A Contribution to Better Organized Winter Road Maintenance by Integrating the Model in a Geographic Information System

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INTRODUCTION

Optimization of transportation costs in logistics as well as in transportation is of increasing importance. The level of optimization and savings in practical applications can be considerably improved when mathematical models are integrated with GIS (Thill, 2000), see also (Choi et al., 2009). In this article (original paper, with more sophisticate examples can be seen in (Kramberger et al., 2012)) we consider a transportation problem and show how integration of an advanced mathematical model with GIS technology can be beneficial providing a powerful tool for testing sophisticated ARP models.

The first truly operational GIS was introduced more than four decades ago. Since then GIS has been improved from a simple tool to technology, and finally to Geographic Information Science (Goodchild, 1992). Among the wide range of potential applications GIS can be used for, lately especially the transportation issues have received a lot of attention. A specific branch of GIS applied to transportation issues, commonly labeled as GIS-T, has emerged (Rodrigue et al., 2009).

Mathematical models usually provide an efficient way to understand and predict the behavior of natural and human systems. Presenting and testing results gained from a mathematical model in reality sometimes can cause difficulties. For example when we are dealing with problems which are modeled as Arc Routing Problem (ARP), the underlying structure is usually a combinatorial object with a few additional features. Consequently, the results obtained with an exact algorithm or heuristics can be optimal or near optimal in the mathematical model, but when we map them into the real world, we could find some discrepancy.

BACKGROUND

One of the most challenging situations from real life is sanding icy winter roads. If the roads are not ploughed or slippery roads are not scattered, participants in traffic are exposed to great danger. Weather conditions often cause traffic jams and have negative economic effect, thus causing great dissatisfaction with people. In several papers (e.g. (Chapman & Thornes, 2011; Shao & Lister, 1995; Cypra & Seidl, 2012) the problem of winter road de-icing is considered using different formulations. In his Ph.D thesis Kršmanec (2013) proposed a new method for the construction of hierarhical regression models. The results are comparable with well known METRo method (Crevier & Delage, 2001). Chapman and Thornes claimed that the decision support system should replace the 'local knowledge' of the winter maintenance personnel. A negative bias should be added to the forecast in order to ensure that the highway remains safe and secure for all users (Chapman & Thornes, 2011). Marti et al. (2010) introduce a new multiagent system (MAS) used to support traffic management when the meteorological problems appear in the road network. Despite all technological solutions there are still problems with the reliability of information so Kaare et al. indicate that there are still problems with the reliability of information about road weather conditions. The possible solution is to gather data about key performance indicators and to give feedback about constructed road sections by comparing the data from distinct sensors and locations (Kaare et al., 2012). Chen and Chen used a holistic deterministic model to provide useful assessment and prevention information for traffic and

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emergency management (Chen & Chen, 2010). Ahmed et al. (2012) suggest that real-time weather information and traffic statuses are essential to address the crash frequency models, particularly for mountainous freeways with adverse weather conditions.

To deal with the problem properly, the security, economical and environmental effects have to be considered. Regarding security, the most exposed and first icy road network spots should be given priority. From the economical point of view, all these roads have to be scattered one after another using the cheapest route. From the environmental point of view we should minimize the undesirable effects that are result of different mechanisms of transporting salt from the roadway to the surroundings.

In the following section we will briefly describe the mathematical model (Kramberger et al., 2009), which uses a generalization of the Chinese postman problem on weighted graphs, where in addition the priorities are given to a subset of nodes. The cost function is designed with the aim to both, minimize the total distance traversed and at the same time minimize the time in which the most important (i.e. dangerous) sites are salted.

The Model

Before formal statement of the problem studied in this article, we briefly introduce some notation (Kramberger et al., 2009). For basics of graph theory and combinatorial optimization not defined here, we refer to (Korte & Vygen, 2002). Let $G(V, E, \lambda)$ be an undirected weighted graph where $V = V(G) = v_1, v_2, \ldots, v_n$ is the set of nodes, $E = E(G)$ is the set of edges and λ is a weight function assigning a positive cost of traversing edges. Denote by

$$\Lambda\left(G\right) = \sum_{e \in E(G)} \lambda(e)$$

the cost of traversing all edges in G. In addition, let β: $V(G) \rightarrow R_+$ be a function that defines nonnegative penalties for delays. If $\beta(v) = 0$ the node is called *normal*, and if $\beta(v) > 0$, then the node v is a *priority node*. Based on penalties, we have a total (or, linear) order of priority nodes, and in special case, when all nonzero penalties are different we have a strict linear order, i.e. a sequence of priority nodes. We will assume that the set of priority nodes has k elements, denoted by

$$V^* = \left\{v_1^*, v_2^*, \ldots, v_k^*\right\},$$

and, for brevity, let $\beta_i = \beta\left(v_i^*\right)$.

For a walk $W = w_0 w_1 w_{2..} w_N$ starting at w_0 we define

$$d_W\left(v_j\right) = \min\left\{\sum_{i=1}^{k} \lambda\left(w_{i-1} w_i \mid w_k = v_j\right)\right\}. \tag{1}$$

If W does not meet v_j then we set $d_W(v_j) = \infty$. Hence, $d_W(v_j)$ is the length one needs to traverse along the walk W before first meeting the vertex vj. The set of edges traversed by walk W will be denoted by $E_W = \{w_0 w_1, \ldots, w_{N-1} w_N\}$. The standard graph distance $d(v_i, v_j)$ is the length of a shortest walk between nodes v_i and v_j.

The problem studied in this article can formally be defined as follows:

PROBLEM: Chinese Postman Problem with Priority Nodes (CPP-PN)

INPUT: Undirected weighted graph G(V, E, λ) and a function β: $V(G) \rightarrow R_+$ that defines nonnegative penalties for delays. (Function β gives rise to a set of k priority nodes

$V^* = \left\{v_1^*, v_2^*, \ldots, v_k^*\right\}$ with $\beta_1 \geq \beta_2 \geq \ldots \geq \beta_k > 0$.)

TASK: The objective is to find a walk which traverses each edge at least once and minimizes the cost.

COST: The cost of a walk W is

$$COST(W) = \Lambda(W) + B(W) \tag{2}$$

where

$$\Lambda\left(W\right) = \sum_{w_{i-1} w_i \in E\left(W\right)} \lambda\left(w_{i-1} w_1\right)$$

is the cost of the walk length and

$$B\left(W\right) = \sum_{i=1}^{k} \beta_i \cdot d_W\left(v_i^*\right)$$

is the total cost of delays in graph G.

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