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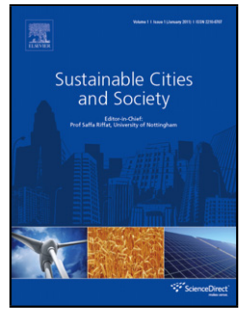

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A sustainable approach for selecting and timing the urban transportation infrastructure projects in large-scale networks: A case study of Isfahan, Iran

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Highlights

- The multi-objective multi-period network design problem is considered.
- A solution approach for large networks with many candidate projects is proposed.
- The proposed approach is implemented in a real urban network.

Abstract

Decision making about transportation infrastructure projects is one of the important issues in transportation planning, especially in developing cities. Transportation authorities need a systematic approach to determine which projects should be selected from a set of candidate projects and when the selected projects should be carried out. In this paper, a new approach is proposed by which selecting and timing urban transportation projects is done simultaneously. A bi-level mathematical programming model is presented and a two-phase hybrid solution procedure is developed. The presented approach has two prominent features. First, it is capable of considering large transportation networks with many candidate projects. Second, it selects and schedules projects based on sustainable development. To verify the efficiency of the suggested approach, Isfahan transportation network is selected as the case study, and 31 road projects (construction and widening) along with 12 Bus Rapid Transit (BRT) projects are scheduled for a 10-year planning horizon (2016-2026). It was found that the proposed approach can effectively solve network development planning problem of large transportation networks with many projects.

Keywords: Transportation, Project selection, Scheduling, Network design, Sustainable development.

1. Introduction

Transportation of goods and passengers is one of the crucial needs of society. The development of the urban network to facilitate transportation has been recognized as the one of most challenging issues in the field of transportation due to the inherent complexity of the network design. Not only does an optimal expansion of the transportation network provide efficient transportation, which is a key to sustainable economic growth, but it also results in the most return the investment. Hence, one of the most important concerns for transportation management system is evaluation, prioritization and selection of transportation projects for investment that arrive at the optimal network expansion. This type of transportation problem is known as Network Design Problem (NDP). NDP is defined as the problem of improving or expanding transportation networks to optimize certain objective(s) under resource constraint(s) (Poorzahedy and Rouhani, 2007; Yang and Bell, 1998).

The authorities are consistently encountering several development projects for transportation network to choose from, and due to different purposes and limitations, it is a complex process to evaluate and prioritize them. Evaluating and prioritizing transportation projects affect directly public life, so various impacts of projects must be considered correctly to avoid worsening transportation network which will lead to social discontent. Therefore, it can be inferred that expansion of transportation networks is very sensitive and critical.

A sustainable transportation approach looks for a balance between environmental, social, and economical qualities at present time and into the future (Xu et al.; 2016). Good transportation planning must be responsible in maintaining sustainability of economy, society and environment. However, with developing transportation infrastructures, many environmental problems have appeared, such as land occupancy, noise pollution, and air pollution (Rao et al.; 2018). Developing transportation infrastructures according to urban sustainability criteria propels cities toward social justice, desirable environment, and economic development. Mahmoudi et al. (2019) identified 38 sustainability criteria related to urban transportation networks.

Transportation researchers all admit that NDP is a complicated problem intrinsically (Yang and Bell, 1998; Farahani et al., 2013). Some things can increase this complexity, including scale-up in network size, increase in number of projects, and extension of criteria (objectives). Accordingly, network design in a metropolis with numerous candidate projects considering a variety of criteria is much more complicated than usual NDP. Moreover, if the timing (scheduling) of projects will also be considered in NDP, its complexity will grow significantly (Hosseininasab and Shetab-Boushehri; 2015).

This paper focuses on large-scale urban networks and proposes a new approach developed to prioritize and schedule urban transportation projects subject to the limitations in the budget and implementation with regard to sustainable development. The paper is organized as follows: Section 2 reviews the literature and reveals the existing research gaps. Section 3 presents the problem description, the mathematical formulation, analysis of the obstacles toward solving the model, and the solution approach driven from the model properties. Results of implementing the proposed methodology on a realistic road network of Isfahan, Iran, are reported in Section 4 and through this the applicability of utilizing the proposed approach on large road networks with many projects is demonstrated. The paper is concluded in Section 5 and future research directions are suggested.

2. Literature review

In recent decades, efficient urban network development has attracted many researchers in the field of transportation. Published studies can be classified according to different aspects, such as: continuous/discrete, single-objective/multi-objective, exact/approximate, and selection/timing. Based on this classification, the studies are reviewed in the following.

2.1. Continuous/discrete form

Based on continuous or discrete kind of decision variables used in the model, NDP can be divided to three kinds: Continuous Network Design Problem (CNDP) which deals with the optimal capacity expansion of existing links in the network, Discrete Network Design Problem (DNDP) which deals with the addition of new links to a transportation network, and Mixed Network Design Problem (MNDP) which involves both the discrete and continuous decision variables simultaneously (Yang and Bell, 1998). Combinatorial nature of DNDP and MNDP makes them far more complicated than CNDP, and that is why CNDP is used more. The readers are referred to Farahani et al. (2013) to see a summary of the studies in these areas.

2.2. Exact/approximate solution

Leblanc (1975) solved the bi-level DNDP using the branch-and-bound (B&B) algorithm. The main drawback of this exact solution was the inadequacy of the lower limit. Farvaresh and Sepehri (2013) developed a method for determining the lower limit of the B&B algorithm. They showed the superiority of their method in most of the lower-level computational tests once compared to LeBlanc. Because of inherent difficulties of NDP, finding optimal solution of a bi-level NDP is very difficult even for small networks (Magnanti and Wong, 1984; Gao et. al., 2005). Therefore, most of solution approaches presented in the literature are approximate to assess a trade-off between accuracy and speed of the solution. Poorzahedy & Rouhani (2007) have classified these approaches into eight categories.

2.3. Single-objective/multi-objective

Most researchers that have employed NDP considered the urban network development as a single-objective because of its simplicity while the nature of this issue is multi-objective and utilizing single-objective optimization leads to sub-optimal solution. The multi-objective network design problem was first introduced by Friesz and Harker (1983). They adopted the multi-objective CNDP and used the Gafferin exchange method to solve it. Later, Ãhern and Anandarajah (2007) solved the problem by minimizing a multi-objective function that summed up different factors multiplying their corresponding weights. Avineri et al. (2000) defined several non-compensatory decision rules on goals and utilized a weighted fuzzy mean function to model a multiple-objective problem as a knapsack problem with budget constraints being taken into account. The multi-objective transportation infrastructure project selection problem (MTIPSP), as a multi- objective optimization problem based on the zero-and-one multi-objective knapsack problem, was first developed by Teng and Tzeng (1996) in which binary decision-making variables (zero-and-one) were used to represent different investment options. Iniestra and Gutiérrez (2009) improved the modeling of Teng and Tzeng (1996), and proposed the multi-dimensional issue of selecting transport infrastructure projects as a multi-objective knapsack problem of zero and one with a few additional limitations. Zhang and Gao (2009) presented a MNDP model that included both the expansion of links and the addition of new links into the network, and its upper level objective function was considered as the weight of three different objective functions. Then, the proposed bi-level model was converted to a one-level equivalent problem and was solved by a gradient-based method along with a penalty function. Miandoabchi et al. (2013) proposed a multi-objective DNDP model in order to find the optimal combination of one-way and two-way streets, the configuration of lines in two-way streets, new road construction, and the line addition to the existing streets. The objectives in their study were network service capacity optimization and two time-related indicators. Also, three meta-heuristic algorithms were proposed for solving the defined problem. Haas and Bekhor (2017) aimed to minimize travel time in the network and maximize the safety for network design. They used a multi-objective genetic algorithm for this purpose. The network under study was a real network with many candidate projects for adding into the network. Kolak et al. (2018) formulated network optimization problem as a bi-level multi-objective model with a sustainability perspective. This study deals only with enhancing the capacities of the existing links (no addition of new links).

2.4. Selection/timing

Most of NDP studies consider project selection without timing. Since budget and technical constraints do not allow implementation of many projects simultaneously, the timing of projects become an important feature in NDP. The timing of projects involves allocating available resources among projects over a planning horizon according to their priority such that the most return on the investments is achieved. There are few studies dealing with the timing of projects.

Weng and Qu (2009) proposed a model for timing the road construction projects. In this model, it is assumed that the road construction projects have been defined in advance and what is needed is the timing of the construction during different planning periods. They solved the problem in the form of a single-objective planning model by considering budget limitation, in which the objective function is to maximize the benefit by reducing the origin-destination distances in the network as a result of the construction of new roads. A simplifier assumption in this study is that the time required to construct each road is equal to one planning period.

Szeto et al. (2010), Miandoabchi et al. (2015), Kim et al. (2008) and Hosseininasab and Shetab-Boushehri (2015) considered the problem of adding new streets to the network along with their timing. The study by Szeto et al. (2010) proposes a single-level single objective discrete network design framework considering the land-use transport interaction over time. Multimodal transport interaction is also captured in this framework. They used a commercial solver to solve the proposed model. Kim et al. (2008) proposed a bi-level DNDP to select investment projects and to determine their timing in a planning horizon. They presented a genetic algorithm and a simulated annealing algorithm to solve the model.
Miandoabchi et al. (2015) formulated the problem of selecting and timing of road construction and widening projects as a bi-objective DNDP and proposed two multi-objective evolutionary algorithms to solve the model. They assumed that the projects do not require more than one year (period). Such assumption is usually unrealistic as Hosseininasab and Shetab-Boushehri (2015) criticized the assumption of considering fixed duration for projects. They considered that the progress of a project depends on technical and budget limitations, i.e., if more (less) funds are allocated to a project, it might be operated earlier (later). Based on this assumption, they developed a new single-objective DNDP model to integrate selecting and scheduling of urban road construction projects in which duration of each project is not pre-defined as a parameter, but it will be determined by solving the model. Hosseininasab et. al. (2018) have expanded the work of Hosseininasab and Shetab-Boushehri (2015) to a multi-objective form by developing two new criteria related to spatial equity and user satisfaction over time. They proposed two multi-objective evolutionary approaches (an interactive and a-posteriori) to solve the model. They implemented the proposed approach on a large-sized network, but with a few (ten) projects. Because of great complexity, their approach cannot satisfy problems with large number of projects in large-sized networks.

2.5. **Literature review conclusion**

NDP is an attractive, practical and wide research area which encompasses various complex problems. Therefore, the literature is full of studies addressing this area from different aspects. One of these aspects is the integration of selecting and timing transportation projects which is known as time-dependent NDP or multi-period NDP. Several studies in this topic have been done thus far. Some shortcomings of these studies may be noted as follows:

- Because of great complexity of the problem, most of the proposed models were implemented inevitably on small networks or large networks with limited number of projects.
- Excluding two studies, others considered a fixed and pre-defined duration (makespan) for each project that is an unrealistic assumption.
- The majority of studies neglected sustainable development of cities.

The main aim of this paper is to eliminate the above-mentioned shortcomings. This study considers the selecting and timing of various transportation network development projects including the road construction and widening, Bus Rapid Transit (BRT) and metro lines for large networks with many candidate projects via developing a practical approach which can ameliorate the city's future by considering requirements of urban sustainability. Therefore, the main novelty of this paper is about developing a proper approach to solve the multi-objective multi-period DNDP for large-size networks with many projects.

3. Methodology

In this section, a mathematical programming model of the problem is formulated and described. Afterward, an overall solution approach to make the problem solvable in large-size networks with many projects is proposed. Finally, details of the solution approach are presented.

3.1. Model formulation

As discussed in Section 2, several models of multi-period DNDP are proposed in the literature. Among these models, the one suggested by Hosseininasab and Shetab-Boushehri (2015) assumed the duration of each project to be variable. Thus, the model presented here is based on the suggested model by Hosseininasab and Shetab-Boushehri (2015). This model is a bi-level DNDP in which the upper level problem represents the decision making problem of the network authority to select and schedule the projects that can be added to the network, and the lower level problem represents the network users' behavior in choosing travel routes that specifies the traffic flows on the network links based on the solutions determined at the upper level. The lower level problem is called deterministic user equilibrium

(DUE) traffic assignment problem. Since this problem is well-known, its formulation is omitted for brevity. The mathematical model of upper level problem is formulated as follows:

$$Min \quad \mathbf{f}_v = (f_l(v), f_2(v), \dots, f_L(v)) \qquad (1)$$

S.t:

$$\sum_{q \epsilon Q} C_q\, y_t^q \leq B_t \qquad \text{t} = 1.2. \dots .\text{T};\ q \epsilon Q \qquad (2)$$

$$\sum_{p=1}^{t} y_p^q \geq x_t^q \qquad \text{t} = 1.2. \dots \text{T};\ q \epsilon Q \qquad (3)$$

$$\sum_{p=1}^{T} y_p^q \geq x_t^q \qquad \text{t} = \text{T}+1. \dots .\text{T}';\ q \epsilon Q \qquad (4)$$

$$y_t^q \leq \alpha_q \quad \text{t} = 1.2. \dots \text{T};\ q \epsilon Q \qquad (5)$$

$$x_t^q \epsilon \{0.1\} \quad \text{t} = 1.2. \dots \text{T}';\ q \epsilon Q \qquad (6)$$

$$y_t^q \geq 0 \quad \text{t} = 1.2. \dots \text{T};\ q \epsilon Q \qquad (7)$$

The symbols used in the suggested model are defined as follows:

- Parameters:
  I_t: impact (importance) factor of period *t*
  C_q: total cost of project q
  α_q: maximum progress rate of project q that can be occurred in each period based on technical limitations ($0 < \alpha_q \leq 1$)
  B_t: available budget in period t
  T: planning horizon (number of planning periods)
  T′: evaluation horizon (number of evaluation periods) (T′>T)
  L: number of objectives
- Decision variables:
  x_t^q: binary variable that indicates the completion status of project q in period t (completed or uncompleted).
  y_t^q: continuous variable between zero and one that indicates the progress rate of project q in period t
  v_t: vector of flow volume on the links of network in period t

- Functions:
  $f_l\ (v)$: objective function l for network flow (v) during the evaluation horizon
  $f_{l.t}\ (v_t)$: objective function l in period t for network flow in period t (v_t)
- Others:
  t: indicates the period number (t=1, 2, …,T′)
  l: indicates the objective number (l=1, 2, …,L)
  Q: set of suggested projects (road projects and BRT lines)

The upper level problem is multi-objective. Thus, $\mathbf{f}_v$ in equation (1) is a vector of L different objectives. To achieve a sustainable city, these objectives should cover all dimensions of sustainable development appropriately. Therefore, objective selection is an important step in building up the model. Since the value of an objective at the upper level problem is different in each period of evaluation horizon, each objective function can be defined as the weighted sum of its values in the evaluation horizon: $f_l\ (v) = \sum_{t=l}^{T'} I_l\ f_{l.t}\ (v_t)$.

Equation (2) shows budget limitation in each period. According to this equation, the budget that is allocated to each project in a specific period is equal to the product of the total cost of project (C_q) and progress rate of the project in that year (y_t^q). It is assumed that transferring the remaining budget of a period to its following periods is not permitted. Equations (3) and (4) show the relation between $x_{\mathrm{t}}^{\mathrm{q}}$ and y_t^q. They indicate a project can be utilized ($x_t^q = 1$) only when its progress is completed ($\sum_{p=1}^{t} y_p^q = 1$). Equation (5) shows technical limitations of each project. α_q is an approximate parameter that indicates the maximum possible progress of project q during a period according to technical limitations and without considering the budget limitation. For example, if, considering the technical limitations, it is possible to construct a road in one year or less, the parameter value for this road is 1. Similarly, if it is not possible to complete a road construction in less than 2 years considering the technical limitations, the parameter value is 0.5. Equations (6) and (7) also demonstrate the type of decision variables at upper level problem.

3.2. The solution approach

Generally, the common NDP has been proved to be strongly NP-hard because of its bi-level structure (Hansen et al. 1992). Therefore, finding optimal solution of a bi-level NDP is very difficult even for small networks (Magnanti and Wong, 1984; Gao et al. 2005). However, the model presented in Section 3.1 is much more complicated than common NDP because of being multi-objective and multi-period, especially if the model wants to be used in large-size networks with a large number of candidate projects. To handle this complexity, a solution approach is presented to establish an appropriate trade-off between simplification and accuracy. In this approach, the following points are considered to make the model solvable in a reasonable time with an acceptable accuracy:

a) The main problem is decomposed into two successive sub-problems. In the first problem (first phase), the planning horizon is divided into macro periods and candidate projects are selected and assigned to these periods. Therefore, the length of each macro period should not be less than the maximum of project durations. In the second problem (second phase), macro periods are broken into micro periods and the projects assigned to each macro period will be scheduled in its micro periods. For example, as shown in Figure 1, consider a problem in which the planning horizon is 15 years. In the first problem, the planning period can be divided into three 5-year periods and the projects are selected and assigned to these three macro periods. Further, each macro period is broken to five annual periods and the assigned projects to each 5-year period are scheduled yearly. Both of these problems will be formulated separately based on the model presented in Section 3.1 and then should be solved respectively. This approach reduces the complexity of the problem significantly because as the number of periods increases, the complexity of the problem grows exponentially.

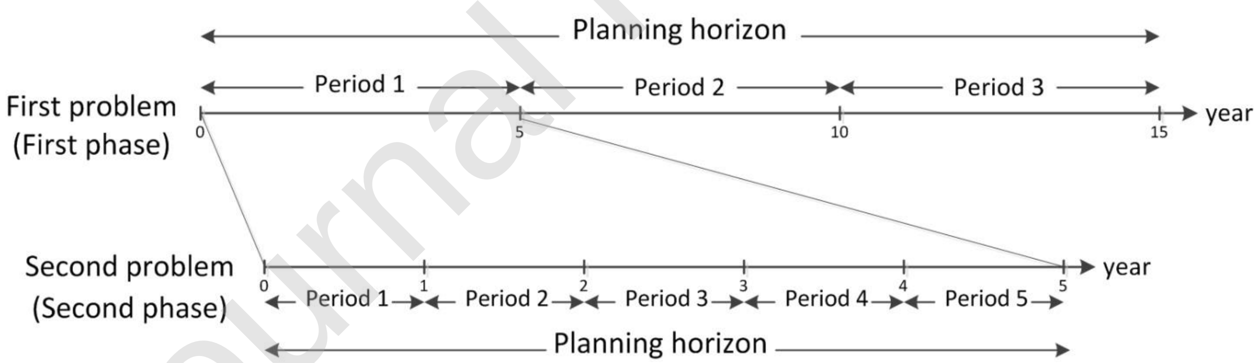

Figure 1- Decomposing the main problem into two successive sub-problems

b) To handle the bi-level nature of the model, a nested evolutionary optimization strategy is adopted. In this strategy, also called as point-to-point strategy, lower level problem is solved corresponding to each and every upper level solution. Nested evolutionary algorithms are a popular approach to handle bi-level problems (Sinha et al.; 2018). In the proposed solution approach, a genetic algorithm (GA) for the upper level optimization and Frank-Wolfe algorithm for the lower level are used.

c) A priori approach is used to handle the multi-objective nature of the model. Generally, multi-objective decision making methods can be classified as a priori approach, interactive approach, and a posteriori approach where preference information is incorporated from the decision maker (DM) before, during, and after the optimization process, respectively (Hwang and Masud; 1979). Each of these categories has its advantages and disadvantages. Among them, a priori approach has the lowest computational cost. What is common among a priori methods is that, by receiving some preferred information from DM before solving the problem, the multi- objective problem can be turned into a single-objective problem.

The above-mentioned points specify the framework of the proposed solution approach. Based on this framework, the proposed solution approach is an iterative process with six steps as shown in Figure 2. Details of each step are described in the following.

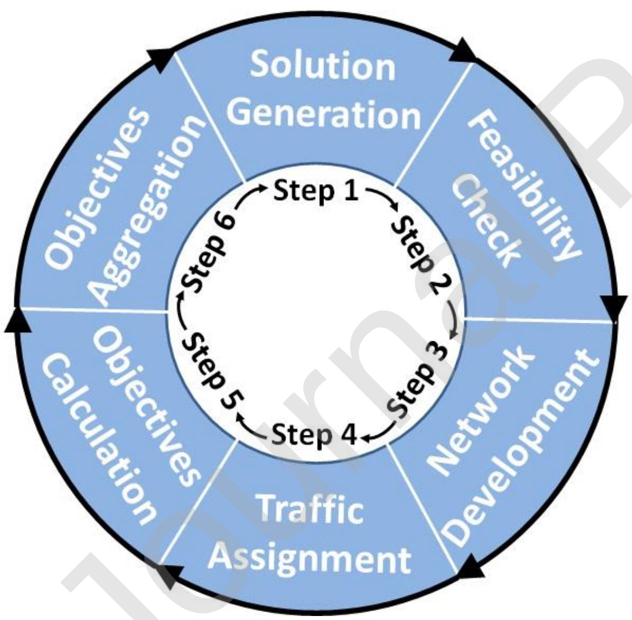

Figure 2- Steps of the proposed solution approach

Step 1: solution generation. A set of solutions for the upper level problem is generated using GA by its crossover and mutation operators. These solutions are in terms of decision variables *x* in the model. A sample of solution representation as a chromosome in GA is shown in Figure 3. Each gene expresses the period number in which the related project is completed. If a project is not selected at all, its value will be 0.

2	**0**	**1**	**2**	**0**	**3**

Figure 3- A sample of solution representation as a chromosome

Step 2: feasibility check. The upper level problem consists of two types of decision variables, i. e. x, y. Since only x variables can be found by solutions representation, it must be checked whether there are valid y values for the specified values of x. Because of linear structure of upper level problem constraints, this test can be done by the phase-I of two-phase simplex method (Bazara et al.; 2011). Therefore, the solutions that are not in the feasible region of the upper level problem are abandoned.

Step 3: network development. Each feasible solution found in Step 2 represents a possible scenario for network development, because it specifies which projects will be added to the network in which periods. To simulate and evaluate each scenario, it is needed to develop the network in different periods separately.

Step 4: traffic assignment. After determining the network configuration and estimating origin–destination (O–D) demand matrix, the lower level problem can be solved. To this end, frank-wolfe algorithm is used. Frank-Wolfe algorithm is one of the most efficient algorithms to solve the traffic assignment problem. The algorithm starts with a feasible initial solution and successively generates a number of linear programming problems whose solutions are expected to converge to the solution of the original problem (Sheffi, 1985). By solving the lower level problem, the flow volumes in the network for each period are obtained.

Step 5: objectives calculation. As shown in equation (1), the objectives of the upper level problem are functions of flow volumes (v). Therefore, it is possible to calculate the final values of different objective functions after traffic assignment.

Step 6: objectives aggregation. By using the objective weighting method as a priori multi-objective decision making method, the calculated values for different objectives are aggregated and then used as the fitness value of each solution in GA to reproduce new solutions. To use objective weighting method, first, the relative weights of objectives should be determined. A pairwise comparison and eigenvector method, as applied in Analytical Hierarchy Process (AHP), to determine these weights was used. Secondly, values of different objectives should be normalized. Normalization aims at obtaining comparable scales for different objectives.

The above iterative process continues until reaching the termination condition and, at the end, the solution with the highest fitness value is chosen as the best scenario for network development.

4. Case study

The proposed methodology was implemented in Isfahan, the third populated city of Iran, with an area of 8345 square kilometer and population of 2,112,767 as of 2016. According to Comprehensive Urban Transportation Studies of Isfahan Metropolitan in 2000, the city has 12 districts and 186 traffic zones. In 2014, the transportation network of Isfahan had 2144 nodes and 3145 links with the total length of 2226 kilometers not including alleys. This city was chosen for two reasons. First, its transportation network can be deemed as a real large-scale network. Second, all data of this network required to build the presented model was available for the authors.

4.1. Candidate projects

In the development plan of Isfahan city transportation network, 43 streets are suggested to be added or widened and 12 BRT lines should be constructed until 2026. Specifications of these projects are provided in Table 1. Proposed streets and BRT lines are also shown in Figure 4 and Figure 5, respectively.

Table 1- Specifications of the candidate projects for developing network of Isfahan city

Project code	Type of project	Cost of project (thousand dollars)	Minimum required time to do the project (month)
1	construction	71.4	4
2	construction	4285	24
3	construction	4937.4	12
4	construction	2521	12
5	construction	7285.7	19
6	construction	1781	18
7	construction	2675	24
8	construction	24285	36
9	construction	36904.8	36
10	construction	4761.9	18

11	construction	119.1	2
12	construction	3381	18
13	construction	3809.5	24
14	construction	1095.2	12
15	construction	904.7	9
16	construction	1428.5	18
17	construction	2238.1	24
18	construction	6188.1	12
19	construction	2833.3	18
20	construction	8600	24
21	construction	785.7	6
22	construction	666.7	6
23	construction	1904.8	12
24	widening	3314.3	28
25	widening	600	5
26	widening	5421.4	25
27	widening	5000	30
28	widening	14761.9	29
29	widening	952.4	14
30	widening	8377.6	15
31	widening	952.4	8
32	BRT	6157.1	12
33	BRT	6966.7	12
34	BRT	1930.6	4
35	BRT	15047.6	12
36	BRT	15022.6	12
37	BRT	15765.5	12
38	BRT	8859.5	12
39	BRT	9527.4	12
40	BRT	11244.1	12
41	BRT	9451.2	12
42	BRT	8658.3	12
43	BRT	11202.4	12

Figure 4- Candidate streets to be added or widen in the development plan of Isfahan’s transportation network

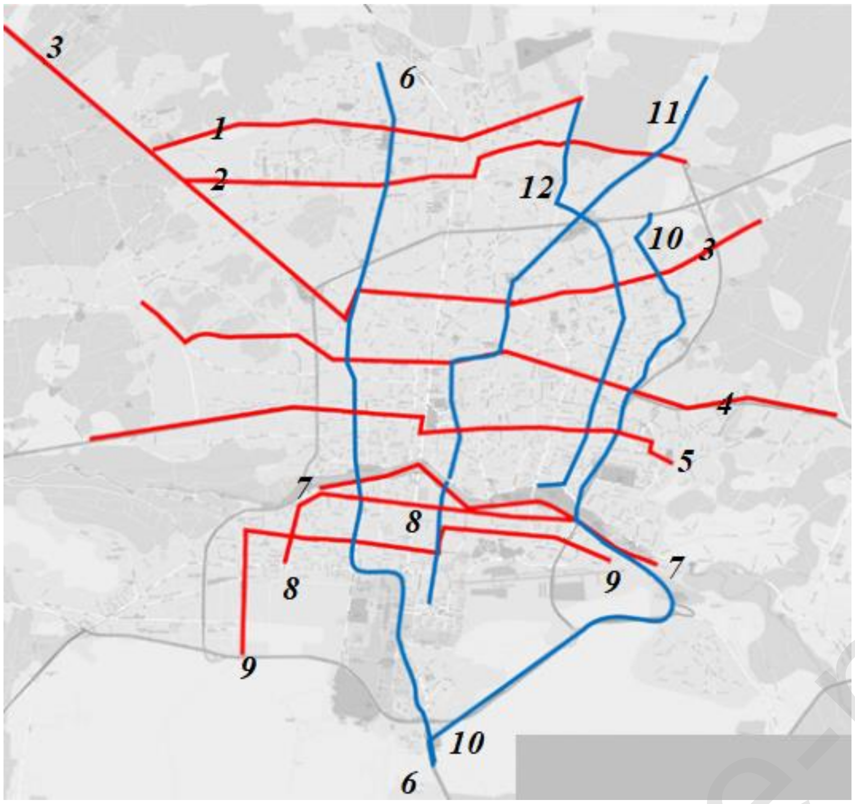

Figure 5- Candidate BRT lines to be added to the Isfahan public transit network

4.2. Planning and evaluation horizons

Since the planning horizon of the development plan of Isfahan's transportation network, in which these candidate projects were obtained from this plan, is to 2026, the planning horizon in this study was set equal to 10 years (2016-2025) and the evaluation horizon was considered 15 years (2016-2030). As noted in Section 3.2, the problem is decomposed into two successive sub-problems, the first with macro periods and the second with micro ones. In the first sub-problem, planning horizon was broken to two 5-year periods. In the second sub-problem, planning horizon and evaluation horizon were set to five and seven years, respectively which include annual periods.

4.3. Evaluation indexes

To evaluate and compere the quality of scenarios (solutions), it was needed to define some indexes. These indexes specify objectives of the upper level problem. For this purpose, a list of various indexes, which can evaluate the status of network development, was originally provided. Since it is difficult to deal with a large number of indexes, it seemed necessary to screen this list. To this end, three following criteria were considered:

- Criterion 1. The selected indexes cover all three dimensions of sustainable development.
- Criterion 2. The selected indexes have more importance than others.
- Criterion 3. There are sufficient and timely data to calculate the indexes.

By considering above criteria, four indexes were selected including total travel time, spatial equity, traffic congestion, and air pollution. The last two indexes were used just for central business district (CBD) of Isfahan, because of emphasis on the upstream conditions.

In the next step, it was needed to assign a weight to each index. To this end, 26 people were chosen on behalf of three different groups of network administrators, citizens, and academic specialists. Then a questionnaire was designed based on pairwise comparison as applied in AHP. The validity of fulfilled questionnaires was checked by calculating Saaty's consistently ratio (Saaty, 2000). Consistently test showed that all questionnaires were consistent. Finally, weights of indexes including “total travel time”, “spatial equity”, “traffic congestion” and “environmental pollution” were calculated by eigenvector method as 0.335, 0.208, 0.261 and 0.196, respectively. These indexes are described in the following:

a) Total travel time

The total travel time within a network is the mostly used index as the objective of the transportation network design problem. In this paper, total travel time in a planning period is considered as the total travel time of passengers on network links. Therefore, this index can be calculated by equation (8):

$$TT^t = \sum_{(i.j)\epsilon A^t} x_{ij}^t t_{ij}^t \quad (8)$$

Where:

TT^t : total travel time in the network in the planning period *t*.

A^t : the set of links in the network in the planning period *t*.

x_{ij}^t: volume of passenger car equivalent (at equilibrium) on link (i,j) in the planning period *t*.

t_{ij}^t: travel time (at equilibrium) on link (i,j).

b) Spatial equity

Implementation of a network design scenario can increase or decrease travel time in different origin-destination pairs in the network and, therefore, can have positive or negative effects on network users. Spatial equity in transportation is associated with the geospatial location of an individual, group or zone affected by a transportation infrastructure project (Thomopoulos et al.; 2009). The spatial equity index in this paper is extracted from Hosseininasab et al. (2018). The calculation of this index for period *t* consists of four steps as the following:

- Step 1: Calculate the average travel time from each zone to others during period t-1 (A_{t-1}^{r}) and the average travel time in the network during period t-1 (A_{t-1}) by equations (9) and (10), respectively:

$$A_{t-1}^{r} = \frac{\sum_{s=1}^{K} P_{t-1}^{rs} \tau_{t-1}^{rs}}{\sum_{s=1}^{K} P_{t-1}^{rs}} \quad r = 1, 2, \dots, K \tag{9}$$

$$A_{t-1} = \frac{\sum_{r=1}^{K} \sum_{s=1}^{K} P_{t-1}^{rs} \tau_{t-1}^{rs}}{\sum_{r=1}^{K} \sum_{s=1}^{K} P_{t-1}^{rs}} \tag{10}$$

Where:

P_{t-1}^{rs}: number of trips from the origin zone *r* to the destination zone *s* during period t-1.

τ_{t-1}^{rs}: travel time from the origin zone *r* to the destination zone *s* during period t-1.

K: total traffic zones in the network.

- Step 2: Determine the improvement (compensation) weight for each zone (w_t^r) by equation (11). Then normalize the calculated weights by equation (12).

$$w_t^r = e^{\left[\frac{\theta(A_{t-1}^{r} - A_{t-1})}{A_{t-1}}\right]} \quad r = 1, 2, \dots, K \tag{11}$$

$$w_t'^r = \frac{w_t^r}{\sum_{r=1}^{K} w_t^r} \quad r = 1, 2, \dots, K \tag{12}$$

θ in (11) is the compensation factor determined by the network decision makers. It is assumed equal to 1 in this study. According to equation (11), the poorer the zone accessibility, the higher improvement weight needs to be assigned to it in order to achieve better spatial equity. $w_t'^r$ in (12) is the normalized improvement weight of zone *r* in period *t*.

- Step 3: Compute accessibility of each zone in period *t* by equation (13). acc_t^r is the average travel time to the facilities for an individual car in the zone *r* in period *t*.

$$acc_t^r = \frac{\sum_{s=1}^{K} P_t^{rs} \tau_t^{rs}}{\sum_{r=1}^{K}\sum_{s=1}^{K} P_t^{rs}} \quad r = 1, 2, ..., K \qquad (13)$$

- Step 4: Calculate the spatial equity index of a transportation network development scenario in period t (SE_t) by equation (14).

$$SE_t = \sum_{r=1}^{K} w_t'^r \times acc_t^r \qquad (14)$$

c) Network congestion index

One of the main problems leading to dissatisfaction of the network users is traffic congestion. Not only does the traffic congestion increase the probability of the accident occurrence and pollution in a network, but it also undermines the appropriate performance of the network in the viewpoint of the network users. Delay in work or educational trips due to traffic congestion results in numerous issues for the users. Thus, one of the criteria that should be considered in the network design is the network congestion.

Network congestion index in period *t* ($Cong_t$) can be expressed by equation (15).

$$Cong_t = \frac{\sum_{(i,j)\in A_e^t} \left(\frac{t_{ij}^t}{t_{ij}^{0\,t}}\right)^{\lambda} S_{ij}^t}{\sum_{(i,j)\in A_e^t} S_{ij}^t} \qquad (15)$$

Where:

$t_{ij}^{0\,t}$: free travel time in the street (i,j) in period *t*.

t_{ij}^t: travel time in street (i,j) in period *t*.

S_{ij}^{t}: area of street (i,j) in period *t*.

A_{e}^{t}: set of links in zone *e* (the study zone) in period *t*.

λ is the factor of congestion importance in the network which can be determined based on the analysis. It is assumed equal to 2 in this study.

d) Air pollution index

The pollution due to motor-vehicle traffic is a major problem in metropolises, especially in central business districts (CBD). In this study, the pollution index in period *t* (Pol_t) is determined by equation (16).

$$Pol_t = \sum_{(i.j)\in A_e^t} x_{ij}^t \times l_{ij}^t \times Z\left(speed_{ij}^t\right) \qquad (16)$$

Where:

x_{ij}^{t}: volume of passenger car equivalent on link (i,j) in period *t*.

l_{ij}^{t}: length of link (i,j) in kilometer in period *t*.

$Z\left(speed_{ij}^{t}\right)$: the function of pollution determination based on the speed of vehicles on link (i,j).

4.4. Software platform

Implementation of the proposed methodology in every transportation network needs a software platform to facilitate the massive amount of computing that should be carried out. Efficiency of this platform has a significant impact on the quality of the results and the solution time. In this study, a software platform is developed in which Matlab, Gauss, and EMME programs are used in interaction with each other. GA, the phase-I of two-phase simplex, and objective weighting method are coded in Matlab. The model of forecasting O–D demands was already developed in the Gauss environment. Also, network modification macros are developed in Gauss to modify the network configuration for each scenario (solution). EMME/4 software is used to assign the traffic flow on network links. In each iteration of the proposed solution approach, solutions are generated by GA in Matlab, firstly. Next, feasibility of each solution is checked by the phase-I of two-phase simplex method in Matlab. For each of feasible solutions, the network configuration in each period is modified by the macro written in Gauss. Also, O–D demands in every period are forecasted by the model developed in Gauss. These two data sets are sent to EMME/4 and after assigning the traffic demands, EMME/4 provides the data of traffic flow and travel time in the network links. After obtaining these data for each scenario, the values of all four indices are calculated and then aggregated in Matlab.

4.5. Results

The proposed approach was composed in two phases. The results of each phase are discussed as follows.

4.5.1. Project selection (first phase)

27 out of 43 projects were selected to be executed in the first 5-year period (2016-2020) as shown in Table 2 and Figure 6, and others were assigned to the second 5-year period (2021-2025). As shown in Figure 6, selected projects are distributed all over the urban network, but the focus on eastern part of the city is more. This result can be confirmed for two reasons. First, eastern zones of the city have developed less and spatial equity requires more attention to these zones. Second, due to the agricultural land use of the western zones, less development and construction are seen in order to preserve such land use which can be an obvious sign of implementing urban sustainability in selecting projects.

Figure 6.b indicates multiple intersections of BRT lines. These intersections allow travelers to switch their line. Since some of these lines are east-west and others are north-south, this arrangement of BRT lines improves travel times and accessibility level of the city zones.

Table 2- Selected projects for the first 5-year period (2016-2020)

No. of selected project	Project code	Type of project
1	1	Construction
2	2	Construction
3	4	Construction
4	6	Construction
5	7	Construction
6	8	Construction
7	10	Construction
8	11	Construction
9	12	Construction
10	13	Construction
11	15	Construction
12	16	Construction
13	19	Construction
14	23	Construction
15	24	Construction
16	25	Widening
17	26	Widening
18	27	Widening
19	28	Widening
20	30	Widening
21	31	Widening
22	32	BRT
23	34	BRT
24	35	BRT
25	38	BRT
26	41	BRT
27	42	BRT

(a) Selected streets

(b) Selected BRT lines

Figure 6- Position of selected projects for the first 5-year period (2016-2020) on Isfahan's network

4.5.2. Project scheduling (second phase)

In the second phase, these projects were scheduled yearly. The details of budget assignment to each project, which is one of the capabilities of this model, are shown in Figure 7. In this figure, each box demonstrates the number of selected project (1 to 27) and the annual budget assigned to it in terms of thousand dollars. As shown in Figure 7, constructing new streets is focused more on early years and, on the contrary, widening existing streets is concentrated more on final years of planning horizon. This result comes from the fact that constructing a new street usually reduces travel time more than widening an existing street.

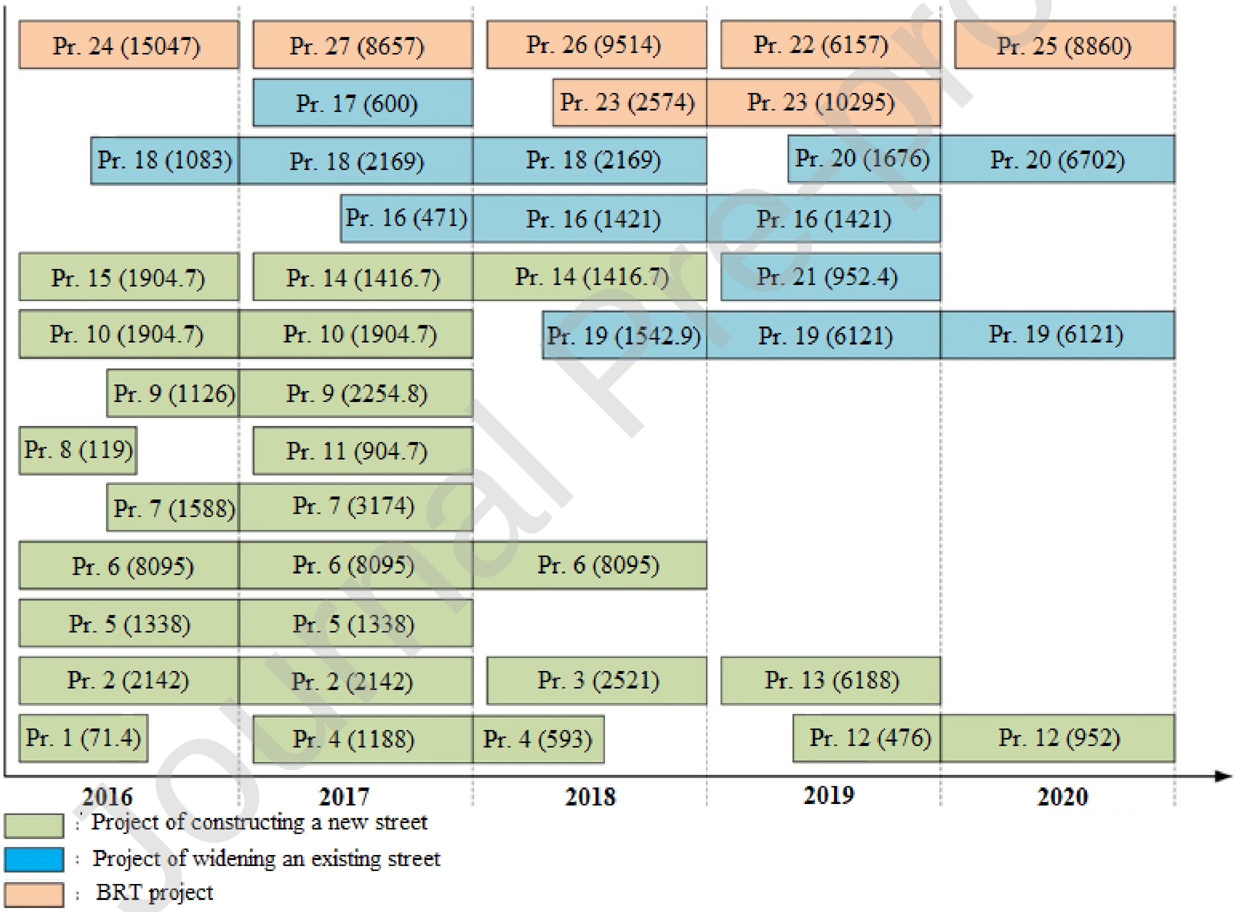

Figure 7- Budget assignment and timing for the selected projects in the first 5-year period

5. Conclusion

In this paper, the selection and scheduling of urban transportation projects were investigated. First, the previous studies related to the problem were reviewed and the differences between this study and other researches were explored. Table 3 shows differences between this study and past studies on multi-period NDP.

Table 3- Comparison of this study with past studies on multi-period NDP.

Reference	Single/multi objective	Fixed/variable duration of projects	Sustainable development (Y/N)	Real case study (Y/N)	Number of projects in the case
Kim et al. (2008)	Single	Fixed	N	N	-
Szeto et al. (2010)	Single	Fixed	N	N	-
Miandoabchi et al. (2015)	Multi	Fixed	N	N	-
Hosseininasab and Shetab-Boushehri (2015)	Single	Variable	N	N	-
Hosseininasab et. al. (2018)	Multi	Variable	N	Y	10
This study	Multi	Variable	Y	Y	43

In this paper, the main effort was focused on finding a reliable approach to select and schedule transportation projects in large networks in the case of a large number of projects. To this end, a bi-level, multi-period, and multi-objective discrete network design model was employed and a nested evolutionary algorithm was proposed to solve the model in a reasonable time. Finally, it was implemented for the urban network of Isfahan, Iran, and the results were discussed.

The advantage of the proposed approach in this study over the previous ones is its applicability for large networks with many projects rather than only for small networks or large networks with limited number of projects. Furthermore, unlike previous studies with the focus mainly on road construction and widening, here, broader range of transportation projects for developing the network such as streets, BRT and Metro lines were considered.

This paper opens up a number of research issues. First and foremost, indexes which are used to evaluate productivity of network can be modified and improved as covering more aspects of urban sustainability. Secondly, in the proposed methodology, by using the objective weighting method, the multi-objective decision making problem is turned into a single-objective decision-making problem. Considering alternative methods to exchange the multi-objective problem to single-objective problem such as goal programming (GP) can be a different angle for the future research.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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