Interactive multi-objective route planning for sightseeing on Time-Expanded Networks under various conditions

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Abstract

This paper proposes a versatile and interactive route planning problem for sightseeing under various conditions based on constraints of required traveling times and total satisfaction of sightseeing activities, which are time-dependent. In general, traveling times among sightseeing places and the satisfactions of activities also change dependent on various conditions such as weather, climate and season. It is important to represent a satisfying route to ensure the large satisfaction even if any assumable condition happens. In order to incorporate the above-mentioned situations, a multi-objective route planning problem is formulated as a network optimization problems based on Time-Expanded Network to represent time-dependent parameters in a static network. Furthermore, an interactive approach based on the Satisficing Trade-Off Method is introduced to transform the multi-objective into the single. In addition, the proposed problem is equivalently transformed into an extended model of network optimization problems by introducing parameters, and the interactive algorithm is developed.

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1. Introduction

Tourism is an important resource to attract a lot of visitors and money all over the world, and hence, it is also important to decide the appropriate tourism policy to rejuvenate towns and country. In addition, the rapid development of information communication and technologies (ICT) including the Web technologies enables tourists to use multimodal information and recommendations and to construct their personal tour planning for sightseeing by themselves. Therefore, it is necessary to develop a decision support system for tour planning to suit personal satisfactions under various constraints such as budget and the total sightseeing time. Furthermore, tourists should specially consider traveling and activity times, and hence, it is also necessary to do a suitable
management of these times for the effective utilization of sightseeing activities. Thus, the tour planning should be prepared in advance, considering the above-mentioned situations.

Existing studies on the tour planning problem are divided broadly into several groups. Some studies devote solving the problem from a mathematical point of view. The other studies devote dynamically planning an optimal itinerary which is related to finding a path, and designing intelligent tour planning systems based on the personalized tour recommender, etc. There are recently various tour planning problems such as tourist trip design problem (Souffriau et al. [14]), tour planning problem in a multimodal and time-scheduled urban public transport network (Zografos and Androutsopoulos [18]), and time-dependent tour planning methodology to design a time-limited tour based on the maximum total priority value (Abbaspour and Samadzadegan [1]).

Some factors such as uncertainty and time-dependency on required times of traveling and satisfaction values of activities often become important in route planning for sightseeing. For instance, tourists may estimate the traveling time based on traffic data. However, the actual traveling times are often different from the predictions in some degree, and it is difficult to set traveling times as fixed values. Therefore, it is important for tourists to select their favorable route in the given network considering such uncertainty initially. Furthermore, weather and climate conditions are also important factors to change satisfactions of activities in climate or weather-sensitive sightseeing places. Existing mathematical models for route planning for sightseeing do not include such important factors. In order to overcome these drawbacks in existing researches and to construct the more general framework of tour planning, we develop a new mathematical model of tour planning with uncertain traveling times and satisfactions of activities. In this paper, we propose a route planning problem based on Time-Expanded Network (TEN) to represent uncertainty and time-dependent variables from a mathematical point of view. The TEN contains a copy to the set of nodes in the underlying static network for each discrete time step. The advantage of this approach is that it turns the problem of determining an optimal flow over time into a classical static network flow problem on the TEN. Many researchers have considered applying the TEN to practical problems since the 1970s and 1980s. In most recently, TEN-based models also have been proposed for various practical problems (Engineer et al. [2], Guo et al. [5], Hane et al. [6], Kliewer et al. [10], Shah et al. [12], Yan and Chen [16]). In this paper, the time-dependency on traveling and activity times in each weather or climate condition can be represented in a TEN.

In addition, tourists may prefer only one route not to change according to weather and climate conditions, because tourists are confused how they select an appropriate plan in these routes if these routes are utterly different each other, and this approach will not become a better decision support system for sightseeing. Furthermore, tourists also prefer a route satisfying their target satisfaction level of each condition. Thus, it is important for tourists to have the same route plan considering target satisfaction levels under various conditions. Therefore, we formulate our proposed model as a multi-objective programming problem, and introduce an interactive approach based on Satisficing Trade-Off Method proposed by Nakayama [11] in order to solve it in a mathematical programming problem with one objective function.

This paper is organized as follows. In Section 2, we introduce a definition of Time-Expanded Network for time-dependent parameters in each condition. In Section 3, we explain our assumed situations in this paper, and formulate our proposed route planning problem for sightseeing in mathematical programming. Since this formulated problem is the multi-objective, we introduce an interactive approach based on Satisficing Trade-Off Method and transform the initial problem into an extended model of network optimization problems. Furthermore, we develop an interactive algorithm to obtain an appropriate route for tourists. Finally, in Section 4, we conclude this paper.

2. Time-Expanded Network

Time-Expanded Network (TEN) contains a copy to the set of nodes in the underlying static network for each discrete time step. Mathematical programming problems derived from the TEN can be solved by well-known
network flow algorithms. The TEN-based methodology involves (i) identifying and quantifying switching values of parameters, (ii) creating an optimization model based on the concept of TEN, and (iii) solving the model under probabilistic or manually generated scenarios for parameters to identify optimal designs.

The methodology of TEN-based decision making generally consists of the following five steps introduced by Silver and Weck [13].
1. Designing an initial set of feasible system configurations
2. Quantifying switching parameters and creating a static network
3. Creating the time expanded network
4. Create scenarios and run optimization
5. Modifying system configurations: Iterative design

In this paper, we construct the TEN as the following steps based on previous studies and above-mentioned steps of TEN based on Hasuike et al. [7].

2.1. Expansion of the static network

The first step constructing the TEN is to consider discrete time steps and make a copy of the original static network for every time step from time zero to the time horizon \( T \). For instance, consider the given static network in Fig.1. We create a copy to set of nodes for each time period as described in Fig. 2.

Fig. 1 Example of static network

The route planning problem is generally regarded as a discrete time model due to train and bus transportations running on schedule such as every 10 minute, and hence, it is possible to formulate our proposed time-
dependent model as the TEN-based network model, and to obtain an optimal set of nodes in feasible tour routes of the TEN by solving the proposed model using network optimization.

2.2. Connecting nodes with directed edges

The second step constructing our proposed TEN-based model is to connect nodes with directed edges according to the corresponding time durations. Fig.3 shows a part of TEN-based tour planning problem extending the static network in Fig.1. This example assumes that place 1 is the departure point of the tour. For instance, directed edge (a) represents that tourists can travel from place 1 at time 0 to place 2 at time \( t_1 \) by taxi. On the other hand, directed edge (b) also represents the travelling time duration of place 1 at time 0 to place 2 time \( t_2 \) by bus. This difference arises from the usage of different transportations. Furthermore, directed edges (c) and (d) represent the activity duration times of place 2 in different clock times. If we assume that place 2 is crowded after time \( t_2 \), and it may take more active duration times than usual conditions.

Using the TEN, we can deal with different travelling and activity time durations to the same route and activity in the static network.

2.3. Setting satisfaction values and costs to each directed edge

In a similar way to travelling and activity time durations, we can set different satisfaction values and costs \((s,c)\) with respect to each directed edge for every time step. Fig. 4 shows a part of our proposed model with satisfaction values and costs.
For instance, in subsection 2.2, we mentioned that the difference of traveling times to directed edges (a) and (b) arose from the usage of different transportations. According to this assumption, we set values of costs to edges (a) and (b) as Fig.4, because taking a bus is generally cheaper than a taxi. Thus, using the network model obtained through these steps to construct TEN from the static network model, we propose and formulate a personal tour planning problem with time-dependent parameters.

### 3. Formulation of Our Proposed Route Planning Problem

#### 3.1. Notation of parameters in our proposed model

In this paper, we assume $m$ conditions, i.e. $k \in \{1, 2, ..., m\}$, and only satisfaction value changes according to each condition. Let $G = (V, E)$ be a connected graph in TEN. $E$ is the set of directed edges and $V$ is the set of nodes mathematically defined as $M \cup \{s, f\}$ where each set is derived from the following conditions, respectively.

$s$: index of departure place

$M$: index set of sightseeing places where the tourist can visit. In this paper, we assume $n$ sightseeing places, i.e., $M = \{1, 2, ..., n\}$

$f$: index of final destination

We can also extend our proposed model to the case that we find not only appropriate departure place but also final destination according to the optimal tour route. However, to simplify the following discussion, departure place and final destination are initially fixed.

The notation of parameters for the TEN is as follows:

$T$: total tour time initially set by the tourist, which means the time horizon

$t$: time step satisfying $t \in S_i = \left\{0, \frac{T}{n}, \frac{2T}{n}, ..., T\right\}$ where $n$ is the total step decided by the tourist

$a_{ij}^k(t, t')$: satisfaction values to obtain by travelling from site $i$ at time $t$ to site $j$ at time $t'$ under condition $k$. 

![Fig.4 A part of TEN for the tour planning model with satisfaction values and costs (s,c)](image-url)
Particularly, in the case of sightseeing of place $i$, satisfaction value $a^k_{ij}(t,t')$ represents this situation. In this paper, we assume that all satisfaction values are initially set by tourist’s hobby and purpose, and the other tourists’ information on the Web using the Web intelligence analysis.

$c_{ij}(t,t')$: costs to travel from site $i$ at time $t$ to site $j$ at time $t'$. In this paper, we set same values every condition.

$b$: minimum visiting points initially decided by the tourist

$C$: total budget available for the tour

$x_{ij}(t,t')$: 0-1 decision variables satisfying the following condition;

\[ x_{ij}(t,t') = \begin{cases} 1, & \text{if the tourist travels from site } i \text{ at time } t \text{ to site } j \text{ at time } t' \\ 0, & \text{otherwise.} \end{cases} \]

$x_{ii}(t,t')$: 0-1 decision variables satisfying the following condition;

\[ x_{ii}(t,t') = \begin{cases} 1, & \text{if the tourist does sightseeing at place } i \text{ from time } t \text{ to time } t' \\ 0, & \text{otherwise.} \end{cases} \]

3.2. Constraints in our proposed model

TEN-based models are generally formulated as a network optimization problem. Our proposed route planning problem includes the following constraints derived from general network structures in mathematical programming. We consider the constraint in the case of condition $k, (k \in \{1,2,\ldots,m\})$.

(1) Route construction constraint in network optimization

If the tourist visit place $j$ from the other sightseeing place at time $t'$, i.e., $x_{ij}(t',t) = 1, t' < t$, the tourist would leave this place to the next only one place $p$ in the next time, i.e. $x_{jp}(t,t'') = 1, t < t''$, or do sightseeing this place, i.e., $x_{ii}(t,t'') = 1, t < t''$. This flow of tourist is mathematically formulated as follows in network optimization:

\[ \sum_{t' \in S_j} \sum_{t' < t} x_{ij}(t',t) - \sum_{t' \in S_j} \sum_{p \in M} x_{jp}(t,t'') = 0, \]

\[ (\forall j \in M, \forall ((i,t),(j,t')) \in E, 0 < t \leq T) \]

(2) Departure place constraint

The tourist starts sightseeing at time 0 from departure place $s$, and goes to only one sightseeing place $j$ at time $t'$. Therefore, this constraint is represented as the following form:

\[ \sum_{t \in S_i} \sum_{j \in M} x_{ij}(0,t') = 1, (\forall (s,0),(j,t')) \in E \]

(3) Final destination constraint

In similarly, the tourist certainly arrives at the fixed finale destination $f$ until time $T$ from only one sightseeing place $j$ at time $t' (t' < t < T)$. Therefore, this constraint is represented as follows:
(4) Number of visiting places constraint

From the notation of \( x_{ji}(t, t') \), \( x_{ji}(t, t') = 1 \) means that the tourist does sightseeing at sightseeing place \( i \) from time \( t \) to \( t' \). Since parameter \( b \) means minimum visiting points initially decided by the tourist, we formulate visiting places constraint as follows:

\[
\sum_{t \in S_{t}, \ t' \in T} \sum_{i \in M} \sum_{j \in M} x_{ji}(t, t') \leq b \quad (\forall (i, t), (i, t') \in E)
\]

(5) Constraint to each sightseeing place

The tourist can also visit sightseeing places as time permitting, i.e., the tourist does not visit them if there is no travelling time. On the other hand, there isn’t much point in doing sightseeing of the same place, i.e., the tourist can visit each sightseeing place only one time. This situation is mathematically formulated as the following inequalities:

\[
\sum_{t \in S_{t}} x_{ii}(t, t') \leq 1 \quad (\forall i \in M, \forall (i, t), (i, t') \in E)
\]

(6) Cost constraint

It takes some money costs to travel between two places and do sightseeing at a sightseeing place. Therefore, the cost constraint is introduced as follows:

\[
\sum_{(i, t), (j, t') \in A} c_{ij}(t, t') x_{ij}(t, t') \leq C
\]

where \( A \) is the connected graph with time-dependent parameters \( t, t' \in T \), and \( C \) is the target level of total cost set by the tourist.

(7) Constraint of 0-1 decision variable

From the notation of parameters \( x_{ji}(t, t') \), if route \( x_{ji}(t, t') \) in TEN is included in the optimal route of our proposed model, \( x_{ji}(t, t') \) is equal to be 1. If not, \( x_{ji}(t, t') \) is equal to be 0. Therefore, the following constraint is introduced:

\[
x_{ij}(t, t') \in \{0, 1\}, \forall (i, t), (j, t') \in A
\]

We set a feasible region derived from constraints (1) to (7) as \( X \), i.e., \( x \in X \).

### 3.3. Formulation of our proposed model and development of interactive algorithm

The objective function in this study is maximizing the total satisfaction value of all sightseeing places visited by the tourist each condition. The total satisfaction value of condition \( k \) is formulated as

\[
\sum_{(i, t), (j, t') \in A} a_{ij}(t, t') x_{ij}(t, t')
\]

and hence, our proposed model is formulated as the following multi-objective TEN-based route planning problem (TEN-TPP) maximizing the total tourist satisfaction of all conditions:
Maximize $Z_{a1}(x) = \sum_{(i,t),(j,t') \in A} a_{ij}^1(t,t')x_{ij}(t,t')$

Maximize $Z_{a2}(x) = \sum_{(i,t),(j,t') \in A} a_{ij}^2(t,t')x_{ij}(t,t')$

\vspace{1em}

Maximize $Z_{am}(x) = \sum_{(i,t),(j,t') \in A} a_{ij}^m(t,t')x_{ij}(t,t')$

subject to $x \in X$

(8)

This problem is a multi-objective programming problem, and hence, it is hard to obtain an optimal solution maximizing all objective function, simultaneously. If there is a function $f_{agg}$ to integrate all objective function of problem (8), this problem is transformed into the following single-objective problem:

Maximize $f_{agg}(Z_{a1}(x), Z_{a2}(x), ..., Z_{am}(x))$

subject to $x \in X$

(9)

However, it is generally difficult to define the integrated function $f_{agg}$, and hence, we consider a set of Pareto optimal solutions which is one of the solution concepts for multi-objective programming problems. In this paper, in order to obtain a satisficing solution of tourists in a set of Pareto optimal solutions of problem (8) efficiently, we introduce an interactive approach based on Satisficing Trade-Off Method proposed by Nakayama [11]. We set target levels of objective functions as $\hat{z}_k, k = 1, 2, ..., m$, and obtain a Pareto optimal solution according to $\hat{z}_k, k = 1, 2, ..., m$ under the minimax optimal criterion. This Pareto optimal solution is obtained by solving the following problem:

Minimize $\max_k \left\{ \frac{\hat{z}_k - Z_{ak}(x)}{z_{up}^k - z_{nad}^k} \right\} + \rho \sum_{k=1}^{m} \left( \frac{\hat{z}_k - Z_{ak}(x)}{z_{up}^k - z_{nad}^k} \right)$

subject to $x \in X$

(10)

where $z_{up}^k$ is a value satisfying $z_{up}^k \geq \max \{ Z_{ak}(x) | x \in X \}$, and $z_{nad}^k$ is a value satisfying $z_{nad}^k = \min_{i \neq k} \{ Z_{ak}(x_{opt}^i) \}$ where $x_{opt}^i$ is a optimal solution of $\max \{ Z_{ai}(x) | x \in X \}$. $\rho$ is the sufficiently small value. Problem (10) is equivalently transformed into the following problem by introducing parameter $\nu$:

Minimize $\nu + \rho \sum_{k=1}^{m} \left( \frac{\hat{z}_k - Z_{ak}(x)}{z_{up}^k - z_{nad}^k} \right)$

subject to $\frac{\hat{z}_k - Z_{ak}(x)}{z_{up}^k - z_{nad}^k} \geq \nu, (k = 1, 2, ..., m)$

$x \in X$

(11)

Consequently, by solving problem (11) using the following interactive algorithm, we can show the appropriate route for sightseeing to each tourist.
Interactive algorithm

STEP1: Calculate $z_k^{\text{rad}}$, $(k = 1, 2, ..., m)$ and set $z_k^{\text{up}}$, $(k = 1, 2, ..., m)$ and $\rho$. Go to STEP2.

STEP2: Set $\hat{z}_k$, $(k = 1, 2, ..., m)$ by the tourist. Go to STEP3.

STEP3: Solve problem (11), and obtain an optimal route $\mathbf{x}^*$. Go to STEP4.

STEP4: If the tourist is satisfied with the route $\mathbf{x}^*$ obtained in STEP3, terminate this algorithm. If not, reset target levels $\hat{z}_k$, $(k = 1, 2, ..., m)$, and return to STEP 3.

In this algorithm, STEP3 is the most important step, because problem (11) is an extension problem of constrained network optimization problems. We may solve the problem using the network optimization method exact algorithm in the case of small-scale problem, and heuristic algorithm in the case of large-scale problem. Most recently, tabu search-based algorithms are widely used in various types of large-scale practical problems formulated as 0-1 programming problems (Gendreau et al. [4], Katagiri et al. [8, 9], Tang and Miller-Hooks [15]). Therefore, we will solve large-scale problems of our proposed model by directly applying or improving these tabu search-based algorithms.

Since the proposed tour planning problem can apply time-dependent parameters to the coefficients simply and replace edges according to the change of required time, we also decide not only the optimal tour route satisfying the tourist’s satisfaction but also appropriate time scheduling of the tour route, simultaneously.

In addition, in our previous study (Hasuike et al. [7]) whose model is single-objective programming problem based on TEN, we introduced a simple example of traffic data and represented some advantages of our model. We will straightforwardly apply the numerical example to our proposed multi-objective programming problem in this paper and show some advantages of it compared with previous route planning approaches, because some main constraints of our proposed model derived from the TEN are same as those of Hasuike et al. [7].

4. Conclusion

In this paper, we have proposed a versatile and interactive route planning problem for sightseeing under various conditions such as time-dependent parameters and changing satisfaction values of sightseeing places according to various conditions. From a general concept that tourists prefer the same route independent of weather and climate conditions, we have formulated a multi-objective problem satisfying target satisfaction levels derived from Time-Expanded Network to incorporate time-dependent parameters into a static network optimization problem. Furthermore, we have transformed the initial problem into a constrained network optimization problem using interactive approach based on Satisficing Trade-Off Method, and developed an interactive algorithm. By solving our proposed model, the tourist will simultaneously obtain not only the optimal tour route of usual condition but also appropriate tour route under the other conditions. Therefore, our proposed model will be more useful model than existing tour route planning problem.

With respect to the proposed models as well as general models, the problem is strongly NP-hard (Fischetti et al. [3]) due to mixed integer linear programming problem. We have listed some existing efficient solution algorithms in Subsection 3.3, but it may be still computationally difficult to solve large-scale tour planning problems. Therefore, we are now studying the development of efficient heuristic solution algorithms based on soft computing approaches and examining the efficiency using practical “Big” data for sightseeing. It is important but difficult to collect the “Big” data for sightseeing. We will plan how to collect such data appropriately and efficiently and how to represent each optimal plan for the tourist solving our proposed model rapidly and strictly.
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