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Sustainable optimization of winter road maintenance services under real-time information

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Abstract

In the last couple of years the climate change is becoming more and more obvious. The temperature extremes are increasing, both maximum temperatures in the summer, as well as temperature minimums in the winter. This causes severe problems for the winter road maintenance service that has to deal with sudden cold spells followed by precipitation and difficulties it brings with. The research was conducted by reviewing present situation of winter road maintenance service of Kraljevica - a city with lot of everyday commuters toward two larger urban areas, Crikvenica and Rijeka. The problem arises when the cold front brings unusual weather conditions. The objective of this research is to provide a sustainable optimization of winter road maintenance service by maximizing the potential of the service to ensure steady traffic conditions. The problem was reviewed through a vehicle routing model. The model has been used to review the current situation in winter road cleaning based on the weather conditions over the last five years, and the worst case scenario was chosen for the simulations. The winter road cleaning optimization was carried out, and it led to possible solutions for adjustments of the winter road maintenance service in the city of Kraljevica. The results of the optimization have shown that there is room for improvement of the current winter road maintenance service conditions in the city, making it more sustainable in the future. Further, models presented in this paper could be used for improvement of maintenance services in other urban areas as well. Suggested possibilities could be used for service improvements, as well as cost and time optimization of the city budgets.

Keywords: cost optimization; operational research; time optimization; winter road maintenance service

1. Introduction

Winter road maintenance service involves a large number of operations, representing a notable challenge to municipal government. These operations include spreading of chemicals and abrasives, snow plowing, loading snow into trucks, and hauling snow to disposal sites. Decision-making at the supervisory level of winter maintenance operations is complex and often constrained by time and resources. For example, at the beginning of a snow storm, maintenance supervisors must decide when to start sanding, what operation routes and sequence to follow, and how much chemical agent or abrasives to apply. All these variants can be modeled and solved using operations research techniques. Many maintenance services still rely in large part on decision rules dictated by field experiences when making vehicle routing and depot location decisions. The limited progress in the use of optimization models is somewhat surprising given that even a small increase in efficiency or effectiveness through optimization could result in significant savings, improved mobility, and reduced environmental and societal impacts. The objective of this research is to provide a sustainable optimization of winter road maintenance service by maximizing the potential of the service to ensure steady traffic conditions.

This paper is divided into two sections. The first section presents a case study on Kraljevica winter road maintenance service. The road network is presented, as well as the model used for optimization, its structure and data input is explained. The second section shows the comparison of the results obtained by different inputs into the model presented in the first section and possibilities that could be used for winter road maintenance service improvements are suggested.
2. Problem formulation and solution approach

The research was conducted by reviewing present situation of winter road maintenance service of Kraljevica - a city with lot of everyday commuters toward two larger urban areas, Crikvenica and Rijeka (Figure 1). Its area extends over 17 square kilometers, and it has approximately 30 kilometers of roadway with three main road entries to the city. Current winter maintenance service is obtained by a private company. Decisions pertaining to when and where to deploy service vehicles are typically made by a human supervisor, based on mostly static weather forecasts, the first hand reports of deployed vehicles, and personal experience. As such, it is not only difficult for knowledge to be quantified and transferred between supervisors, but also to soundly compare alternative treatment plans, or to perform ‘what-if’ scenarios without actually carrying them out in real life (Fu, Trudel & Kim, 2009). Its manager and working crew were interviewed about the maintenance routes, time necessary to complete the winter maintenance operations, and what operations are planned for the winter.

Decision-making at the supervisory level of winter maintenance operations are often complex and constrained by time and resources. At the onset of a snow storm, maintenance managers and supervisor must decide when to start sanding, what operation routes and sequence to follow, and how much chemical agent to apply (Fu, Trudel & Kim, 2009). Their opinion of possible improvements has been used for the beginning of the research.

The problem arises when the cold front brings unusual weather conditions. Based on the weather conditions given by Croatian Meteorological and Hydrological Service over the last five years (2007-2012), the worst case scenario was chosen for further research. Worst case occurred on the days between 30th of January and 4th of February of the year 2012. Temperatures were ranging from -6.1 to -2.2°C, north wind blowing up to 6 Beauforts and precipitation was measured approximately 0-45 mm/day. The main objective of this paper is to develop an operation plan for the available service vehicles, maintenance routes and review of possible fleet changes. This research is questioning could a sustainable optimization of winter road maintenance service be made by maximizing the potential of the service to ensure steady traffic conditions in long term.

In spite of the difficulty of winter road maintenance vehicle routing problems, recent models tend to take into account a larger variety of characteristics of the problems arising in real-world applications, and the proposed solution methods are often based on local search techniques (Perrier, Langevin & Campbell, 2007). There is an extensive literature of academic research on various issues related to the planning, design and management of winter road maintenance operations, summed up by Perrier et al. (2010). Since Kraljevica is located in mild Mediterranean climate area, there is no need for planning the plowing or snow disposal operations, so case study is concentrating on the spreading operations of winter road maintenance.

Spreading operations are directed at achieving three specific goals in winter road maintenance: anti-icing, deicing, and traction enhancement. The selection of the appropriate spreading operation is based on economics, environmental constraints, climate, level of service, material availability, and application equipment availability (Perrier et al., 2007). Because of its low price, ready availability, ease of application, and reliable ice-melting performance this paper will review spreading salt mixed with sand. The operations of spreading chemicals and abrasives concern the service of a set of road segments by a fleet of vehicles, which are based at one or more depots located in one or more sectors, and travel over an appropriate transportation network. Vehicle routing problems related to spreading are generally formulated as arc routing problems (Corberan & Prins, 2010; Perrier
et al., 2010). The problem can be described as the problem of designing optimal delivery or collection routes from one or several depots to a number of geographically scattered cities or customers, subject to side constraints (Laporte, 1992).

In particular, vehicle routing problems for spreading operations consist of determining a set of routes, each performed by a vehicle that starts and ends at its own depot, such that all road segments are serviced, all the operational constraints are satisfied, and the global cost is minimized (Perrier et al., 2007). However, in the time-dependent variant of the vehicle routing problem for spreading operations, the timing of each service pass is of prime importance. That is, the cost to service a road segment depends on the time of beginning service. Recently, Tagmouti et al. (2007) proposed a nonlinear, mixed integer program and a column generation algorithm for a salt spreader routing problem with capacity constraints and time-dependent service costs. In this problem, the service cost on each required road segment is a piecewise linear function of the time of beginning of service.

The transportation network is presented through a graph, whose arcs and edges represent streets to be serviced, and whose nodes correspond to the road junctions and to the vehicle and materials depot locations. In Kraljevica there are total of 119 nodes, including nodes for vehicle and material depot location. Associated with the transportation network is a maximum time for completing spreading operations based on political and economic considerations. For this case study one model with two different variations was programmed. The first model variation calculates optimal routes for the current winter maintenance service, and the second model variation increases the number of vehicles and depots for given network.

2.1. Optimization of routes with current winter maintenance service

Currently there is one vehicle assigned for the whole network. Total time needed to complete the operation is two days, according to the winter maintenance service manager. Since agencies have finite resources that generally do not allow the highest level of service on all roads, they must then prioritize their response efforts. The roads of the chosen network were partitioned into four classes which induced a service hierarchy (Fu et al., 2009; Gabor, 2010).

From Operational program for winter maintenance of local and county roads (Road Administration, 2013) and Operational program for winter maintenance of unclassified roads and other public-traffic areas (Utility Service Department, 2013) main entrances to the city were defined as top priority, followed by road connecting the center of the city with both entrances. Roads that lead to ambulance, school and kindergarten were selected as third priority roads, and the rest of the network were given the minimum priority. The routes performed for spreading operations can start and end at one or more vehicle depots (Cai, Liu & Cao, 2009). Associated with every vehicle depot are a given number of vehicles of each type, in this case one vehicle for one depot at node 2 assigned to maintain Kraljevica road network (Figure 2).

![Figure 10. Main entrances into the city and depot locations](image)

Spreading operations are performed using a fleet of vehicles, called spreaders, whose size and composition can be fixed or can be defined according to the level of service policies, the configuration of the streets and sidewalks, land use and density of development, and times for spreading completion for each class. The capacity of the spreader is expressed as the maximum quantity of chemicals or abrasives the spreader can discharge.
(Feillet et al., 2004; Perrier, Langevin & Campbell, 2007). In this case the spreader type is like the one already used for the purposes of road maintenance in Kraljevica, with the capacity of 4 tons and application rate of 180 kilogram-per-lane-kilometer.

The routes must satisfy several operational constraints, which depend on the level of service policies, and on the characteristics of the transportation network, road segments, sectors and spreaders. The routes start and end at one or more depot locations and each route can end service at a depot other than the original starting depot. In anti-icing operations, routes must start at the proper time for effective spreading of chemicals. The decision must take into account such factors as type of snow, expected temperature conditions at the time of, and following, application, anticipated variations at the critical freeze-thaw point, methods of application, and types of chemicals. To balance the workload across routes, they are often approximately the same length and duration. This helps ensure that all spreading operations will be completed in a timely fashion. Service connectivity requires that sub graph induced by the set of road segments serviced by a spreader is connected. The configuration of routes may also need to conform to existing sector boundaries. Routes crossing these boundaries must be avoided from an administrative standpoint. Some operational constraints can be treated as hard constraints and others as soft requirements or as terms in an objective function. Finally, several, and often conflicting, objectives can be considered for the routing of spreaders.

2.2. Optimization of routes with depot and fleet increase

For the second model variation the number of the depots and vehicles has been increased. Another depot and same type vehicle have been added to the model at node 105, so the total number of depots and associated vehicles equals two. Locations of the depots are on the opposite sides of the city. Nodes 2 and 105 are representing the depots location in second model (Figure 2). The second model variation has been programmed to review the possible improvements for the winter maintenance service. The routes must satisfy several operational constraints, which depend on the level of service policies, and on the characteristics of the transportation network, road segments, sectors and spreaders. The routes start and end at two depot locations and each route ends service at the original starting depot.

3. Results

The two scenarios have been carried out and led to expected results. Current maintenance fleet number and depot location are sufficient for optimal road maintenance of a small town like Kraljevica. Nevertheless the route optimization shows great possibilities for improvement of maintenance service time and cost management. By following optimal routes, the amount of time needed to complete the spreading operation is decreased. According to the analysis and route optimization, Figure 3 presents a part of the generated optimal routes for both models.

![Figure 1](image1.png)

Figure 1. Part of generated routes for both model variations

The first model with current winter road maintenance service fleet is shown on Figure 3a, and the second with depot and fleet increase is shown on Figure 3b.
The winter road cleaning optimization was carried out according to the model flow diagram (Figure 4). The model was formulated with Python, a programming language created by Guido van Rossum, based on earlier operations research models for routing of spreader vehicles (Perrier et al., 2007; Perrier et al., 2010). Current road maintenance service was examined. According to the road network of the city, nodes were associated with every conjunction on the roads, giving the road network a total of 119 nodes. Parameter $d$ was defined as a matrix for distances between each node:

$$
d = \begin{bmatrix}
n_{1,1} & \ldots & n_{j,1} \\
\ldots & \ldots & \ldots \\
n_{1,i} & \ldots & n_{i,j}
\end{bmatrix}
$$

Constraints were formulated by above mentioned conditions. Locations of the depots were set at node 2 for the first model variation, and at nodes 2 and 105 for the second model variation. Route distance was limited by spreader capacity - 180 kilogram-per-lane-kilometer is equal to 17 kilometers per one route for one spreader. Road network was divided into four service hierarchy classes. Road prioritization was formulated with the prioritization matrix $p$, for every connection between two nodes, a priority level was defined:

$$
p = \begin{bmatrix}
p_{1,1} & \ldots & p_{j,1} \\
\ldots & \ldots & \ldots \\
p_{1,i} & \ldots & p_{i,j}
\end{bmatrix}
$$
The main objective of the model is to minimize total distance traveled with a guarantee that every arc is serviced at least once (Omer, 2007). Given result for the first model show that a significant time can be saved while performing spreading operations, almost 40% of time usually spent for the operation. While the new model demonstrates impressive capabilities to include more issues important to the operating agencies, there is still a large gap between state-of-the-art models and actual implementations. Some reasons for this gap include the difficulty of the problems, the unfamiliarity in the practitioner community with the advantages and benefits of OR models, and problems of technology transfer to a decentralized area such as winter maintenance (Perrier et al., 2010).

4. Conclusion

The research described in this paper was conducted by reviewing present situation of winter road maintenance service of Kraljevica. Although located in the mild Mediterranean climate, the cold front in the last couple of years brings unusual weather conditions. The objective of this research was to provide a sustainable optimization of winter road maintenance service by maximizing the potential of the service to ensure steady traffic conditions. The problem was reviewed through capacitated vehicle routing problem with the worst weather scenario chosen for the simulation. The winter road cleaning optimization was carried out, and showed room for adjustments of the winter road maintenance service in the city. The results of the optimization have shown that there are optimal maintenance routes that improve time management of the maintenance service. Model presented in this paper could be improved with more informations and constraints, and used for improvement of maintenance services in other small town areas with similar climate conditions as well. Suggested model could be used for service improvements, as well as cost and time optimization of the city budgets.

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