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The planning of cycle trips in the province of East Flanders

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ABSTRACT

Traditional route planners assist in finding the shortest or fastest route from one place to another. This paper presents a novel approach to path finding in a directed graph, namely a target distance, motivated by the problem that a recreational cyclist deals with when searching a nice route of a certain length. The problem is defined as a variant of the arc orienteering problem (AOP), a new combinatorial optimisation problem in which the score of a route in a directed graph has to be maximised by visiting arcs, while each arc can be visited at most once and the total cost of the route should not exceed a predefined cost. The contribution of this paper is threefold: (1) a mathematical model of the AOP is provided, (2) a metaheuristic method that solves AOP instances to near optimality in 1 s of execution time, is proposed and evaluated, and (3) two real-life applications of the method are presented. An on-line cycle route planning application offers personalised cycle routes based on user preferences, and an SMS service provides cyclists "in the field" with routes on demand.

1. Introduction

In countries like Belgium and the Netherlands, cycling is a popular sport and a widespread recreational activity. Many cyclists try to combine sport and leisure by traversing scenic cycle routes, enjoying beautiful sights or riding quietly along a canal or river. Cyclists are an important source of income for the local economy of East Flanders, as they spend 10.90 euro on average when going for a ride, mainly for drinks during the route or afterwards.[1] Regional tourist offices market their region by offering recreational cyclists a number of products. These products have evolved over the years from static printed route maps to state-of-the-art on-line applications. First, static scenic routes were developed. A tourist office determined a fixed route, baptised it with a commercial name, placed signposts along the track and started to sell maps. The cyclist could then follow the route in either direction. Although popular, these routes have a clear drawback of being inflexible, both with respect to the track and the length. In order to overcome this limitation, a more versatile concept resulted in the so-called cycling networks. These networks are graphs consisting of nodes (intersections) interconnected by cycle-friendly arcs (tracks). The East Flanders' network is a concatenation of five regions and is composed of 989 nodes and 2963 arcs, with a total of 3585 km. At first, these networks were published as maps, of which in a period of three years (2006–2008), 193,208 were sold in East Flanders. With a map of the network, users could plan custom-built routes, tailored to their personal preferences involving length, area, difficulty, etc. Planning a route that satisfies all these requirements is a somewhat complicated problem. Therefore, the Belgian province of East Flanders came up with an on-line version of their cycling network, which facilitates creating routes, printing or downloading these to a personal navigation device and sharing route information with friends through social networking sites. Furthermore, an automated route planning tool has been developed and is incorporated into the software. This particular planning tool is presented in this paper.

The route planning problem can be perceived as a variant of the orienteering problem (OP), a combinatorial optimisation problem in which the score of a route has to be maximised by selecting a number of locations while not violating a budget constraint [1]. This model has already been successfully applied in the field of tourism in order to calculate personalised walking routes in historic cities [2,3]. For the automated planning of cycle routes, an arc routing variant of the OP should be considered.

A recent survey about the OP, practical applications and solution strategies can be found in [4]. Golden et al. [5] prove that

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the OP is NP-hard, which implies that exact solution algorithms are very time consuming and thus for practical applications heuristics are necessary. Only a few papers consider arc routing variants of the OP where a profit is associated with each arc. Feillet et al. [6] proposed a branch-and-price approach for the "profitable arc tour problem". Aráoz et al. [7] introduce the "privatised rural postman problem", which was later called the "prize-collecting rural postman problem" by Aráoz et al. [8]. In these problems, the objective is to maximise the difference between the profit and the total travel distance. Archetti et al. [9] describe the "undirected capacitated arc routing problem with profits". The objective of this problem is to determine a route for each available vehicle in order to maximise the total collected profit, without violating the capacity and time limit of each vehicle. In the next section, the differences between these models and the East Flanders model for cycle route planning is explained.

The remaining of this paper is structured as follows: in Section 2, the problem is described in detail by means of a mathematical optimisation model. Section 3 describes a heuristic solution approach for the bike route planning problem. Section 4 validates the approach on real-world data and compares the results with those obtained by a commercial solver. Section 5 elaborates on the present use of the system in East Flanders. Section 6 concludes the paper and points out directions for further research.

2. The arc orienteering problem

A cycle route planning tool allows recreational cyclists to choose a starting and ending point in the cycling network and the length of their route. It should immediately design a route in the network corresponding to the requirements. This problem was mathematically modelled as an "arc orienteering problem" (AOP). The AOP can be defined with the aid of a directed graph $G=(V,A)$, where $V=\{v_1,\ldots,v_n\}$ is the vertex set and A is the arc set. With each arc $a_{ij} \in A$ a cost c_{ij} and a non-negative score S_{ij} are associated. The AOP consists of determining a path $G' \subset G$, including pre-set start vertex v_1 and end vertex v_n, with a cost smaller than C_{max}. The goal of the AOP is to determine a path that maximises the total collected score.

Making use of the notation introduced above, the AOP is formulated below as an integer program (u_i=position of vertex i along the path; $x_{ij} = 1$ if arc (v_i,v_j) is included in the path, 0 otherwise):

$$\text{Max} \sum_{i=1}^{n}\sum_{j=1}^{n} S_{ij}x_{ij} \tag{1}$$

Subject to:

$$\sum_{j=2}^{n} x_{1j} = \sum_{i=1}^{n-1} x_{in} = 1 \tag{2}$$

$$\sum_{i=1}^{n} x_{ik} = \sum_{j=1}^{n} x_{kj} \le 1; \quad \forall k=2,\ldots,n-1 \tag{3}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}x_{ij} \le C_{max} \tag{4}$$

$$2 \le u_i \le n; \quad \forall i=2,\ldots,n \tag{5}$$

$$u_i - u_j + 1 \le (n-1)(1-x_{ij}); \quad \forall i,\ j=2,\ldots,n; \quad i \ne j \tag{6}$$

$$x_{ij} \in \{0,1\}; \quad \forall i,\ j=1,\ldots,n \tag{7}$$

The objective function (1) maximises the total collected score. Constraints (2) guarantee that the route starts in vertex 1 and ends in vertex n. Constraints (3) ensure the connectivity of the route and guarantee that each vertex and each arc is visited at most once. Constraint (4) limits the cost of the route. Constraints (5) and (6) prevent sub-tours.

Formulation (1)–(7) does not allow multiple visits of a vertex. This requirement can be easily relaxed; in the case of East Flanders, it was imposed to design more conventional cycle trips. Typically, cost coefficients c_{ij} are equal to arc distances. Value C_{max} is often not a strict upper bound. Recreational cyclists aim at riding a certain number of kilometres, but they do not mind riding a bit more if this brings the total length closer to the requested length. Therefore, C_{max} was always enlarged by 1 km. In the present applications, the score values (S_{ij}) are also taken equal to c_{ij}. As a result, the total length of a trip will indeed be very close to the length requested by the cyclist. In the future, it will be easy to include other types of cyclists' preferences. Examples of such preferences are: avoid or include steep inclines, dirt roads as much as possible, etc. The score of each arc can easily be modified in order to take these preferences into account, when the necessary data is available. Perhaps it will be necessary to set explicitly a lower bound on $\sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}x_{ij}$.

The difference between the AOP as formulated in (1)–(7) and the prize-collecting rural postman problem [8] or privatized rural postman problem [7] is that in the AOP the available cost is limited. The main difference with the profitable arc tour problem is that in the AOP every arc can be visited at most once. The difference with the "undirected capacitated arc routing problem with profits" [9] is that (a) the AOP uses a directed graph, (b) considers only one route, and (c) has no capacity constraints.

3. Solution approach

The solution approach implemented in the East Flanders case is based on a greedy randomised adaptive search procedure (GRASP), a metaheuristic first introduced by Feo and Resende [10] and successfully applied to the Team OP, which is the OP with multiple vehicles, by Souffriau et al. [11]. First, Section 3.1 defines a number of concepts and describes how a solution to the AOP is represented. These solutions are related to each other by means of a neighbourhood structure (Section 3.2) and form a search landscape. Finally, Section 3.3 describes how to explore this landscape efficiently.

3.1. Concepts and solution representation

In a network, we define a "path" between two vertices as a list of consecutive arcs, visiting any vertex at most once. The cost of a path is the sum of the costs of the individual arcs. The cost between two arcs is the cost of the cheapest path between the end vertex of the first arc and the start vertex of the second arc.

In the solution approach, a "route" is represented by a list of visited arcs. In contrast to a path, these arcs are not required to be connected. A corresponding path can be constructed by augmenting the route with the cheapest paths between the non-consecutive arcs. The cost and score of a route are respectively equal to the cost and score of its corresponding path. A route is a valid solution to the AOP if

- its corresponding path starts at vertex 1,
- its corresponding path ends at vertex n,
- its corresponding path does not contain any arc more than once,