Route Optimization for Winter Road Maintenance

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Abstract

In this paper we present the current state of the art in route optimization for winter road maintenance. We found that an evolutionary approach is known to give good results for this kind of problem. Because the problem is NP-hard with the naturally occurring instances being of a vast size, tailoring the approaches to each instance produces the best results in the most time efficient matter.

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1 Introduction

This paper is the result of a pre-project for a masters thesis in computer science at the Norwegian University of Science and Technology (NTNU). The goal is to lay the foundation for our further work, and obtain the necessary background material.

What we want to do is to explore how route optimization can help improve the work with winter road maintenance in the municipality of Trondheim in Norway. The problem is highly complex as the routing problem in itself is NP-hard and the relevant road network is huge.

1.1 Structure of this paper

After some initial work we found out that optimization of routes is a problem that there has been done a lot of work on, and exists in many different forms. There will first be given a brief historical background of the problem. As there is a lot of available material on the subject, so we did a structured literature review to help us find the most relevant information. We will present our literature search protocol along with what we found to be the state of the art on the subject. At the end of the paper we will give our suggestions for future work, that summarizes our most important findings on the subject and makes suggestions for what questions would be interesting to see more research on.

1.2 History

In the early 18th century the inhabitants of Königsberg debated whether it was possible to form a closed walk across all the seven bridges over the river Pregel, without crossing the same bridge twice. The problem is know as the "Seven bridges of Königsberg Problem", and has historical importance both in mathematics and the study of arc routing problems.

In 1735, the Swiss mathematician Leonhard Euler presented his solution to the problem. He had generalized the problem and formulated it mathematically. The generalization is now known as the Eulerian path problem, and can be written as follows.

Given a graph G=(N,E), determine if there exists a cycle that passes through every edge in E exactly once.

A cycle that passes through every edge of a graph exactly once is called an Euler tour. Euler proved that an Euler tour exists if and only if every node of the graph has even degree (Wøhlk (2008) [30]).

The next big happening in arc routing was over 200 years later. In 1962 the chinese mathematician, and former postman, Mei-Ko Kwan extended Euler's

problem to what is now known as the Chinese Postman Problem (CPP). It can be formulated as follows:

Given a graph G = (N,E,C), where C is the distance matrix for the edges, find a tour with minimal total distance that passes through each edge in E at least once (Wøhlk (2008) [30]).

Both Euler's problem and the CPP looks at graphs with respect to the edges, but in contrast to Euler's problem the CPP asks to find find the tour rather than determining whether it exists or not.

The CPP can be solved in polynomial time if the edges are either exclusively directed or undirected, but if the graph contains both directed and undirected edges the problem becomes NP-hard (Wøhlk (2008) [30]).

Many variants of the CPP have later been studied, and the field of arc routing has arisen.

2 Structured Literature Review Protocol

The following literature review is based on the method outlined in Kofod-Petersen (2014) [14].

2.1 Search Terms

We were considering our problem to be a variant of the Arc Routing problem. Based on this and the fact that our assignment is to be solved using artificial intelligence methods, the search terms given in Table 2 and Table 1 were chosen.

The reason two search term matrices were chosen was that we wanted material focusing specifically on route optimization concerning winter road maintenance (table 2) and literature regarding general arc routing problems from an AI standpoint (table 1).

	T1	**T2**	**T3**	**T4**
Search term	route	optimization	arc routing	Artificial intelligence
Synonym 1	path	finding	capacitated arc routing	ai
Synonym 2	navigation	optimal	undirected capacitated arc routing	genetic algorithm
Synonym 3			multi-depot arc routing	ga
Synonym 4			multi depot arc routing	local search
Synonym 5			chinese postman problem	global search
Synonym 6			CPP	
Synonym 7			rural postman	
Synonym 8			vehicle routing	
Synonym 9			multi-depot routing	
Synonym 10			multi depot routing	
Synonym 11			periodic vehicle routing	

Table 1: First search term matrix

	T1	T2	T3	T4
Search term	route	optimization	winter road maintenance	chinese postman problem
Synonym 1	path	finding	snow	CPP
Synonym 2	navigation	optimal	plowing	arc-based
Synonym 3				vehicle routing problem

Table 2: Second search term matrix

We constructed one search string for both of the term matrices above, using the following procedure:

1. Create a group for every term by combining the term and its synonyms with the OR operator.
2. Construct the final search query by combining the groups using the AND operator.

The resulting search strings were as follows.

Search string 1

```
(route OR path OR navigation) AND (optimization OR finding OR optimal)
AND (arc routing OR capacitated arc routing OR undirected capacitated
arc routing OR multi-depot arc routing OR multi depot arc routing OR
chinese postman problem OR CPP OR rural postman OR vehicle routing
OR multi-depot routing OR multi depot routing OR periodic vehicle routing)
AND (Artificial intelligence OR ai OR genetic algorithm OR ga OR local
search OR global search)
```

Search string 2

```
(route OR path OR navigation) AND (optimization OR finding OR optimal)
AND (winter road maintenance OR snow OR plowing) AND (chinese postman
problem OR CPP OR arc-based OR vehicle routing problem)
```

2.2 Search engines

Based on the recommendations of our supervisors, peers and Kofod-Petersen (2014) [14], we selected the search engines listed in table 3.

Engineering Village
IEEE
Web of Science
ScienceDirect
CiteSeer
Springer Link

Table 3: Search engines

Despite their recommendation, we chose not to use Google Scholar, ACM or Wiley, due to issues with reproducibility and lacking support for of searches consisting of logical operators (making it hard to create comparable and reproducible searches across the engines).

2.3 Inclusion and Quality criteria

To remove irrelevant papers, we used the inclusion and quality criteria listed in table 4 and table 5 respectively. We noticed that our search results contained a lot of papers focusing on unrelated types of route optimization (e.g. routing in discrete computer networks, routing in telecommunication networks and route finding in open environments without movement restrictions), so we focused on removing them as early as possible in the process.

Inclusion Criteria	Criteria
IC1	Paper must be in English
IC2	Paper must be finished before conclusion of the review (October 2014)
IC3	If there are duplicates from several search engines, only one instance of the paper is included
IC4	At least some of the search terms have to be in the title (doesn't necessarily have to have both routing and snow in title, but should have at least one)
IC5	Title must not be about (internet/telecom) network routing
IC6	Paper must be available to us digitally

Table 4: Inclusion criteria

Quality Criteria	Criteria
QC1	Paper should clearly manage to convey what it is about.
QC2	Paper should mention which algorithms were used if it mentions route optimization.
QC3	If the paper is about general route optimization, applications of what is discussed for winter road maintenance should be at least suggested.
QC4	If the paper is about winter road maintenance, optimization of routing should be mentioned.
QC5	Paper must to some extent cover route optimization (eg. no papers about how absence of winter road maintenance leads to less safety)
QC6	If paper is on routing in networks, the networks must resemble road networks. E.g. no routing in open planes, computer networks, etc.
QC7	When paper is on routing in traffic: Real time optimization of route to handle traffic flow, and trying to minimize congestion/take congestion into account is not relevant

Table 5: Quality criteria

2.3.1 Results

For details on the complete list of papers that were found, and what papers came through to each iteration of the work, see appendix A. After processing what remained, the following summary of the current state of the art and suggestion for future work was created.

3 State of the art

3.1 Edge routing problems

3.1.1 CPP

The Chinese Postman Problem (CPP) asks to find a closed route that goes through all the edges of a graph. When the graph is either completely directed or completely undirected, there exists polynomial time algorithms that solves the problem, however if the graph contains both directed and undirected edges the problem becomes NP-hard (Wøhlk (2008) [30]) (this is discussed in the section about Mixed CPP).

3.1.2 RPP

The rural postman problem (RRP) is a variation of the CPP, where not all the edges have to be serviced (Algorithms for the rural postman problem, 1995). In the RPP there can be both edges and arcs (undirected/directed connections between the nodes), and the nonrequired edges can be traversed (usually at a cost) to reach the edges that have to be services.

Although algorithms to solve the RPP optimally exist, the problem has been shown to be NP-complete if the required set of edges do not form a weakly connected network, which makes finding the exact solutions not feasible for practical applications (Pearn et. al (1995) [22]). However, it is possible to obtain good approximate solutions to the RRP using heuristic algorithms.

In practice, the RPP can be used to model for an instance snow removal on secondary roads, such as sidewalks or bicycle paths (Holmberg et. al (2010) [13]).

3.1.3 HCPP

When the edges of the graph is partitioned into a hierarchy of clusters $(E_1, .., E_n)$, where every single edge in E_p must be served before E_{p+1} is started, we get the hierarchical chinese postman problem (HCPP). Looking at snow plowing, the HCPP approach is relevant if a set of streets has a higher priority than others.

For the special case of HCPP, where all the clusters are connected and there exists a linear relation specifying the order of which the clusters are to be traversed, Ghiani et. al (2000) [11] introduces a polynomial time algorithm to get the optimal solution.

For general HCPPs, Cabral et. al (2004) [7] introduces procedures for transforming the HCCP into a RPP. The RPP can be solved using approximation

algorithms as discussed in the RPP section above, and the paper shows that a solution to the RPP can then be transformed back to a solution of the HCCP.

HCPP can be approximated directly using heuristic algorithms. Perrier et. al (2008) [25] presents a model and two heuristic approaches based on mathematical optimization to solve the problem. The paper discusses topics such as turn restrictions, load balancing, tandem service and deadheading time, which are realistic constraints in a real world HCPP problem.

3.1.4 MCPP

The mixed chinese postman problem (MCPP) is when you want to solve the CPP in a graph with both directed and undirected edges (Pearn et.al (1995) [23]). MCPP is of interest because route optimization problems in practice often take place in mixed networks, e.g. road networks where there exists roads that can be traversed in any direction and roads that are one way only.

Pearn et.al (1995) [23] presents the MIXED algorithms, that convert MCPP into graphs with undirected edges and even degree to obtain approximate solutions. They suggest modifications that significantly improve the quality of the solutions, however they do not take into account some factors that might affect the goodness of the routes (such as fleet sizing, different vehicles, etc).

Yaoyuenyong et. al (2002) [31] used a heuristic based on Minimum Cost Flow to improve on Pearn et.al (1995) [23] versions of the MIXED algorithms, which they called Shortest Additional Path Heuristic (SAPH). They found that SAPH performed better than all other heuristic improvements of MIXED that they tested against.

3.1.5 WPP

The windy postman problem (WPP) is concerned with graphs where the same edge can have varying cost for each time you traverse it (Dussault et. al 2013 [10]). This is seen in problems where servicing a road takes a lot more capacity than simply passing through it (which might be done on the way back, or to access other roads in the network) for an instance.

Dussault et. al (2013) [10] proposed an algorithm that found near-optimal solutions to the WPP in networks with a relatively low number of nodes.

The Min-Max k-Chinese Postman Problem looks at connected undirected graphs, where one of the nodes of the graph serves as a depot node. The task is to find the k tours that starts and ends in the depot node, such that all the edges in the graph are served and the length of the longest tour is minimized (Wøhlk (2008) [30]).

Ahr et. al (2001) [1] looks at this variation of the CPP. They introduce two heuristics for the problem, giving lower bounds to help further increase of heuristic quality.

3.1.6 ARP

The term arc routing problem (ARP), is used to describe problems where the main goal is to service arcs in graphs modelling networks used for transport. It is strongly related to the CPP (some argue that variations of the CPP fall in under ARPs, other that ARPs are special cases of the CPP). But in general as ARPs focus more on transportation networks and vehicles, it therefore also has close ties to the vehicle routing problem (VRP). The terminology when describing ARPs tend to be more focused on vehicles and roads than what is the case with the special cases of the CPP that often refer to edges and postmen (Hertz (2005) [12], Assad et. al (1995) [2]).

3.1.7 CARP

A Capacitated Arc Routing Problem (CARP) is a problem where the demands are placed on the edges of the graph. The edges are to be serviced by a given number of identical vehicles with a given capacity, initially located at a node that serves as a depot. The problem's objective is to find the tours that minimizes the total cost, under the conditions that each arc with positive demand is served by one, and only one, vehicle and no vehicle serves a larger demand than it's capacity (Wøhlk (2008) [30]).

Since CARP has been proven to be NP-hard (Wøhlk (2008) [30]), only small problem instances can be solved optimally in a reasonable amount of time. Belenguer et. al (1998) [3] gives an approach to finding optimal solutions for problem instances consisting of 7 or less vehicles. The algorithm performs best when the numbers of vertices is between 24 to 41. An algorithm later introduced by Belenguer et. al (2003) [5] further increased the number of vertices to 50 and edges to 97.

As it is infeasible to find optimal solutions for large problem instances, several metaheuristic algorithms has been introduced. Brandão et. al (2008) [6] proposes a tabu search algorithm to approximate a solution to CARP. The paper shows that a pretty straightforward implementation of a tabu search algorithm can give high quality solutions to CARP in an efficient manner. Santos (2010) [29] presents an ant colony optimization based metaheuristic to solve the CARP. The presented algorithm produced good solutions, in terms of both solution quality and running time, compared to state of the art metaheuristic approaches. Other metaheuristics are reported to produce solutions of similar quality, as for instance the Greedy Randomized Adaptive Search Procedure with path-relinking presented by Luiz et. al (2013) [19], which gives solutions

comparable to solutions of tabu search and ant-colony optimization, but unfortunately the algorithm is outperformed when it comes to execution speed. Rao et. al (2011) [28] shows that A* can be used find approximate solutions to CARPs. The paper used A* to find routes for snow-plows, and routes found by the algorithm performed much better than the routes that were already in place in the municipalities they worked with. However they had a significant tradeoff between their implementations ability to find solutions fast, and finding good solutions. Test results were also only presented for relatively small graphs (less than 25 vertices and less than 75 nodes).

Christiansen et. al (2009) [9] approached CARP with a probabilistic approach. The demand on each edge is modelled by a random variable and the goal is to find the routes with the least expected cost, under the constraint that the vehicle capacity is not exceeded. The paper formulates the problem as a set partitioning problem and solves it with a branch-and-price algorithm.

Evolutionary computation approaches have been reported to perform even better than the approaches mentioned above. Lacomme et. al (2001) [18] looks at how to solve the CARP with a genetic algorithm (GA). They give a good overview of the data structure they used, and details on the implementation of the algorithm. At the time the paper was published, their implementation performed better than the current best known approach (which was tabu-search), and improved some of the best known solutions. An important factor for their performance was that they used local search for the mutation operator. When doing the mutation of each child, they did a local search to determine which of the possible mutations gave the best child, and used this mutation. Lacomme et. al (2006) [16] looks into optimizing both shortest total distance and also minimizing total spent time the longest route.

A variation of CARP worth mentioning is one where an edge can be serviced by several vehicles. That is, if a vehicle runs out of capacity while serving an edge, another vehicle can take over and finish the rest of it. Belenguer et. al (2010) [4] looks at this variant of CARP and introduces a cutting-plane algorithm to find the lower bounds, and presents an evolutionary local search approach to find the upper bounds.

3.1.8 ECARP

The extended capacitated arc routing problem (ECARP) looks at the same problem as the CARP, but with additional constraints. It takes into account that the graph can have both directed and undirected edges (that can be parallel), that servicing and passing through edges have different costs, that some some turns in nodes are penalized and others are forbidden (such as turning left and doing u-turns), and that each trip can not be longer than a certain threshold (because the servicing vehicles can not perform unlimited servicing per trip) (Lacomme et. al (2004) [17]).

Lacomme et. al (2004) [17] approached the ECARP with a Memetic Algorithm (MA), which they found performed really well. At the time of its publication the algorithm found all the already best known solutions, improved several of them, and found one tight lower bound that had not yet been found.

Lacomme et. al (2004) [17] is also a very useful paper for future work because they have a good documentation of relevant implementation details such as the genetic encoding, the calculation of the heuristics, how the local-search mutation component was done, and thorough documentation of the performance.

3.1.9 VRP

The Vehicle routing problem (VRP) is the converse of the ARP, where vehicles service the nodes of a transport network instead of the edges as they do in ARPs. One can find applications where a problem can be expressed as either an ARP or VRP (such as snow plowing), and where problems have been viewed as a combination of ARPs and VRPs (Prins et. al (2005) [27]).

Prins et. al (2005) [27] wanted to model garbage collection, and found that it is necessary to service both edges (undirected and directed) and nodes. Therefore they use a more general problem category that they call Node, Edge, and Arc Routing Problem (NEARP), which essentially is the combination of the VRP and ARP. To solve it they used a MA, which they argue performs comparable to other heuristic methods used for the ARP and VRP.

3.2 Sectoring

Sectoring is concerned with partitioning a graph into smaller subgraphs, to reduce problem sizes, and make management practical (Mourão et. al (2009) [20]). When doing this, it is important to keep in mind that it should be possible to solve the ARP in each sector (i.e. each sector should be a connected graph), and that it might be important to ensure that each sector has certain facilities, such as depots or garages for an instance (Labelle et. al (2002) [15]). The Sectoring Arc Routing Problem (SARP) a mix of CARP and Sectoring problems, and its goal is to partition a graph into smaller subgraphs, called sectors, in such a way that the total cost of all the sectors are minimized and that each sector can be serviced by a single vehicle (Heuristic methods for the sectoring arc routing problem). To find the cost of a sector a CARP must be solved, and the problem is thus reducible to CARP when only one sector is used. SARP can be approximated using heuristics, and Mourão et. al (2009) [20] proposes three heuristics to aid this problem.

In winter road maintenance the existence of e.g. snow disposal sites and vehicle depots, and the fact that some parts of the road network can be serviced by private companies makes sectoring desirable. Perrier et. al (2006) [26] and Perrier

et. al (2006) [24] focuses on the system design process related to snow plowing operations. Amongst the processes introduced in the papers, they present algorithms to partition the road network into strategic sectors for snow disposal sites and vehicle depots. Methods considering road network partitioning, utilizing depot locations as the main concern, is also introduced in Muyldermans et. al (2002) [21]. Labelle et. al (2002) [15] discusses techniques for snow removal after the snow plowing vehicles have completed their tasks. It presents a decision support system for designing sectors for snow removal operations with various relevant constraints.

3.3 Winter Road Maintenance

Winter road maintenance is at its core about servicing infrastructure. There are many things to take into account, such as equipment, storage, and road safety concerns. However, due to that what being serviced are roads, and that they can very effectively be modelled as graphs (and often already are), the CPP, ARP, and their derivatives are good approaches to improve current several aspects of winter road maintenance.

Campbell et. al (2005) [8] offers a good and concise overview of concerns in winter road maintenance beyond just routing, and gives examples from work done in Montreal, in 1994.

4 Future Work

Because ARPs are NP-hard, it is not feasible to find exact/optimal solutions for large (realistic) problems instances. Winter road maintenance is usually done on road networks of significant size, therefore when we model winter road maintenance as an ARP finding approximate solutions with heuristic algorithms seem the best choice for finding good solutions within reasonable time.

To be able to use algorithms based on heuristics as efficiently as possible, we need good heuristic functions, both for estimating the goodness of partial solutions, and to give an idea of how far off a given solution is of an ideal solution. Finding good estimates that are computationally cheap to obtain, and simple to implement, is therefore of vital importance to the field, and efforts should be made to improve what are currently the best known approaches.

For practical reasons, both to reduce the problem size, and to facilitate administration when solutions are applied to cases, sectoring is an important issue. If one can improve how the problems are sectored one can make better and more efficient routes.

There are various methods for finding good solutions to ARP, but the ones that have shown the most promising results are evolutionary algorithms, especially GAs and MAs. When trying to solve new problem instances or improve on existing solutions using GAs or MAs should be strongly considered.

There has been done a lot of work on finding general solutions to ARPs, and good attempts at using this to solve instances of ARPs in fields where it is applicable, such as winter road maintenance. However, as solutions tailored to a specific instance do not translate to work ideally for other instances, there is a lot of potential in making systems that are easy to tailor to concrete instances, or creating new solutions for cases that have not yet been attempted optimized, or cases solutions have been found for.

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A Appendices

A.1 Papers found in first search iteration

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