP with nonlinear and *multi-objective programming* (MOP). The nondominated solutions solved by SLM can be used as the alternative sketch maps for urban planning, on which the tasks of evaluation and detailed design are based. A feasible solution is nondominated (or also known as Pareto-optimal, noninferior, efficient) if there exists no other feasible solution that will yield an improvement in one objective without causing a degradation in at least one other objective. For example in Fig. 1, solution A and B are both nondominated, but solution C is dominated (to B). The nondominated solutions exist as the objectives considered in MOP are conflict (or existing trade-off relationships) with each other. Since the nondominated solutions can not be compared with each other, the decision maker should evaluate them by using other criteria.

The SLM was developed for three phases. SLM-I and SLM-II can be applied in real cases. SLM-III considers the distribution of public facilities by integrating SLM-II and the *Maximal Covering Location Problem* (MCLP). However, until now, the SLM has ignored the types of roads in the transport network. This study considers the travel demand in SLM to identify the link types in the network layout.

This study developed SLM-IV by bi-level programming to address the travel demand in SLM. SLM-III is employed in the upper problem, and determines the integrated layout of land use, transport network and public facilities. The lower problem is a *combined trip distribution/assignment model* (CDA) simulating travel demands according to the layout taken from the upper problem. The travel times simulated by the lower problem become the given conditions for the upper problem.

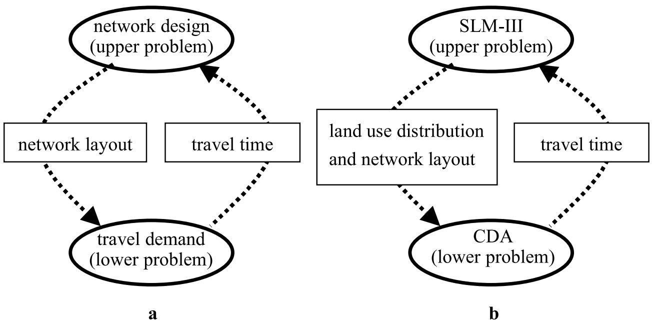

Fig. 2a,b. Model framework. **a** bi-level framework for NDP; **b** bi-level framework for SLM

The paper continues as follows. The conceptual framework is described in the second section. The problem is defined and the model is formulated in the third section. The developed model is tested by a numerical example in the fourth section. Finally, conclusions and recommendations are made.

2. Model framework

A road network consists of different types of link, for example: arterial roads, collectors, and local streets. When designing a network, a planner must specify not only the layout of links but also the classification of link functions. According to the past LNDP studies, SLM has ignored travel demand – an important factor in the classification of roads – to limit the complexity of model. Accordingly, SLM can not classify the type (or function) for each link and the capability of the model is limited.

The NDP model is reviewed to consider the travel demand in SLM. NDP involves the optimal decision on the expansion of a street and highway system in response to a growing demand for travel (Yang and Bell 1998). To date, NDP is generally considered to be a Stackelberg game and bi-level programming is used to formulate the model. For example, Ben-Ayed et al. (1988), Kim and Suh (1988), LeBlanc and Boyce (1986), Marcotte (1988), Suh and Kim (1992), Tzeng and Tsaur (1997), and Yang and Bell (1998). There are two decision-makers in this problem as shown in Fig. 2a. The leader determines the network layout in the upper problem, while the travelers, or so called followers, present their travel demands in the lower problem according to the network layout of the upper problem. The travel time (or cost) of links determined in the lower problem then become the given conditions for upper problem.

The bi-level framework is used to improve the SLM as it can clearly and systematically describes and analyzes the travel demand in NDP. The model framework of SLM-IV is established as in Fig. 2b. SLM-III is the upper problem, according to which the layout of land use, transport network and public facilities is determined. The CDA is used in the lower problem because the land use distribution and network layout both vary in the upper problem. Boyce and Janson (1980) and Kim and Suh (1988) also recommended CDA in bi-level programming NDP.

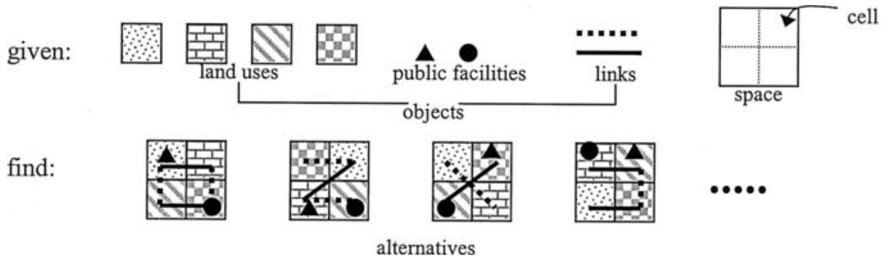

Fig. 3. Problem definition for SLM-IV

3. Model formulation

The layout of a physical plan consists of two entities: *objects* and *space*. Objects indicating different types of land uses, transport links and public facilities are located in space. The space is equally divided into *cells* containing these objects. The area of each type of planned land use is given by the number of cells occupied. The capacity of the planned area equals the sum of the areas of the planned land uses as shown in Fig. 3. The types of planned links and the travel cost function are both given. The service area for each type of planned facility is given. This model seeks alternative sketch maps in which objects are optimally arranged, as shown in Fig. 3.

The notation used in the SLM-IV is as follows.

[in general]

- k, k': type of land use (e.g. residence, industry, etc.), given;
- l: type of link (e.g. major arterial, minor arterial, etc.), given;
- f: type of public facility (e.g. park, school, etc.), given;
- i, j, i', j': the cells in analyzed area, given;
- $i^*, j^*, i^\wedge, j^\wedge$: the cells in planned area, given;
- $(ij, i'j') \in$ set of O-D pairs possibly connected by link, given;

[for upper problem/land use]

- X^k: area of land use k measured by the number of cells, given;
- X_{ij}^k: binary decision variable; 1 if land use k is located at cell ij; 0 otherwise;
- $d_{ij,i'j'}$: flying distance between cell ij and cell $i'j'$, given;
- $h_{kk'}^d$: $\in[0, 1]$, harmony level associated with land use k on land use k' which is d flying distance away, given;
- C^k: set of cells unsuitable for accommodating land use k, given;

[for upper problem/transport network]

- $Y_{ij,i'j'}^l$: binary decision variable; 1 if link type l is located between cell ij and cell $i'j'$; 0 otherwise;
- $r_{kk'}$: $\in[0, 1]$, interaction level (for example, travel demand) between land use k and land use k', given;
- $A_{ij,i'j'}$: $\in[0, 1]$, traffic accessibility between cell ij and cell $i'j'$, determined by $tt_{ij,i'j'}$;
- $w_{ij,i'j'}^l$: cost equivalent of link type l between cell ij and cell $i'j'$, given;

- β: parameter, $\beta > 0$, given;
- M: an infinitely large number, given;
- C^l: set of cell pairs (i.e., two different cells) in which the link can not be located, given;
- $tt_{ij,i'j'}$: the travel time of shortest path between cell ij and cell $i'j'$; determined by network layout (Y) of upper problem and $t_a(q_a)$ of the lower problem;

[for upper problem/public facility]

- C^f: set of cells which unsuitable for accommodating facility f, given;
- F^f: number of facility f, given;
- p_k^f: demand level of land use k on facility f, given;
- N^f: reasonable service travel time for facility f, given;
- Z_{ij}^f: binary decision variables; 1 if facility f is located at cell ij; 0 otherwise;
- m_{ij}^f: 1 if cell ij is covered by facility f; 0 otherwise; determined by Z;

[for lower problem]

- $t_a(q_a)$: travel time on link a with flow q_a, determined by q_a of lower problem and network layout (Y) of upper problem;
- q_a: flow on link a, determined by ff;
- γ: parameter, given;
- $T_{ij,i'j'}$: trip distribution from cell ij to cell $i'j'$, determined by ff;
- $ff_{ij,i'j'}^h$: flow on path h between O-D pair ij-$i'j'$, decision variables;
- O_{ij}: total number of trips leaving the cell ij, determined by X of upper problem;
- D_{ij}: total number of trips arriving the cell ij, determined by X of upper problem;
- OR^k: leaving rate (trips/hour) for land use k, given;
- DR^k: arriving rate (trips/hour) for land use k, given;
- $\delta_{ij,i'j'}^{a,h} = \begin{cases} 1, & \text{if link } a \text{ is on path } h \text{ between O-D pair } ij\text{-}i'j' \\ 0, & \text{otherwise} \end{cases}$, determined by Y of upper problem.

The formulae of the Sketch Layout Model – type IV (SLM-IV) are expressed as follows based on the model framework:

[upper problem]

$$\text{Max} \quad \text{Min}\left\{10^{M(1-X_{i^*j^*}^k)}\left[\sum_{ijk'}(X_{ij}^{k'}h_{kk'}^d)\right], \forall i^*, j^*, k; ij \neq i^*j^*\right\} \tag{1}$$

$$\text{Max} \quad \left\{\sum_{(i^*j^*,ij)}\left[1-\left|\sum_{k,k'}(X_{i^*j^*}^k X_{ij}^{k'} r_{kk'}) - A_{i^*j^*,ij}\right|\right]\right\} \div \sum_{(i^*j^*,i^\wedge j^\wedge)}(w_{i^*j^*,i^\wedge j^\wedge}^l Y_{i^*j^*,i^\wedge j^\wedge}^l) \tag{2}$$

$$\text{Max} \quad \sum_f \sum_{i^*j^*} \sum_k (p_k^f X_{i^*j^*}^k m_{i^*j^*}^f) \tag{3}$$

$$\text{S.T.} \quad \sum_{ij} X_{ij}^{k} = X^{k}, \ \forall k \tag{4}$$

$$\sum_{l} Y_{ij,i'j'}^{l} \leq 1, \ \forall (ij, i'j') \tag{5}$$

$$\sum_{i^*j^*} Z_{i^*j^*}^{f} = F^{f}, \ \forall f \tag{6}$$

$$\sum_{k} X_{ij}^{k} = 1, \ \forall ij \tag{7}$$

$$tt_{i^*j^*,i^\wedge j^\wedge} \neq \infty, \ \forall (i^*j^*, i^\wedge j^\wedge) \tag{8}$$

$$X_{ij}^{k} = 0, \ \forall ij \in C^{k} \tag{9}$$

$$Y_{ij,i'j'}^{l} = 0, \ \forall (ij, i'j') \in C^{l} \tag{10}$$

$$Z_{ij}^{f} = 0, \ \forall ij \in C^{f} \tag{11}$$

$$X_{ij}^{k} = 1, \ \forall k \text{ existed in cell } ij \tag{12}$$

$$Y_{ij,i'j'}^{l} = 1, \ \forall \text{ link type } l \text{ existed between cell } ij \text{ and cell } i'j' \tag{13}$$

$$Z_{ij}^{f} = 1, \ \forall f \text{ existed in cell } ij \tag{14}$$

$$m_{i^*j^*}^{f} \leq \sum_{ij \in Q_{i^*j^*}^{f}} Z_{ij}^{f}, \ \forall i^*j^*, f \tag{15}$$

$$\text{Where } X_{ij}^{k}, Y_{ij,i'j'}^{l}, Z_{ij}^{f}, m_{i^*j^*}^{f} \in \{0, 1\}, \ \forall k, ij, (ij, i'j'), f \tag{16}$$

$$A_{i^*j^*,ij} = (tt_{i^*j^*,ij})^{-1/\beta} \tag{17}$$

$$d = d_{i^*j^*,ij} \tag{18}$$

$$Q_{i^*j^*}^{f} = \{ij \mid tt_{i^*j^*,ij} \leq N^{f}\} \tag{19}$$

$$tt_{ij,i'j'} \text{ is decided by lower problem} \tag{20}$$

[lower problem]

$$\text{Min} \quad \sum_{a} \int_{0}^{q_a} t_a(x)\, dx + \frac{1}{\gamma} \sum_{ij,i'j'} (T_{ij,i'j'} \ln T_{ij,i'j'} - T_{ij,i'j'}) \tag{21}$$

$$\text{S.T.} \quad \sum_{h} ff_{ij,i'j'}^{h} = T_{ij,i'j'}, \ \forall ij, i'j' \tag{22}$$

$$\sum_{i'j'} T_{ij,i'j'} = O_{ij}, \ \forall ij \tag{23}$$

$$\sum_{ij} T_{ij,i'j'} = D_{i'j'}, \ \forall i'j' \tag{24}$$

$$ff^{h}_{ij,i'j'} \geq 0, \ \forall h, ij, i'j' \tag{25}$$

$$q_a = \sum_{ij}\sum_{i'j'}\sum_{h} ff^{h}_{ij,i'j'} \delta^{a,h}_{ij,i'j'}, \ \forall a \tag{26}$$

$$\text{Where } \delta^{a,h}_{ij,i'j'} = \begin{cases} 1 & \text{if link } a \text{ is on path } k \text{ between O-D pair } ij\text{-}i'j' \\ 0 & \text{otherwise} \end{cases} \tag{27}$$

$$O_{ij} = \sum_{k} (X^{k}_{ij} OR^{k}) \tag{28}$$

$$D_{i'j'} = \sum_{k} (X^{k}_{ij} DR^{k}) \tag{29}$$

$$\text{Land use distribtion } (X) \text{ and network layout } (Y) \text{ are decided by upper problem} \tag{30}$$

There are three binary decision variables in the upper problem: X^{k}_{ij} stands for the land use k being (=1) or not being (=0) assigned to cell ij. $Y_{ij,i'j'}$ stands for the link type l being (=1) or not being (=0) located between cell ij and cell $i'j'$. Z^{f}_{ij} stands for the facility f being (=1) or not being (=0) located in cell ij.

Cell-object combination, termed as ij-k, is defined as the situation in which land use k is assigned to the cell ij. The first objective as shown in Formula (1), which stands for environment harmony, is to maximize the harmony level of the cell-object combination, which is the lowest among those of all cell-objects in a layout. The [•] indicates the sum of the harmony level associated with a specific $i^{*}j^{*}$-k, while $10^{M(\bullet)}$ is the correctness of the object k assigned to cell $i^{*}j^{*}$. In the event that object k is not correctly assigned to cell ij, the X^{k}_{ij} will become zero and M which acts as penalty will lead the value of this objective to an infinitely large number for which the minimum will not be feasible for this ij-k combination. The second objective as shown in Formula (2), which stands for development efficiency, is to maximize the efficiency/cost ratio. The numerator indicates the relative level of public investment cost. The denominator denotes the total efficiency of the layout, in which [1-| • |] indicates the efficiency of two combinations, $i^{*}j^{*}$-k and ij-k'. A smaller difference between interaction level of land uses and accessibility level of cells in two combinations (i.e., | • |), leads to a higher efficiency. The third objective as shown in Formula (3), which stands for facilities service, is to maximize the population covered by the service area of facilities. Feng and Lin (2000) concluded that the trade-off exists among these three objectives. The nondominated solutions

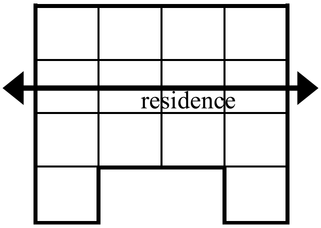

Fig. 4. Assumed space of numerical example

of these three objectives can be used as the alternative sketch maps for urban planning.

The upper problem involves six groups of constraints. Formulae (4) and (6) indicate that all of the land use and facility objects should be assigned to the planned area, while Formula (5) indicates that no more than one type of link can be located between a pair of cells. Formula (7) indicates that a cell can only accommodate a single land use object. Formula (8) indicates that at least one path exists between two cells. Formulae (9), (10) and (11) indicate those unsuitable locations for each object must be excluded. Formulae (12), (13) and (14) define the decision variables for the cells in which some kind of object is present. Formula (15) identifies whether cell i^*j^* is located in the service area of facility f. In addition, formula (16) defines the value interval for all of decision variables. Formula (17) defines the function of accessibility between two cells. Formula (18) defines the origin and destination of d. Formula (19) defines the set of cells covered by the service area of facilities. Formula (20) declares that the travel time, $tt_{ij,i'j'}$, is determined by the lower problem.

The *doubly constrained entropy distribution/assignment problem* (Evans 1976; Sheffi 1985) is formulated in the lower problem. This CDA model simultaneously creates the trip distribution for the maximum entropy model (or doubly constrained gravity model) and the traffic assignment for the user equilibrium model. The trip generation, O_{ij} and D_{ij}, are determined by the upper problem as defined in Formulae (28), (29) and (30).

4. A numerical example

An example involves fourteen cells in a space, in which one residential cell and one path with three major links already exists, as shown in Fig. 4. The objects include seven types of land use, two types of facility, and two types of link, as described in Table 1 and Table 2. The parameters, β and γ, are both assumed to be 1. The input data, harmony level $h^d_{kk'}$ and interaction level $r_{kk'}$, taken from Lin (1999) are used in this study.

Two types of link are considered in this example; major link ($l = 1$) and minor link ($l = 2$). The relationship function between traffic flow and travel time on link a is assumed to be:

$$t_a = t_0 \times \left[1 + 0.15\left(\frac{q_a}{CAP_a}\right)^4\right] \tag{31}$$

Where t_a and q_a are defined in SLM-IV; t_0 represents the free flow travel time,

Table 1. Assumed land use objects

k	Land use	Number assigned	Number existed	Total number X^k	Trip leaving rate (OR^k) pcu/hr	Trip arriving rate (DR^k) pcu/hr	Demand on facility (p_k^f)	
							Fire station ($f = 1$)	Primary school ($f = 2$)
1	Residence	5	1	6	400	100	8	10
2	Commerce	2	0	2	200	600	10	8
3	Industry	2	0	2	200	500	7	0
4	Waste plant	1	0	1	100	100	1	0
5	Recreation	1	0	1	100	200	1	0
6	Administration	1	0	1	100	300	7	0
7	College	1	0	1	100	200	7	0
	Total	13	1	14	–	–	–	–

Table 2. Assumed facility objects

f	Facility	Service object	Number assigned F^f	Reasonable service travel time N^f
1	Fire station	All of land uses	2	1.5 Minutes
2	Primary school	Residence, commerce	1	3 Minutes

and CAP_a stands for the capacity. In this example, the free flow travel time for each link is assumed to be 1 and the analysis scenario is morning peak hour.

The *cumulative genetic algorithm* (CGA) developed by Xiong and Schneider (1995) is modified to an heuristic algorithm to generate approximating non-dominated solutions for SLM-IV. The flowchart in Fig. 5 illustrates the algorithm, of which a detailed description can be found in Feng and Lin (1999a). The *convex combination algorithm* described in Sheffi (1985) is used in step 3 of Fig. 5 to solve the CDA model in the lower problem.

Five tests under different link capacity conditions, as shown in Table 3, were undertaken. Test 1 involved the highest link capacity, almost negating the impact of traffic flow on travel time; while Test 5 assumed the lowest link capacity, significantly affecting travel time by traffic flow.

The results of the tests, as described in Table 4, are discussed here.

1. All tests give similar first objective values because the objective function is independent to travel time.
2. The second objective want to minimize the difference between interaction level of land uses and accessibility level of cells in two combinations, that means high interaction pairs with high accessibility and low interaction pairs with low accessibility. The decrease of links' capacities will decrease the efficiency between two high interaction land uses (negative effects) but also increase the efficiency between two low interaction land uses (positive effects). Therefore, all tests give similar second objective values although travel time is considered in this objective function because that the negative and positive effects of travel time offset each other.
3. The third objective value is significantly affected by link capacity or travel

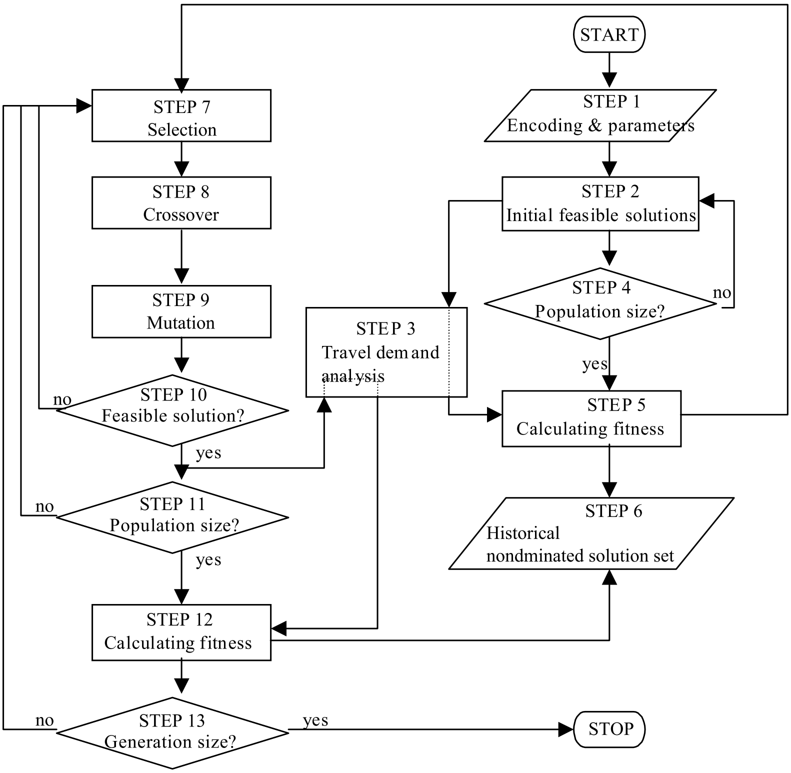

Fig. 5. Flowchart of the heuristic algorithm

Table 3. Assumed capacities for tests

Test	1	2	3	4	5
Major link	1000	400	200	100	20
Minor link	500	200	100	50	10

Unit: pcu/hr °

Table 4. Outputs of tests

Test	Objective value			Number of nondominated solutions	Calculating time (in seconds)
	1	2	3		
1	2.8∼3.2	3.43∼4.66	61∼114	10	11,191
2	2.0∼3.7	2.77∼5.18	71∼125	11	11,392
3	1.2∼3.1	2.54∼4.56	71∼110	12	12,069
4	2.4∼3.3	3.21∼5.26	9∼90	14	9,207
5	2.1∼2.9	3.43∼4.36	18∼45	9	14,953

Note: Intel® Pentium® II 300 MHz CPU and Turbo Pascal 6.0 program language are used.

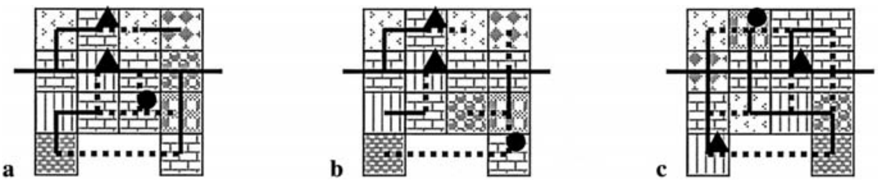

Fig. 6a–c. Layouts for corner point solutions of Test 3. **a** Objective: (3.1*, 3.62, 91); **b** objective: (2.9, 4.74*, 71); **c** objective: (1.9, 2.54, 110*). residence, commerce, industry, waste plant, recreation, administration, college, ▲ fire station, ● primary school, ▬ major link, ▪▪▪▪▪▪ minor link

time. A lower link capacity results in a lower third objective value. The decrease in link capacity increases the travel time on the link, and then the coverage of the facilities (i.e., the third objective) will decrease by Formulae (19), (15), and (3).
4. Although the first and second objective values are not significantly affected by travel time, these two objectives are still affected by the lower problem because there are trade-off relationships among three objectives. The changes of the third objective, which is sensitive to the links' travel time, will lead to the opposite changes of the other two objectives simultaneously.
5. The number of nondominated solutions and the calculating time are both not significantly related to the assumed capacity.

Three corner point solutions of Test 3 are presented in Fig. 6 to describe the outputs of SLM-IV. They present the rough layout of different types of land uses, transport network and public facilities. The alternative 6a gets the highest level of environment harmony (the first objective), but the other two objectives maintains on lower level for its more links and concentrated facilities. Because the alternative 6b layouts the fewest number of links, it gets the highest level of development efficiency (the second objective), but the facilities services are awfully decreased. The alternative 6c gives the best service of facilities (the third objective) under the fully linking between every two neighboring cells and the dispersed distribution of facilities, but it causes the worst situations on the other two objectives. The other nine alternatives solved in Test 3 get the trade-off among these three corner point solutions. Based on the twelve alternatives generated in Test 3, the alternative evaluation and detailed design of the urban development map can be proceeded from these sketches.

5. Conclusions

This study develops the fourth phase of SLM, a land use-network design problem, into bi-level programming. SLM-IV uses a CDA model to analyze the travel demand in the lower problem. Thus, we can consider road types in the integrated sketch layouts of land use, transport network and public facilities.

The model is tested with a numerical example and is considered to be feasible. The objective functions relative to travel time are affected by the link capacities; and calculating time, the number of nondominated solutions, and link capacities are not significantly related.

Two issues in network design in SLM require further exploration. First, the network structure remains weak because the continuity and the hierarchy of two connected links are not considered in the model shown in Fig. 6. Second, the harmony between the link type and the use of the land beside the link is not considered in the model, and some conflicts may exist between them. For example, there may be an environmental conflict between residential, which require amenities, and major-arterial, which serves a volume of large traffic. SLM could be extended to consider both issues in further research.

References

Bammi D, Bammi D (1979) Development of comprehensive land use plan by means of a multiple objective mathematical programming model. Interfaces 9(2):50–63

Bammi D, Bammi D, Paton R (1976) Urban planning to minimize environmental impact. Environment and Planning A 8:245–359

Barber GM (1976) Land-use plan design via interactive multiple-objective programming. Environment and Planning A 8:625–636

Ben-Ayed O, Boyce DE, Blair CE (1988) A general bilevel linear programming formulation of the network design problem. Transportation Research B 22(4):311–318

Boyce DE, Janson BN (1980) A discrete transportation network design problem with combined trip distribution and assignment. Transportation Research B 14:147–154

Brotchie JF (1978) A new approach to urban modelling. Management Science 24(16):1753–1758

Brotchie JF, Dickey JW, Sharpe R (1980) TOPAZ – General planning technique and its applications at the regional, urban, and facility planning levels. Springer, Berlin Heidelberg New York

Dokmeci VF (1993) Multiobjective land-use planning model. Journal of Urban Planning and Development 119(1):15–22

Evans SP (1976) Derivation and analysis of some models for combining trip distribution and assignment. Transportation Research 10:37–57

Feng CM, Lin JJ (1999a) Using a genetic algorithm to generate alternative sketch maps for urban planning. Computers, Environment and Urban Systems 23(2):91–108

Feng CM, Lin JJ (1999b) A land use-network design model to generate alternative sketch maps for urban planning. Journal of the Eastern Asia Society for Transportation Studies 3(4):71–86

Feng CM, Lin JJ (2000) The improvement of sketch layout model: considering the layouts of public facilities. Journal of City and Planning 27(2):233–254 (in Chinese)

Gorden P, MacReynolds WK (1974) Optimal urban forms. Journal of Regional Science 14(2):217–231

Janson BN, Husaini A (1987) Heuristic ranking and selection procedures for network design problems. Journal of Advanced Transportation 21:17–46

Kim TJ, Suh S (1988) Toward developing a national transportation planning model: a bilevel programming approach for Korea. Annals of Regional Science XXSPED:65–80

Leblanc LJ (1975) An algorithm for the discrete network design problem. Transportation Science 9:183–199

LeBlanc LJ, Boyce DE (1986) A bilevel programming problem with user-optimal flows. Transportation Research B 20(3):259–265

Lin JJ (1999) A model to generate alternative sketch maps for urban planning. PhD dissertation, National Chiao Tung University, Hsinchu, Taiwan

Los M (1978) Simultaneous optimization of land use and transportation – a synthesis of the quadratic assignment problem and the optimal network problem. Regional Science and Urban Economics 8:21–42

Los M (1979) A discrete-convex programming approach to the simultaneous optimization of land use and transportation. Transportation Research B 13:33–48

Lundqvist L (1973) Integrated location-transportation analysis: a decomposition approach. Regional and Urban Economics 3(3):233–262

MacKinnon RD, Hodgson MJ (1970) Optimal transportation networks: a case study of highway systems. Environment and Planning 2:267–284

Magnanti TL, Wong RT (1984) Network design and transportation planning: models and algorithms. Transportation Science 18(1):1–55

Marcotte P (1988) A note on a bilevel programming algorithm by LeBlanc and Boyce. Transportation Research B 22(3):233–237

Poorzahedy H, Turnquist MA (1982) Approximate algorithms for the discrete network design problem. Transportation Research B 16(1):45–55

Ridgley MA, Giambelluca TW (1992) Linking water-balance simulation and multiobjective programming: land use plan design in Hawaii. Environment and Planning B 19:317–336

Sheffi Y (1985) Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods. Prentice-Hall, INC, Englewood Cliffs, NJ

Suh S, Kim TJ (1992) Solving nonlinear bilevel programming models of the equilibrium network design problem: a comparative review. Annals of Operations Research 34:203–218

Tzeng GH, Tsaur SH (1997) Application of multiple criteria decision making for network improvement plan model. Journal of Advanced Transportation 31:48–74

Xiong Y, Schneider JB (1995) Transportation network design using a cumulative genetic algorithm and neural network. Transportation Research Record 1364:37–44

Yang H, Bell MGH (1998) Models and algorithms for road network design: a review and some new development. Transport Reviews 18(3):257–278