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Synchronized arc routing for snow plowing operations

M. Angélica Salazar-Aguilar [a,*], André Langevin [b], Gilbert Laporte [a,c]

[a] CIRRELT and HEC Montréal, Canada H3T 2A7
[b] CIRRELT and Département de mathématiques et de génie industriel, École Polytechnique de Montréal, Canada
[c] Canada Research Chair in Distribution Management, HEC Montréal, Canada

A R T I C L E I N F O

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A B S T R A C T

This paper introduces a synchronized arc routing problem for snow plowing operations. In this problem, routes must be designed in such a way that street segments with two or more lanes in the same direction are plowed simultaneously by different synchronized vehicles. A mixed integer formulation and an adaptive large neighborhood search heuristic are proposed. The performance of the proposed algorithm is evaluated over a large instance set, including artificial and real data. Computational results confirm the efficiency of the algorithm.

1. Introduction

Cities with severe winters face each year the difficult task of clearing snow and ice from their streets. Problems arising in winter road maintenance are complex, costly, and site-specific because of the variations of climatic conditions, demographics, economics, and technology. According to Perrier et al. [12–15,10], the importance of winter road maintenance is due to the magnitude of the expenditures associated to these operations, and to the indirect costs resulting from the loss of productivity and decreased mobility. In the United States alone winter maintenance operations consume over $2 billion yearly in direct costs. In Japan and Europe snow removal expenditures are two to three times those of the United States [12]. Moreover, driving conditions can deteriorate dramatically due to snowfalls and ice formation, which causes a significant reduction in pavement friction, increases the risk of accidents, and generates additional costs to motorists and businesses ([21]).

The estimation of the cost and benefits of winter road maintenance has been studied by several researchers [9,21,22]. Snow removal costs can be very high. For example, in Montreal the average cost of a 20 cm snow storm in 2010 was $17 million Canadian dollars (see [23]). Each year, the city has to clear 6550 km of sidewalks and 4100 km of streets. On average, there are 65 weather events calling for response every winter. Snow clearing is performed in four stages: salting, plowing, removal, and disposal. Plowing operations begin as soon as there is an accumulation of 2.5 cm of snow on the ground and continue as long as the storm lasts, ending about eight hours after the snow stops falling.

Winter road maintenance operations such as plowing and spreading deicers play an indispensable role in maintaining good road surface conditions and keeping roads safe [9,21]. In these operations, the efficient application of mathematical optimization techniques can result in substantial savings, improved mobility, and reduced societal impacts.

There exists a relatively limited scientific literature on the practical aspects of snow removal operations [12]. Here we concentrate on the most important publications of the past ten years. Golbaharan [4] has studied a multi-depot snow removal routing problem with time windows. This problem consists of designing a set of least cost routes for homogeneous snow plows, while covering every required road segment exactly once within its associated time window. Every snow plow starts its route at a depot and returns to the same depot. The problem was formulated as a constrained set covering problem and was solved by a column generation algorithm. The performance of the proposed solution procedure was evaluated on real-life data from the district of Eskilstuna, Sweden, involving seven depots, 21 snow plows, 362 nodes, and 814 edges, of which 707 were required. Similar problems have been studied by Sochor and Yu [20], and Razmara [16].

Perrier et al. [11] have proposed a formulation and two solution approaches based on mathematical optimization techniques for the routing of snow plowing vehicles in urban areas. Given a district and a single depot at which a number of plows are based, the problem is to determine a set of routes, each performed by a single vehicle starting and ending at the district depot, such that all road segments are serviced, while satisfying a set of operational constraints and minimizing a completion time objective. The model contains general precedence relation constraints

* Corresponding author.
E-mail addresses: angelica.salazar@cirrelt.ca, angysalag@gmail.com (M.A. Salazar-Aguilar), andre.langevin@polymtl.ca (A. Langevin), gilbert.laporte@cirrelt.ca (G. Laporte).

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with no assumption on class connectivity, different service and deadhead speed possibilities, separate pass requirements for multilane road segments, class upgrading possibilities, and vehicle road segment dependencies. The authors have proposed a model based on a multicommodity network flow structure to impose the connectivity of the route performed by each vehicle, as well as constraints to model a hierarchical objective. The problem is solved by means of two constructive algorithms. The first constructs several routes in parallel by sequentially solving a multiple vehicle rural postman problem with side constraints. The second is a cluster-first, route-second algorithm, which first determines a partition of the arcs into clusters, each having approximately the same work load. A hierarchical rural postman problem with class upgrading possibilities, vehicle road segment dependencies, and turn restrictions is then solved on each cluster.

Fu et al. [3] have developed a real-time optimization model to evaluate alternative resources allocation plans for winter road maintenance operations. Given a fleet of plowing vehicles and a set of predefined maintenance routes, the problem consists in developing an operations plan for the available service vehicles which specify for each of them a route assignment, a service type, and a start time. The scheduling model takes into account both operating costs and quality service requirements, as well as road network topology, road classes, and weather forecasts.

The paper by Dali [1] proposes a sequential constructive heuristic for the design of snow plow routes in a multi-depot network. The minimization of the total deadhead distance is carried out under some side constraints such as service continuity, both-sides service, vehicle capacity, and maximal time for service completion. The problem is modeled as a capacitated arc routing problem.

A project focused on an optimal workforce planning and shift scheduling for snow and ice removal in St. Louis County, Minnesota, was undertaken by Gupta et al. [5]. In the first part of the project, the authors have developed a model to calculate the best way to group road segments belonging to each plow route into passes such that high priority road segments are in the same group, and each group can be processed by a single pass of the plow, and can be plowed and sanded with a single vehicle. The problem was solved by means of a set partitioning formulation to select the arcs that a snowplow should traverse in each pass until all arcs have been serviced. The number of arcs that a snowplow can traverse is constrained by two factors: (1) the total time the snowplow can be away from the depot and (2) the maximal amount of sand or salt that a snowplow can carry. If a pass contains subtours, a heuristic is used to eliminate them by treating each one as a node and solving the underlying Traveling Salesman Problem (TSP).

Finally, Jang et al. [6] have proposed a formulation and a heuristic for a combined depot location, sector design, spreading and plowing route design, fleet configuration and vehicle scheduling problem. Their heuristic integrates depot and sector selection, initial route construction, route improvement, fleet configuration, and scheduling. It iteratively solves these problems until no better solution can be found. The model, which assumes a heterogeneous fleet, takes into account road class service frequency and spreader capacity constraints. Service routes must be established exclusively for each class, but a vehicle can service multiple routes in different classes with different frequencies. Multiple lane roadways are represented with one arc for each traffic lane. The objective considered is to minimize the number of working vehicles. The authors have applied their algorithm to a real transportation network in Boone County, Missouri. This network contains 138 vertices and 452 arcs. Computational results have shown the good performance of their solution procedure: the number of snow plows could be reduced by 21.8% with respect to the current operations.

Fig. 1. Highway 720 during a late day snow storm in Montreal. The Montreal Gazette, March 7, 2011 6:43 PM.

An important practical consideration absent from the literature on the planning of snow plowing operations is the need to synchronize the vehicles required at the same time on the same street segment. For example, when clearing a multiple-lane street, several snow plows must follow one another to push the snow to the side of the street (see Fig. 1). Synchronization is important to avoid building snow mounds in the middle of the street. In this paper we formally introduce, model, and solve the *Synchronized Arc Routing Problem* (SyARP) for snow plowing operations. The SyARP consists of determining a set of routes minimizing the *makespan*, i.e. such that all street segments are serviced within the least possible time, subject to a synchronization constraint. The makespan minimization objective helps to generate balanced routes for drivers. It is also a way to enforce quality of service standards since the population wants the streets to be cleared as early as possible. Each segment is cleared by snow plow vehicles that start and end their journey at the depot. The street segments have different numbers of lanes in one or two directions, and all lanes in the same direction should be plowed by the required vehicles at the same time.

To the best of our knowledge, the SyARP has never been addressed in the arc routing literature, apart from a conference presentation on which this paper expands [18]. Here, we introduce a mixed integer programming formulation for this problem and we develop a heuristic solution technique based on the adaptive large neighborhood search (ALNS) metaheuristic, which is one of the most successful metaheuristics for solving complex routing problems [17]. ALNS was recently applied by Laporte et al. [7] to a capacitated arc routing problem with stochastic demands.

The remainder of this paper is organized as follows. Section 2 is devoted to the detailed description, formulation, and complexity of the problem. The proposed solution procedure is described in Section 3. Experimental work is presented in Section 4, followed by conclusions in Section 5.

2. Problem description, formulation and complexity

Given a network of streets and a fleet of snow plowing vehicles based at a depot, the SyARP consists of determining a set of routes such that all streets, some of which have multiple lanes, are plowed by using fleets of synchronized vehicles in order to minimize the duration of the longest route, called the makespan. The street segments have one or two directions, and each direction has a number of lanes, typically between one and three.