DEGREE PROJECT

Winter Road Maintenance Planning-Decision Support Modelling

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ABSTRACT

Winter in Northern Sweden comes with very harsh and unpredictable condition associated with large amounts of snowfall covering roadways thereby affecting transportation by roads. When the road conditions i.e. the snow depth, road unevenness and friction of the road surface are accessed and found to exceed the threshold, a maintenance action must be carried out to retain the road to the required condition for the user. The aim of maintenance, in this case, is to make the road comfortable, safe and economical for the road user.

Decision support system, therefore, comes in handy to facilitate on deciding what maintenance action to carry out and when the action should be carried out, where the action should be carried out and how to go about the action based on the various data and resources available. This thesis project concentrates on how to carry out a winter road maintenance after receiving an alert of an action to carry out, when to carry it out and the road network that needs to be maintained. The thesis work focusses only on two of the winter road maintenance actions namely snow ploughing of bus stops in Luleå and application of abrasives commonly referred to as sanding of bus stops.

Carrying out winter road maintenance comes at a huge cost from both direct and indirect costs with the Swedish government spending about SEK 1.75 billion every year as indicated by Jana Sochor and Cecilia Yu (Sochor & Yu, 2004). This means that reduction in the maintenance cost of even 5% through optimisation of the maintenance cost would translate into a saving of about 87.5 million SEK per year and in 10 years could amount to close to 1 billion SEK. Optimization also leads to efficiency and effectiveness that could result in improved movement on the road and reduced environmental and social-economic impacts. Maintenance planning thus becomes essential for the effective and efficient execution of work and utilisation of the available scarce resource. This thesis project focusses on the use of Operations research methods to minimise the cost of carrying out a winter road maintenance action by finding the near optimal or if possible optimal solution and still deliver the required service level.

The thesis delivers two main things: It first delivers a framework to support winter road maintenance decision making after an alert of an action is received and secondly an algorithm for the route that minimises the cost of maintenance by providing the route that minimises the travel distance of the ploughing/sanding vehicle from its source depot and back to the depot after completing a maintenance action assuming that the vehicle and material (fuel and sand) are in the same depot. The routes with minimum travel distance will, therefore, be that route that will reduce the labour time and in turn the labour cost, reduce the fuel consumption and the maintenance of the equipment due to reduced usage. The project uses a vehicle routing problem which is a generalised travelling Salesman as the optimisation technique to determine the optimal solution for the allocation of resources for carrying out a maintenance action to facilitate efficient utilisation of the available resources. This is with the help of a commercial optimisation software and support tools namely ArcGIS.

To come up with the algorithm, the first step was a digital representation of the vehicle road network in Luleå for network analysis after which the bus stops were imported from google earth into the network. A two-stage optimisation was then carried out: first was a model for route optimisation based on the road network in ArcGIS with the objective function to minimise the travel distance and constraints based on the available resources. The results of the model were then exported into excel for the second optimisation for the optimal cost of maintenance done through a developed excel algorithm. The total cost of maintenance comprised direct and indirect cost. The direct cost consisted of the cost of fuel, the cost of personnel and the cost of hiring vehicles while the indirect cost results from the penalty fee charged for sanding and ploughing a bus stop after the threshold time given to a maintenance contractor by the municipality. Any bus stop that is ploughed after the threshold attracts a penalty per hour of the exceeded time.

Six penalty threshold times were considered i.e. 30, 60, 90, 120, 150 and 180 minutes and a single parameter deterministic sensitivity analysis was carried out for each cost parameters to determine the sensitivity of the total maintenance cost. The more relaxed penalty thresholds were found to be less sensitive to the direct cost and the total maintenance cost compared to the more sensitive ones. When the penalty threshold is relaxed, the optimal maintenance cost reduces, and the required number of vehicles reduces. The cost of vehicle hire was found to be more sensitive than the other costs.

The results of this project can help the maintenance contractor in developing a work schedule for the maintenance personnel and improve vehicle fleet management. By modelling the worst scenario, a contractor can plan for the maximum number of vehicles required and consequently the personnel required. With the optimal travel route for each vehicle and the total maintenance cost determined, maintenance contractors can determine the sustainability and profitability of their business and be able to negotiate for a better and more sustainable agreement (Contract) or for the relaxation of the penalty threshold time if it does not affect the service level required i.e. the quality and safety requirements. The approach used in this project can also be used for other winter road maintenance problems.

Keywords: *Decision Support System, Winter Road Maintenance, Optimal maintenance Cost, Sensitivity analysis, Road condition, Maintenance framework, digital representation, Operations research.*

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ACKNOWLEDGEMENT

This masters thesis project was done in the Division of Operation, Maintenance and Acoustics Engineering at Luleå University of technology from January 2018 to May 2018 as part of a Winter Road Maintenance (WiRMa) project in the north and was supervised by Dr Stephen Mayowa Famurewa and Dr Johan Odelius. WiRMa endeavours to explore the possibilities of vehicle-based sensory technology to gather real-time road condition and improve winter road maintenance using industrial internet applications.

I would, therefore, like to express my sincere gratitude to Dr Stephen Mayowa Famurewa and Dr Johan Odelius for giving me an opportunity to take up this thesis work, for the support and guidance throughout out the work. Many thanks to Dr Stephen Mayowa Famurewa for enriching me with more knowledge in maintenance planning and areas of maintenance optimisation, for the fruitful discussions, motivation, extra time and effort he put in supervising me and the positivity always. I would lose hope sometimes, but his motivation and encouragement always brought hope and courage to carry on.

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I would not forget to appreciate the spiritual guidance and direction of Pastor Dr Stephen Mayowa Famurewa and Pastor Dr Ogonna Obudulu. I thank God for how he is using you to minister the word of God in this part of the word, I fed on the word of God always that came expressly through you from the throne of grace and helped my spiritual growth.

I dedicate the success of this work to my beloved late parents and my uncle Mr Fredrick Mbiyana for my upbringing, support and imparting good morals in me during my childhood that has helped me to reach this far today.

Finally, I attribute all the glory and honour to God almighty from where I draw my strength from and where my help comes. When I was weak I received strength, the one who gives wisdom and the gift of life. This rare opportunity was because of his grace which is sufficient for me.

Keegan Mbiyana
May 2018
Luleå, Sweden

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List of Abbreviations

Abbreviation/Acronyms	**Description**
WiRMa	Winter Road Maintenance
FMI	Finnish Meteorological Institute
LTU	Luleå University of Technology
IoT	Internet of Things
GPS	Geographical positioning systems
GIS	Geographical information systems
RWIS	Road weather information system
CFM	Continuous friction measurements
SLU	Swedish University of Agricultural Sciences
VRP	Vehicle Routing Problem
LLT	Luleå Local Traffic
TDR_n	Travel Distance covered by $Route_n$
TTR_n	Travel Time (travel plus service) taken to cover $Route_n$
AFC	Average fuel consumption of the vehicle in kilometre per Litre
$C_{f/Ltr}$	Cost of fuel per litre
HLR	Hourly Labour rate per personnel/operator
HCVH	Hourly Cost of Hiring a Vehicle
C_{VH}	Cost of Vehicle Hire
C_p	Cost of Personnel
C_f	Cost of Fuel
P_{fee}	Penalty fee for the time exceeds the threshold
CBM	Condition Based Maintenance
CM	Condition Monitoring
OP	Operations Research
SNRA	Swedish National Road Administration
AADT	Annual Average Daily Traffic
TSP	Traveling Salesman Problem
CPP	Chinese Postman Problem
LIFO	Last in first out
ACO	Ant Colony Optimisation

1. INTRODUCTION

1.1. BACKGROUND OF THE PROJECT

Winter is the season of the year when temperatures are low after the autumn season and before spring. Luleå being one of the most northern cities of Sweden experiences longer winter periods that begins as early as October and lasts for a period of about seven (7) months up to the month of April. Winter temperatures could be as low as -30 degrees Celsius and this is usually in January and February with the average winter temperature of about -5 degrees Celsius. (ltemperatur.nu)

Table 1.1 below shows the minimum daily temperatures for different cities in Sweden based on statistical data by the Swedish Meteorological and Hydrological Institute

	Daily minimum temperature (°C)						
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Kiruna	-4,6	-12,2	-16,7	-18,8	-17,6	-13,9	-8,0
Luleå	-0,6	-0,8	-14,3	-17,0	-16,0	-11,2	-4,0
Östersund	1,2	-4,9	-9,6	-12,8	-11,6	-7,7	-2,7
Stockholm	5,3	0,7	-3,2	-5,0	-5,3	-2,7	1,1
Göteborg	6,5	2,1	-1,4	-3,2	-3,5	-1,0	2,4
Jönköping	3,1	-1,2	-5,1	-6,6	-7,3	-4,6	-1,1
Malmö	6,7	2,8	-0,8	-2,5	-2,5	-0,5	2,4

Table 1.1 Daily Minimum Temperature (℃)
Source: (Anita, 2002)

Annually, local authorities and municipalities during the winter face the challenge of clearing roadways and streets of snow and ice at a great cost. Winter road maintenance operations include spreading of chemicals and abrasives, ploughing of the snow, loading the snow into trucks and hauling the snow to disposal sites. Time and resources are the two main constraints for decision making which can be modelled and solved using operation research techniques to aid maintenance engineers and supervisors in decisions like when and where to sand, the sequences of operations and the routes to take, the number of vehicles and personnel required for an operation and most importantly the cost implication of an operation (Gudac, Maravic, & Hanak, 2014). However, most of these decisions are made from field experience by the drivers and the maintenance supervisors because of very little progress in the optimisation models even when it is evident that just a one percent improvement in the efficiency and effectiveness through the right optimisation technique could enable significant cost savings, minimise environmental and societal impact and greatly contribute to mobility improvement (Gudac, Maravic, & Hanak, 2014)

Winter road maintenance is site specific due to the variations of the climatic condition of the different regions, the available technology, the economic and demographic setup of a region. According to Laporte et al (2011), the average cost of a 20cm snow storm in Montreal, Canada in 2010 was $17 million Canadian dollars and that it experiences an average of about 65 storms annually that would require winter road maintenance operations of either snow ploughing and removal, salting and disposal on about 6550 km of sidewalks and 4100 km of street ways. The cost of winter road maintenance activities is up to SEK 1.75 billion for the Swedish government every year according to Sochor & Yu, (2004).

All these efforts to clear roadways of snow is because disruption of traffic due to roads becoming impassable or unsafe when they become slippery could have a huge impact on a countries economy and safety of the motorists. Winter in most north European countries comes with large amounts of snowfall that could block roads if not cleared at the right time with a trickledown effect on reduced monthly retail sales, factory production and wages and could also result in lost revenue or loss employment to cut down on costs by some manufacturing companies.

Northern Sweden has a lot of industries that transport most of their products and raw materials using road transport ranging from manufacturing, large-scale mining, processing and forest industries and need an efficient transport system to remain viable. Because of the harsh and unpredictable weather in the Nordic regions, there is a need for an effective and efficient winter road maintenance for the transportation of goods, services, and people so that the normal functioning of society is not disrupted. There is need to make the roads safer also, and thus a balance must be struck to optimise the economics of conducting quality winter maintenance services against the available resources without compromising the service level requirements. (Odelius, Famurewa, Forslöf, Casselgren, & Konttaniemi, 2017)

Figure 1.1 below shows the division of Sweden into zones with comparable climates with regards to different aspects of winter road maintenance

Figure 1.1 The division of Sweden into zones with comparable climates
Source: (Anita, 2002))

1.1.1. WiRMa - Industrial Internet Applications in Winter Road Maintenance

The Winter Road Maintenance (WiRMa) industrial internet applications in winter road maintenance project is aimed at developing winter road maintenance in North Europe (Finland, Norway, Sweden) by making use of industrial internet system based on new sensor technology, vehicle observations, road weather and road surface condition forecasting. The WiRMa project is researching, developing and testing new solutions to the challenges of winter road maintenance by utilising vehicle-based sensor data. The project arose from the fact that the road weather station network is not dense enough in the north and could be 10 kilometres to as much as 50 kilometres apart hence the true (real) road weather conditions for road sections that are some kilometres away from the nearest weather stations could be unknown but just approximated. Therefore, utilising vehicle sensor data becomes a gap filler for the long stretches of the road section where the weather condition is just extrapolated from the nearest weather station.

Figure 1.2 below shows the distribution of the stationary weather stations in Sweden in black, blue and white dots

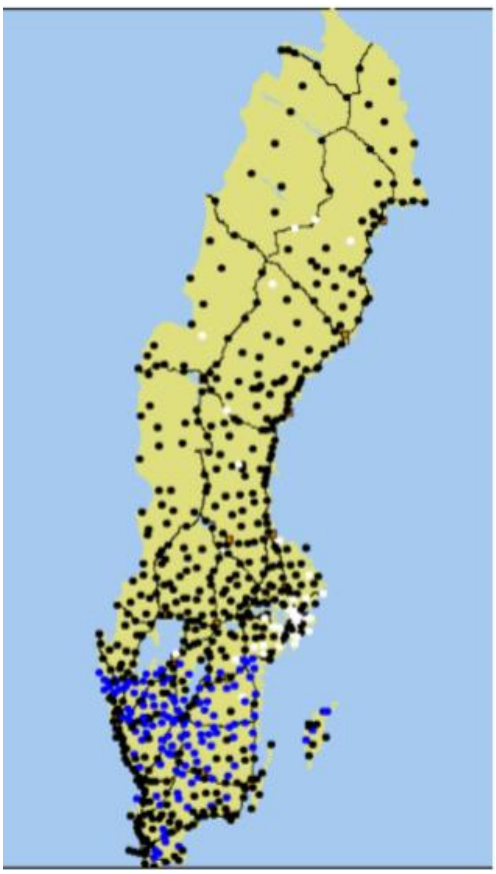

Figure 1.2 The distribution of the 680 stationary weather stations in Sweden
Source: (Anita, 2002))

Figure 1.3 Luleå and Lapland area test area

Figure 1.3 above shows a bus and a Salmon truck fitted with sensors for road condition monitoring in Luleå and Lapland area test areas respectively. As the vehicles travel along the roads, data for the actual weather and the road condition is collected turning the vehicles into moving road weather stations as they are equipped with sensors and equipment to collect the required information. The data from the weather stationary weather station and that collected from the vehicles give a more accurate condition of the road. This collected data needs to be processed and analysed then made available for use by various interested parties. Decision support system in winter road maintenance can make use of this accurate information to decide on the appropriate maintenance actions. Visualisation of these moving weather stations and the data they produce is also of paramount importance.

Figure 1.4 below shows the summary of the WiRMa project.

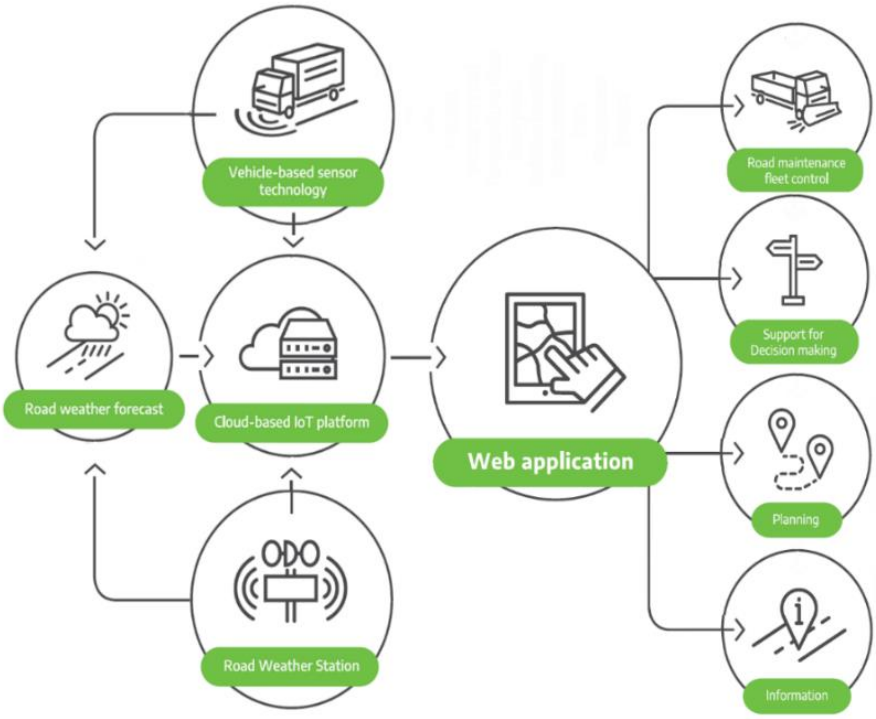

Figure 1.4 Summary of the WiRMa Project

The project has six main partners namely Lapland University of Applied Sciences as the lead partner, Foreca Ltd, Finnish Meteorological Institute (FMI), Luleå University of Technology (LTU), Casselgren Innovation Ltd and The Arctic University of Norway and is split into seven (7) working packages namely:

1. Communication and dissemination
2. Project management
3. Vehicle-based IoT monitoring Systems
4. Winter Road Condition Information
5. Road weather Nowcast and Forecast
6. Winter Road Condition Assessment and Maintenance Decision Support System
7. Demonstrations and Case Studies

1.1.2. WiRMa Working Packages

Communication and dissemination and the project management working packages led by Lapland University of Applied Sciences is responsible for the planning of data management, new research and innovation projects, dissemination of project results, as well communicating with stakeholders and reporting of communication results. The vehicle-based internet of things (IoT) monitoring systems working package also led by Lapland University of Applied Sciences with participants LTU, FMI and Casselgren Innovations AB is responsible for reviewing the state of the art in the field of vehicle-based IoT-platforms and weather measurements sensors suitable for mobile use, designing, implementing and maintaining the monitoring systems as well as specifying the user requirements and technical properties of the system.

The winter road condition information working package led by LTU identifies functional condition indicators and serviceability of winter roads. It makes use of IoT solutions for vehicle-based measurement systems and non-intrusive methods for winter road condition monitoring Optical sensing technology. Extraction methods of winter road condition information are also analysed in this working package such as reflectance and colour to be able to predict road friction. Reflectometry and ellipsometry are studied to investigate the possibility of combining the two techniques for a complete optical characterization of the road surface.

The road weather nowcast and forecast working package led by FMI processes the data from mobile vehicle observations for using road weather model and since the data from vehicles could be large and continuously, post-processing methods for the big data volumes and extraction of information for road weather forecasting system is being developed. The work package also delivers the weather forecasts for integration to the winter road maintenance decision support system and to facilitate visualization of the weather forecasts to maintenance contractors by uploading the weather forecast data to an interface for use by other work packages.

The winter road condition assessment and maintenance decision support system work package from which this thesis project was born and led by LTU makes use of vibration and optic measurement techniques for accessing winter road condition by developing methodologies for winter road condition assessment based on the road condition information and road weather forecasts from the road weather nowcast and forecast working package.

The assessment gives an indication of operational safety and comfort for road users and therefore useful as input for alert management and decision support for maintenance planning. This work package seeks to develop an alert management to indicate a maintenance action required with visualisation of winter road conditions showing the road conditions and alerts in a web or through a mobile phone application. Winter road maintenance decision support seeks to develop a framework and mathematical model for decision support for winter maintenance planning.

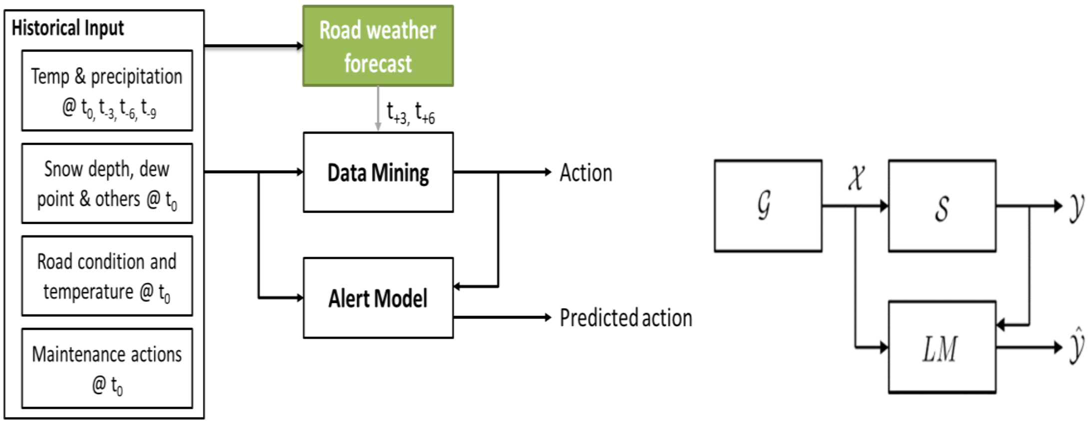

Figure 1.5 Alert model for prediction of Maintenance action as a Decision support
Source: (Johan Odelius, WiRMa Presentation, 2018)

Figure 1.5 above shows the alert modelling to predict the required maintenance action using the current road conditions i.e. the temperature, precipitation, snow depth, dew point and the forecast condition as the inputs to the model using machine learning and historical data. Using data mining, historical maintenance actions are then compared to the current and forecasted conditions to predict the maintenance action to take.

Where:

- G = Data acquisition and manipulation
- S = Data Mining
- LM = Machine learning models
- X = Condition
- Y = actual maintenance action
- $\dot{y}$ = predicted action
- t_0 = The current temperature
- t_{-3}, t_{-6} = The temperature 3 and 6 hours before current temperature respectively
- t_3, t_6 = Forecast temperature 3 and 6 hours ahead of current temp respectively

And lastly, the Demonstrations and the Case Studies working group is responsible for Demonstration and evaluation of hybrid optical techniques and smart winter road maintenance in the study areas namely Luleå in Sweden and Lapland in Finland and then make an evaluation and impact of smart winter road maintenance from the demonstrations.

1.2. Problem Statement

Maintenance of roads in winter comes with its own challenges and one of them being the scarcity of resources needed to carry out maintenance. Resources required include machinery and equipment (ploughs, trucks, spreaders etc), maintenance crew, material like fuels and abrasives, storage depots and disposal sites etc which are limited hence the need to plan for their efficient and effective utilisation and achieve the required service level.

Conducting winter road maintenance (Ploughing, spreading of abrasives, loading of the snow to trucks and disposal of the snow) comes at a huge cost, so maintenance contractors and the local authorities need to devise strategies for optimal utilisation of the available resources. The savings could be used in other areas of the organisation or for the procurement of better machinery and equipment for better service delivery.

Operations research techniques can be used to come up with cost reduction measures by ensuring that the available resources are better managed. This thesis focuses on the 'how' to carry out a winter road maintenance action and concentrates on two maintenance actions namely ploughing the snow from bus stops in Luleå and spreading of abrasives (sanding) to improve the friction.

Therefore, finding routes from the depot to the identified maintenance sites and back to the depot that minimise the travel distance and consequently the travel time of the vehicles is an opportunity to save on the time to complete a maintenance action and avoid indirect costs from penalties, saving on the fuel used by the vehicle and the wages due to the operator and also preserves the equipment from breaking down frequently from prolonged usage thereby reducing on the maintenance costs.

1.3. Research Purpose and Objectives

One of the aims of this thesis is to provide a maintenance framework for two winter road maintenance actions namely ploughing and sanding of bus stops to facilitate decision making and effective winter road maintenance planning.

The thesis works also aims at developing a model and an algorithm for snow ploughing and sanding using a commercial optimisation software and support tools ArcGIS that minimises the distance travelled by the plough or spreader to carry out a maintenance action from the depot and back to the depot. This minimises the total maintenance cost and still achieve the required service level. This is achieved through the following steps below:

- The first step is Network Representation of the vehicle road network of Luleå
- Model formulation using Vehicle Routing problem and Travelling Salesman Problem
- Lastly, a solution algorithm is developed in two stages with the help of the commercial optimisation software and support tools. The first stage being the route optimisation and the second stage being the cost optimisation.

1.4. Research Questions

To achieve the purpose of the thesis work, the following research questions are formulated around which the study is focused.

1. How can the road network be digitally represented as nodes and edges for network analysis such as winter road maintenance planning? What commercial optimisation software and support tools best suit the project?
2. How should the framework for supporting winter road maintenance be to facilitate maintenance planning?
3. Which optimisation problem and solution technique are suitable to support winter road maintenance planning and ensure efficient utilisation of resource?

1.5. Research Scope and Limitations

Maintenance decision support should be able to give information on what maintenance action to take and when to carry out the maintenance, where and how to carry out the maintenance action. This thesis, however, focuses on how to carry out a winter road maintenance action particularly ploughing and spreading of abrasives also known as sanding with the aim of minimising the distance covered by the plough or spreader.

The thesis also delivers a maintenance framework for the two above mentioned winter road maintenance activities.

1.6. Thesis Structure

The thesis contains an abstract which gives a summary of the whole report and the work carried out. Chapter 1 is the introduction that gives a brief background of the entire WiRMa project from which this thesis work was developed while chapter 2 gives the theoretical background of winter road maintenance, maintenance planning, decision support, application of IoT in winter road maintenance and briefly describes the applications of operations research in winter road maintenance. The chapter also discusses the winter road maintenance actions and winter road maintenance techniques.

Chapter 3 gives the methods used while chapter 4 contains the results, analysis and discussion of the results of the work. Conclusions and recommendations are in chapters 5 of this report. Attached also at the end of the report are the references used during the research and an appendix of the bus stops that where considered.

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2. THEORETICAL BACKGROUND

2.1. Maintenance Planning and Decision Support.

Maintenance planning can lead to the effective and efficient execution of work because the execution process becomes less wasteful as all the required tools, materials, human labour, supporting services and facilities are available and ready at the right time when required. In winter road maintenance, effective planning can minimise the maintenance costs significantly and yet still provide the required level of service for the road users (Mohammed, Uday, & Prabhakar, 2016). Maintenance decision support requires information from various sources which includes maintenance data, operations data, and data from the suppliers/vendors of the equipment or facility. A decision support system should be able to give information about what, when, where and how to carry out maintenance by utilizing the data available and transforming this data to notify the maintenance crew of the appropriate maintenance actions (Mohammed, Uday, & Prabhakar, 2016).

To be about to carry out efficient and effective winter road maintenance, decisions are made at different levels of the organisation i.e. at the strategic, tactical and operational levels while some decisions can be made in real time. For the required service level to be achieved, right decisions must be made at the right time and should offer minimum operational cost and the highest level of safety (Perrier, Langevin, & Campbell, 2004). In the book, Introduction to Maintenance Engineering Modeling, Optimization, and Management, Mohammed, B.-D et al (2006) state that maintenance planning is a key element of maintenance management that requires being implemented at the three levels of the organisation namely strategic, tactical and operational levels.

Kociánová (2015) describes a system that is based on monitoring and forecasting of weather conditions and the road surface conditions at selected road locations to provide a solution for intelligent winter road maintenance management. Road weather stations collect and transmit data of the road condition and provide early warnings from weather focast about hazadous situations on the road like frost, ice, mist, wet or snow-covered surface. Weather stations data, data from weather radars and satellites and weather forecasting model data are used to predict the pavement surface state and temperature which is the information required to support maintenance decision and ensure effective and timely treatment of roads in the winter (Kociánová, 2015). The paper also shows that part of the system provides on-line fleet monitoring and management for winter maintenance dynamic dispatching with message signs for drivers of dangerous road sections to ensure optimization and timely intervention and improved traffic safety (Kociánová, 2015)

2.2. Maintenance Framework

Planning and execution require a proper framework with the right data being an important factor. Mohammed, B.-D et al defines a framework as "a logical structure that identifies key concepts, the relationships among the concepts to provide a focus, a rationale, and a tool for the integration and interpretation of information relevant to a decision problem with the structure serving as a starting point for developing models for solving the decision problem." (Mohammed, Uday, & Prabhakar, 2016). The framework should deliver at least one of the following issues with regards to the maintenance problem under consideration.

- To understand the degradation processes, the use of scientific methods should be exemplified.
- Proper collection and analysis of relevant data;
- Decision making with the help of models
- Use of appropriate technologies
- Effective maintenance management

Figure 2.1 below shows an example of a maintenance framework for solving a maintenance decision problem

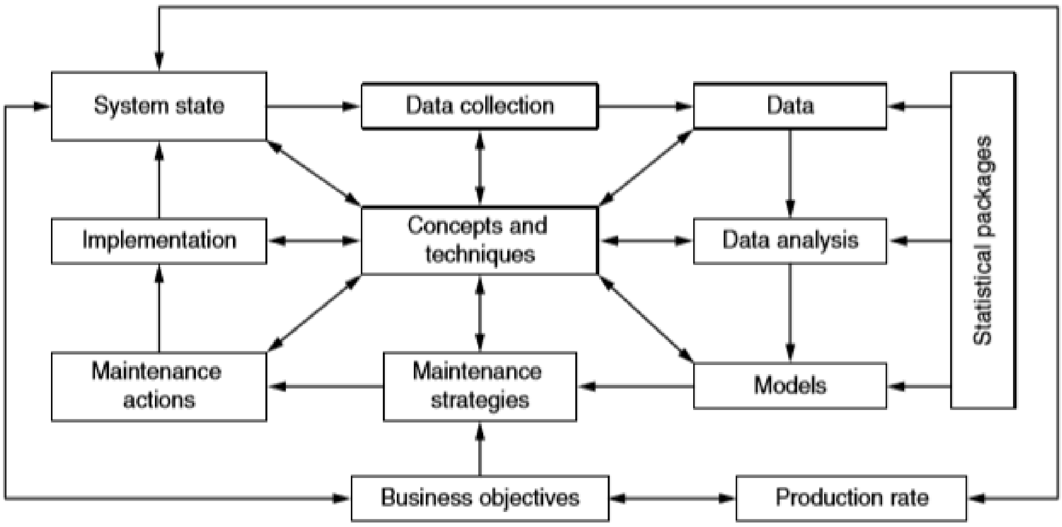

Figure 2.1 Maintenance decision problems solution
Source: (Mohammed, Uday, & Prabhakar, 2016)

Therefore, a framework is a prerequisite for effective maintenance decisions and it should consider the technical, commercial, social, and managerial issues of the organisation with the overall goal being profit maximisation.

Bousdekis et al (2015) have proposed a framework for proactive decision making for condition-based maintenance (CBM). The proposed framework can be used by maintenance managers to carry out CBM using real-time sensor data depending on the type of decision required and gives the steps to be followed for proactive recommendations. From the results of the work by Bousdekis et al a foundation for the development and implementation of proactive Decision Support System (DSS) with regards to maintenance has been created (Bousdekis, Magoutas, Apostolou, & Mentzas, 2015).

2.3. Winter Road Maintenance Actions and some Associated Costs

Winter road maintenance actions/operations include ploughing of the snow from the road surface, applications of chemicals and abrasives to the road surface, loading of the ploughed snow into trucks and hauling the snow to disposal sites.

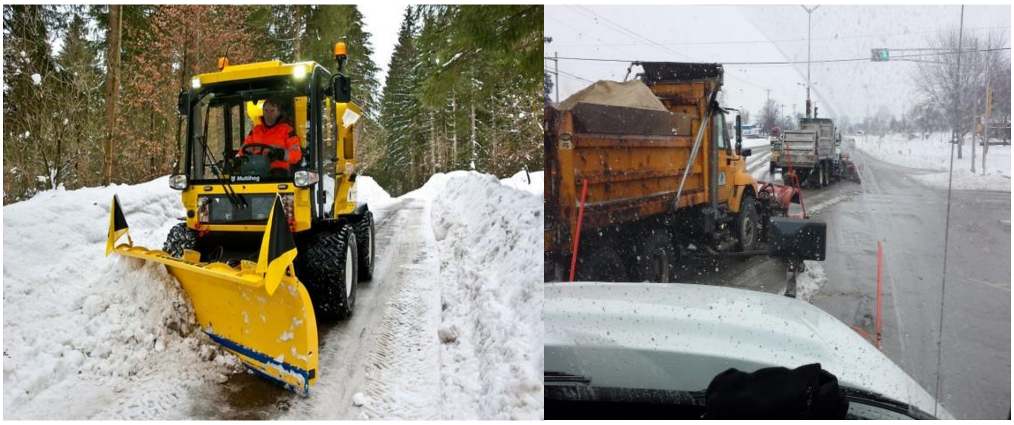

Figure 2.2 Snow ploughing and application of chemical and abrasives.

Figure 2.3 Loading and Disposal of Snow

(Source: https://images.search.yahoo.com/search/images;_ylt=AwrNAT3lRu9a9V4AyU9X)

The four snow highway removal modes for winter road maintenance are “de-icing salt snow removal, manual snow removal, mechanical snow removal and physical snow removal” as described by Xie el al, (2013).

The need of winter road maintenance cannot be overemphasised considering the amount of resources that local authorities spend every winter season so that the required service level is attained as well as avoiding some of the indirect costs associated to loss of productivity because of impassable and the effects of chemicals and abrasives to the environment, vehicles and the infrastructure (Perrier, Langevin, & Campbell, 2004). According to Perrier et al (2004), the United States of America spends an estimated $2 billion each year while Japan and Europe’s expenditure is nearly two to three times higher than that of the United States. Indirect costs such as degradation to infrastructure and vehicles, corrosion, water quality, and other environmental effects as a result of chemicals for winter road maintenance is estimated to cost more than $5 billion a year in the United States.

The type and amount of precipitation received determines the type of winter maintenance response. If the amount of snow received makes pedestrians walking difficult and constrains vehicle traction resulting in increased vehicle traffic, ploughing is the first response to consider and if a thin layer of snow covers the road or ice precipitation is received, chemical application for deicing and anti-freezing and spreading of abrasives would be the appropriate response. Densely populated areas such as cities and some urban areas that receive large volumes of precipitation (snow/Ice) may not be enough space along the roadways and walkways for the storage of the ploughed snow. The snow has to be loaded into trucks for hauling to disposal sites which include rivers or other water bodies, large open areas, sewer system etc to clear the roadways and walkways (Perrier, Langevin, & Campbell, 2004).

When the sewer system is used as a storage site, the snow is first melted before it is discharged into a sewer system. In Japan, Sapporo for example river water or treated sewage is diverted through constructed channels along streets and carries the snow that is dumped with it instead of hauling the snow to disposal sites (Perrier, Langevin, & Campbell, 2004). Snow disposal methods however come with there own costs and benefits and issues such as the haul distances, traffic volumes to and from disposal sites, the consequences of melting snow in rivers and sewer system, and the environmental impact of snow and ice ploughed from roadways that usually contains impurities of chemicals and abrasives as the snow melts and flows together with surface waters or seeps into the ground.

Because winter road maintenance requires that the roadway and roadside parking areas are free from traffic, local authorities have parking regulations to enhance winter road maintenance operations on critical roads and streets that have heavy traffic volume in to avoid delays in clearing the these critical roads. Some of these regulations include stopping street/roadside parking on snow routes, giving alternative side street parking for prescribed times, and banning overnight parking on slow designated routes (Perrier, Langevin, & Campbell, 2004).

2.4. Winter Road Maintenance Categories/Techniques

There are three categories of winter road maintenance techniques that are used to clear roads of snow namely: chemical, mechanical and thermal methods.

2.4.1. Chemical Methods

Chemical methods involve the use of chemicals as freezing-point depressant when applied on the road surface. The chemicals help melt the ice that could have formed on the pavement when applied to pavements and prevents the formation of ice on the road surface. The chemicals also prevent the snow that could have been compacted through traffic action from forming ice and bonding to the pavement as ice, which is usually thicker and irregular. Several chemicals are available for deicing and anti-icing, but salt is most commonly used because it is cheaper, readily available, easy to apply, easily dissolves in water, and is very effective as a melting agent at temperatures around $0°C$ (USROADS.COM, 1997). The level of service, the weather conditions, the form of snowfall whether liquid or solid determine the rate of application.

2.4.2. Mechanical Methods

Mechanical methods, on the other hand, is aimed at clearing the loose snow that accumulates on the road surface or has bonded to the pavement by picking it up or shearing it from the road and move it to a storage area away from the road. Mechanical methods involve ploughing and brooming the snow and require to be carried out effectively to ensure that as such snow and ice as possible is removed before any chemical application for deicing and anti-icing operations. During periods of less traffic, ploughing and brooming can effectively reduce the need for chemical methods (Perrier, Langevin, & Campbell, 2004).

2.4.3. Thermal Method

Application of heat to the road surface from above the roadway surface or from below is the thermal method of removing snow and ice and prevents ice from forming. Heating a pavement (thermal method) reduces traffic delays, personal injury, and property damage from accidents caused by black ice, glaze ice, or packed snow and is more effective compared to the mechanical methods. However, installation and operation of both the fixed and mobile heating systems comes at a very high cost and therefore local authorities prioritise critical locations for the installation of heating systems such as bridge decks, toll plazas, ramps, and steep grades (Perrier, Langevin, & Campbell, 2004).

2.4.4. Effects of Chemicals and Abrasives

Even though chemical methods play a critical role in winter road maintenance, they have negative effects on the surrounding infrastructure, structure of vehicles through corrosion and to the environment in general. Motor vehicle corrosion, infrastructure damage, deterioration of the vegetation along the road, and the infiltration of sodium into the groundwater and water bodies and are some of the negative effects of chemical application in winter road maintenance. (Minsk, 1998). Sand and other abrasives are used in winter road maintenance to improve traction when pavement temperatures are too low for chemical treatments to be effective. Abrasives do not, however, stop or break the bond formed between the pavement and ice but only improve the friction of the road surface. Generally, abrasives are cheaper, but have several negative consequences like damage to cars, requiring cleanup when no longer needed, and cause airborne dust problems (Perrier, Langevin, & Campbell, 2004).

Dindorf et al (2004) studied the costs of using salt in winter road maintenance and the examined cost savings of smart salt use for seven counties of Minnesota and twin cities metro area that uses approximately 349,000 tons of salt annually. The direct and indirect costs were examined for different scenarios of reducing salt use from 10% up to 70% at 10% increments with savings in the amount of salt used ranging from 34,900 tons to 244,000 tons translating to $2.5 million to $17.8 million savings annually for purchases of salt, and $5.6 to $36 million annually in labor and equipment savings (Dindorf, Fortin, Asleson, & Erdmann, 2004). Reduction in the amount of salt used however does not lead to a compromise in the level of service or the safety of the road with the report giving estimates of the cost of damage to infrastructure, automobiles and the environment from using salts for deicing and as anti-freezing agents. The report also gives the ultimate cost to remove salt from our freshwater systems

2.5. Winter Road Maintenance Costs

Winter road maintenance costs can be divided into direct and indirect costs. Indirect cost includes the effect of deicing chemicals and abrasives on the environment, infrastructure, and motor vehicles.

Some of the direct costs are tabulated in Table 2.1 below and are divided into fixed and variable costs of labour, materials, and equipment for the different maintenance activities.

Costs	**Winter Road Maintenance Operations**		
	Ploughing	Spreading Operation	Loading and hauling of the snow
Fixed costs	Cost of ploughing Equipment	Cost of Spreaders	Cost of loading and hauling Equipment
	Cost of vehicle depots	Cost of Vehicle depots	Cost of Vehicle depots
		Cost of materials depots	Cost of Disposal sites
Variable costs	Cost of Fuel	Cost of Fuel	Cost of Fuel
	Labour/Crew Costs	Labour/Crew Costs	Labour/Crew Costs
	Cost of Vehicle maintenance	Cost of Vehicle maintenance	Cost of Vehicle maintenance
	Variable Vehicle depot costs	Variable Vehicle depot costs	Variable Vehicle depot costs
		Cost of Chemicals and Abrasives	Variable Disposal site costs
		Variable material depot costs	

Table 2.1 Direct Costs associated with Winter Road Maintenance.
(Source: Perrier, Langevin, & Campbell, 2004)

Table 2.1 above shows the direct costs associated with Winter Road Maintenance. The impact of winter road maintenance on the economy, the safety effects, the savings from accidents, cost of delays, losses in productivity and wages etc are integral in determining the cost and benefit of any winter road maintenance operation.

2.6. Service Level

The condition of the snow on the roadway, the evenness and the wetness of the snow as well the pavements skid characteristics are used to define the level of service for spreading and ploughing activities. For a higher-level service, more resources are required because it entails ploughing even with little accumulation of snow and no ice pavement bonding is allowed during precipitation making sure that the road surface returns as near normal after precipitation as possible. A low-level service, on the other hand, can only involve ploughing after precipitation has ended and the roadway characterised by slipperiness, unevenness and bumps projecting, causing traction difficult in some places (Perrier, Langevin, & Campbell, 2004).

Because resources are scarce, local authorities prioritise which roads will have the highest level of service and those that will have lower service by mainly considering the traffic volume of the different road networks to prioritize their response efforts. The road network is usually divided into categories according to the traffic volume and roads with the highest volume are assigned a higher-level service and vice versa. In cities and urban areas, priority is given to roads leading to important and critical facilities like streets serving bus routes, hospitals, firehouses, schools, and similar important places and facilities while rural areas may give higher priority to school bus routes (Perrier, Langevin, & Campbell, 2004).

Climatic condition with accurate and timely current weather information conditions and forecasts of future conditions influence the winter maintenance activity and help to ensure efficient and effective winter road maintenance operations are carried out. With accurate and timely weather conditions local authorities can be able to carry out, for instance, chemical treatment and deploy maintenance equipment effectively ensuring that costs are reduced, and environment effects of chemical eliminated as the right quantities of chemicals and abrasives are applied for the current and forecasted conditions (Perrier, Langevin, & Campbell, 2004).

2.7. Winter road maintenance standards in Sweden

2.7.1. Legal obligation

The Swedish National Road Administration (SNRA) is mandated by the Swedish constitution to administer the road transports system in Sweden guided by enacted laws and regulations that influence winter road maintenance. SNRA is required to meet the objectives of the transport policy and ensure that the road transport system is available, accessible and effectively contribute to the regional balance (Anita, 2002). The SNRA is also required to design the road transport system taking into consideration the high demands on environment and traffic safety. According to one “Road Statute” (SFS 1971:954) “road operation includes the removal of snow and ice and taking actions against slipperiness to such a degree that the road is kept accessible to existing traffic, both vehicles and pedestrians (Anita, 2002).”

SNRA is responsible for about 98 000 kilometres (23 %) of road network called state roads which are classified as national trunk roads, regional roads and other state roads of a total of about 420 000 kilometres of the road network in Sweden. Approximately two-thirds of the vehicle mileage is done on the state roads and the municipal streets and roads form about 38 500 kilometres (9 %), while private roads are about 284 000 kilometres (68 %) (Anita, 2002).

2.7.2. General technical description of road operation service levels

"OPERATION 96" gives the general technical description of operation service levels of winter road maintenance on the state roads in Sweden (Anita, 2002). There are six different standard classes according to the traffic volume with the highest having an Annual Average Daily Traffic (AADT) of 16 000 or more and the lowest having an AADT of less than 500 (Anita, 2002).

The roadway having the highest AADT is given more priority and should be cleared of snow and ice within two hours after the snow has stopped falling if the road surface temperature is above -8 ^{o}C while the depth of the snow should not exceed 2 cm and the slush depth should not be more than 1 cm. The roadway with lowest AADT must be cleared of snow through ploughing or any appropriate control measure no later than eight hours after snowing has finished, and that snow depth must never go up to 8 cm (Anita, 2002).

2.7.3. Detailed technical description of road operation service levels

Classes A1-A4 describe the standard classes for snow and skid-free roads with A1 having the highest service level while snow-covered roads are divided into two standard classes B1 and B2 and pedestrian and cycle paths are divided into three standard classes, C1–C3 (Anita, 2002).

Table 2.2 below shows how the choice for a standard class for a road network is done

	Road category	
Traffic flow, AADT	**National road network**	**Regional and local road network**
≥16 000	A1	A2
8000–15 999	A2	A3
2000–7999	A3 or B1	A3 or B1
500–1999	B1 or A4	B1 or A4
<500	B1	B2

Table 2.2 Choice of standard class for a road network
(Source: (Anita, 2002))

Table 2.3 below shows the threshold values for satisfactory friction, slippery and very slippery conditions

Friction class	Friction coefficient*
Satisfactory friction	$\mu \geq 0,25$
Slippery	$\mu < 0,25$
Very slippery	$\mu \leq 0,15$

Table 2.3 Threshold Friction Values
(Source: (Anita, 2002))

2.8. System Design for Winter Road maintenance

Local authorities usually design a system that is efficient and effective for winter road maintenance for assigning level of service policy to roadways, dividing the city/region into sectors, locating the required resources and facilities like vehicle and material depots and disposal sites, contracting other private organizations for the various winter road maintenance operations and planning for the replacement, sizing and maintenance of equipment. Winter road maintenance system design involves designing for spreading and ploughing operations, designing for snow disposal and designing for the fleet size and manpower requirements (Perrier, Langevin, & Campbell, 2004).

2.9. Technology innovation in winter road Maintenance

With technological innovations, winter road maintenance operations can greatly improve in terms of the effectiveness and efficiency and can result in reduced maintenance costs. There have been improvements in technologies in the recent past in materials spreading of abrasives and salting, in mechanical methods, and weather information systems. Improved weather information system could result in effective planning in terms of mobilization of resources to the required road network due to enough lead time to plan. Accurate weather forecast can lead to the effective deployment of winter road maintenance equipment and right application of the amount of chemicals and abrasives (Perrier, Langevin, & Campbell, 2004).

Geographical information systems (GIS) and geographical positioning systems (GPS) are valuable tools for planning winter road maintenance operations in that GIS can reveal which roads segments have been ploughed or sanded while the vehicle location in real time can be monitored using GPS. Advances in weather forecasting play an important role too and it is becoming more common to use “nowcasting” rather than forecasting to predict the road condition. Nowcasting which is the use of real-time information of the weather condition is now used to predict the forecast of the weather condition and the condition of the pavement conditions up to 6 hours ahead with improved technological developments. (Perrier, Langevin, & Campbell, 2004)

2.10. Challenge of Winter Road Maintenance

In general, winter road maintenance challenges differ from one location/region to another. They are site specific due to the different factors that influencing how winter road maintenance operations are conducted which include the geographical location, climatic and weather conditions, economic factors, technology and innovations (for chemical and abrasive application, ploughing, and weather monitoring), regulations and statutory requirements, agreements with contracts and other local authorities around, traffic volume variations, skill and manpower levels, equipment and material availability (Perrier, Langevin, & Campbell, 2004).

Winter road maintenance planning, therefore, must take care of efficiency, effectiveness, and equity. For instance, a balance must be struck on the level of service since a higher level of service costs more for making roadways safer for travelling, reducing costs for travellers, reduces loss in production and sales. The costs and benefits of winter road maintenance can be in two categories; those that can easily be quantified such as the direct expenses from winter road maintenance and the effects of chemicals on the environment, infrastructure, and motor vehicles and those that can be quiet difficult to quantify such as the impact on the safety of motorists and on the local economies which could be savings in accident costs, in delay costs, and loss in wages and productivity (Perrier, Langevin, & Campbell, 2004).

One area in winter road maintenance that has not been fully exploited is optimisation of routing of vehicles and the location of depots in comparison to the advancements in technology. This could be attributed to the complexity of winter road maintenance because it is site-specific with different operating conditions and constraints for each region. In the recent past, many agencies and local authorities have invested in research of optimisation modelling and algorithm tools and in better performance computers to minimise their expenses (Perrier, Langevin, & Campbell, 2005). It has been found that 62% of counties and 55% of cities reassess and make modifications to their winter road maintenance routes for ploughing and application of chemical and abrasive operations annually as shown in the Minnesota report of 1995 survey. Recent studies also show that vehicle routes can also be modified using real-time weather and pavement information/condition (Legislative, 1995) (Perrier, Langevin, & Campbell, 2005).

In the research report, “Optimizing Snow Ploughing Operations in Urban Road Networks” Kinable et al state that snow storm disrupts traffic movement and safety is compromised hence the need for roadways and streets to be cleared as quickly as possible but that most authorities do not have dynamic plans to carry out snowploughing and that decisions of the route are at the discretion of the drivers simply because it is easy to implement and usually achieves the goal of clearing the roadways. However, the snow ploughing operation could be inefficient and a case cited is the storm in 2010 in Pittsburgh when clearing the snow took many days that led to restricted movements (Kinable, Smith (PI), & Hoeve, 2010). The report further mentions that it is difficult to find the optimal solutions for winter maintenance problems but a near optimal solution is possible with some assumptions and approximations whose results can produce significant improvements in the performance of snowploughing with an example of Centennial, Colorado, that reduced the time need to clear streets by 28-40% by optimization of snow ploughing routes (Kinable, Smith (PI), & Hoeve, 2010).

In the same report Kinable et al cites events that would make the planned route impossible to execute or make the route non-optimal such as changes in the snows intensity, sudden breakdown of snow ploughs, some road segments being blocked by vehicles that are stuck, construction projects that were not considered that may warrant deviations from pre-planned routes and therefore requires re-optimization. It is therefore imperative that route optimisation considers the real-time capacity to be able to re-route vehicles when the planned situation changes (Kinable, Smith (PI), & Hoeve, 2010). “The aim of the research was to come up with a snow plough routing system able to produce near-optimal ploughing plans conforming with current operational constraints and reactively maintaining them through execution as unexpected events force changes” (Kinable, Smith (PI), & Hoeve, 2010). The task was to find the shortest route of the longest distance thereby minimising the duration for the longest route for a given network of streets and a fleet of snow ploughs such that the whole network is covered by the road network modelled as a mixed multigraph (Kinable, Smith (PI), & Hoeve, 2010).

This is summarised in Figure 2.4 below with turn-by-turn instructions available in real time to the snow plough operator.

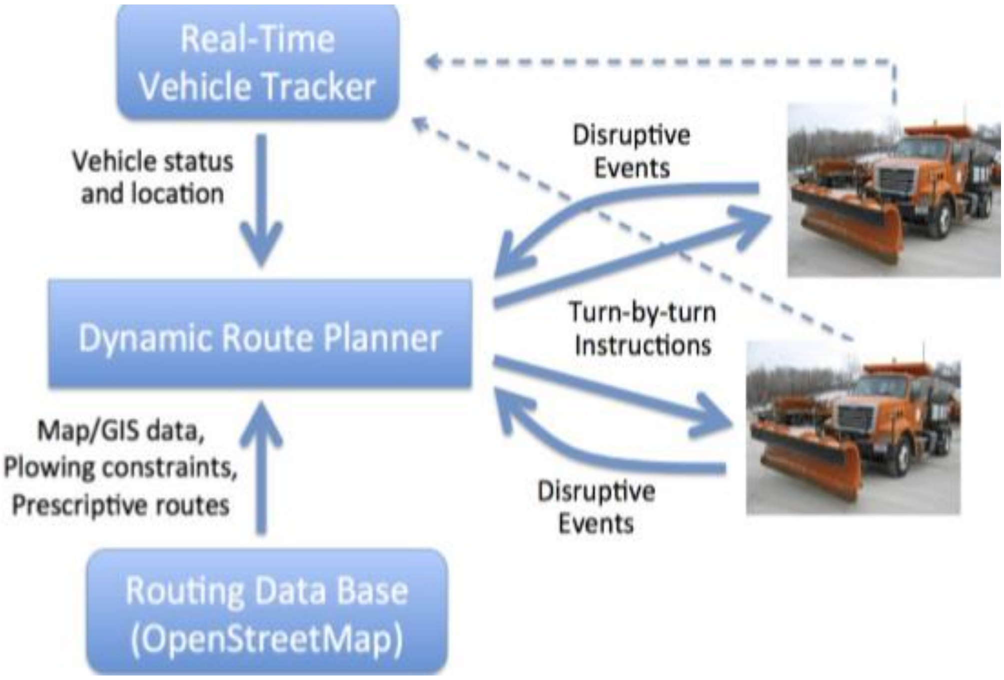

Figure 2.4 Operations Concept for Dynamic Route Planning
Source: (Kinable, Smith (PI), & Hoeve, 2010)

2.11. Road weather and condition monitoring

With advances in technology, various weather and surface condition monitoring techniques are available that help to determine what maintenance action to undertake and when to undertake the action. Some of these include:

- Road weather information system (RWIS) includes stationary metrological stations that measure the pavement condition for a specific portion of the road segment. The measured data includes temperature, humidity, wind speed and direction, the rate of precipitation and can also detect ice formation.
- Thermal mapping which involves the use of an operating vehicle to take measurements of the road surface condition and obtain variations in of the road condition along the route. The information from the thermal mapping is used to complement the information from RWIS.
- Continuous friction measurements (CFM) measures the friction between the tyres of the vehicle and the road with the help of a friction measurement device.
- Web-based surveillance and automatic road surface image recognition where images of the road surface are taken and analysed for snowy or slippery conditions (Hinkka, et al., 2015)

2.12. Operations Research and its applications in winter road maintenance

Operations research methodologies can be used to manage winter road maintenance decision problems. Perriera et al state that in the last few decades, there have been improvements in winter road maintenance technologies that can lead to improved operations and minimises the environmental effects by use of alternative deicing materials and anti-icing methods. These improvements include improved snow removal equipment and more accurate spreaders, better weather forecasting and, road weather information systems. Perriera et al further state that advances in the microcomputer have helped improve the effectiveness and efficiency of winter maintenance operations. However, there has been little research in the use of operations research in winter road maintenance because the challenges that winter road maintenance planners are faced with are quite complex and vary from site to site due to variation in site conditions such like the geography, meteorology, demographics, economics, and technology (Perrier, Langevin, & Campbell, 2004). Factors such as population density, a region's topography, the road network, the level of service policies, and climatic factors such as the rate of snowfall, temperature, number of hours of daylight, and wind affect winter road maintenance operations of a region (Perrier, Langevin, & Campbell, 2004).

Operations research (OR) is a science that involves the application of advanced analytical methods using techniques of mathematical sciences like modelling, statistical analysis optimization, research to obtain the optimal or near-optimal solution to complex problems thereby facilitating better decision making (Taha, 2007). A formulation of an OR model has an objective function that is either maximised or minimised subject to some constraints which are the limitation of the problem. In general terms, an OR model includes the decision variable that the model seeks to find, the objective that is to be optimised and the constraints that need to be satisfied (Taha, 2007).

The OR model suitable for winter road maintenance decision support is the transportation problem. Transportation problems include the Chinese postman problem, the Vehicle Routing Problem (VRP) and the Traveling Salesman Problem (TSP). Optimization of routes in transportation problems involves finding the routes that are most cost-efficient with a lot of factors influencing the route choice such as the number of stops and their location, the turns along the route, traffic congestion depending on the current time of the day among others (Johnson, et al., 2007) (Applegate, Bixby, Chvátal, & Cook, 2006).

2.12.1. Chinese Postman problem

The Chinese postman problem (CPP) was first proposed by the Chinese mathematician Meigu Guan in 1962 and used to find the shortest travelling distance for a postman who picks up mails at the post office, delivers them along a set of streets, and returns to the post office after covering every street at least once. The CPP investigates how to cover every street and return to the post office with the minimum cost. Practically, the direction of the street, the number of postmen, and the capacity of postman must be considered apart from the requirement of travelling all streets. CPP are classified by street direction into three classes namely undirected CPP, directed CPP, and mixed CPP (WANG & WEN, 2002).

Directed CPP are formulated as shown below

$$Minimise \sum_{(i,j)\in A} C_{ij}X_{ij}$$

$$\sum_{(i,j)\in A} X_{ij} = \sum_{(j,i)\in A} X_{ji}\,, \forall i \in V,$$

$$X_{ij} \geq 1 \; and \; integer \; for \; all \; (i,j) \in A$$

2.12.2. Travelling Salesman problem

A travelling salesman problem(TSP) seeks to visit a given set of towns/cities exactly once by starting from a hometown and returning to the hometown after visiting all the towns with the aim of finding the shortest route. TSP finds various real-life applications with models in many Mathematics, Computer Science, and Operations Research with successes recorded in Heuristics, linear programming, and hard combinatorial optimization problems (Ball, Jünger, Reinelt, & Rinami, 1995).

A survey shows that TSP can also be applied in drilling of printed circuit boards, X-Ray crystallography, Overhauling gas turbine engines, order-picking problem in warehouses, computer wiring, scheduling with sequence dependent process times, vehicle routing, mask plotting in PCB production, control of robot motions (Ball, Jünger, Reinelt, & Rinami, 1995)

Boland et al considered using a constrained asymmetric travelling salesman problem with knapsack-like constraints on subpaths of the tour, a problem mostly in routing aircraft and formulated it with an exponential number of variables corresponding to feasible subpaths. They tested the algorithm on random and real instances in airline application (Boland, Clarke, & Nemhauser, 2000).

Malaguti et al have introduced a new generalization of the travelling salesman problem with pickup and delivery for applications maritime logistics, where they represent each port as a node with a known draft limit. Every demand from each customer has a weight, and pickups and deliveries are done by one ship with weight capacity. Only when the weight (amount) of cargo it carries is compatible with the draft limit of the port can a ship can visit a port. They formulated the problem as an integer linear programming and also introduce heuristic procedures and a branch-and-cut exact algorithm as well as examine the impact of the various cuts and the performance of the proposed algorithms through extensive computational experiments (Malaguti, Martello, & Santini, 2018)

Pereira et al have also formulated algorithms for the pickup and delivery using travelling salesman problem with multiple stacks with one vehicle used to fulfil the requests for pickups and deliveries. Items are stored in stacks following the last-in-first-out (LIFO) policy with the objective of finding the route that meets the demand and minimises the travel distance (Pereira & Urrutia, 2018)

2.12.3. Vehicle Routing Problem

A vehicle routing problem (VRP) is a generalization of the TSP which aims at finding the optimal solution for a fleet of vehicles to service a set of orders and was introduced by Dantzig and Ramser in 1959. All the vehicles from a central depot go out from this depot and return to the depot after serving customers with each vehicle having a fixed capacity and every customer having a known demand to be satisfied. The objective of VRP is finding routes for each service vehicle to visit the customers at an optimal minimum total cost. It must ensure that all the customers are served, and that each customer is served by one vehicle, visited only once with the vehicle having enough capacity to serve the request of the customers assigned to it. One single vehicle should be assigned to every respective route, starting and ending at the source depot (Haj-Rachid, Ramdane-Cherif, Chatonnay, & Bloch, 2010).

There are different types of VRPs which include "the vehicle routing problem with time windows (VRPTW), the capacitated vehicle routing problem (CVRP), the multi-depot vehicle routing problem (MDVRP), the site-dependent vehicle routing problem (SDVRP) and the open vehicle routing problem (OVRP)" among others (Pisinger & Ropke, 2007). The CVRP delivers goods to assigned customers whose demand is known by minimising the cost of vehicle routes from and back to the source depot with the vehicles having a fixed capacity and may require that the route some other constraints which limit the length of the feasible routes. The VRPTW is an extension of the CVRP that incorporates time windows (interval during which the customer must be visited) of the customers. The MDVRP is also an extension of the CVRP that allows multiple depots while the SDVRP is a generalised CVRP certain customers can only can be served by specific vehicles and the vehicles are not required to have the same capacity. The CVRP, MDVRP and SDVRP aims to minimize the total travelled distance, while the OVRP and VRPTW aims to minimize the number of vehicles as the main objective and minimizing the travelled distance as a secondary objective (Pisinger & Ropke, 2007).

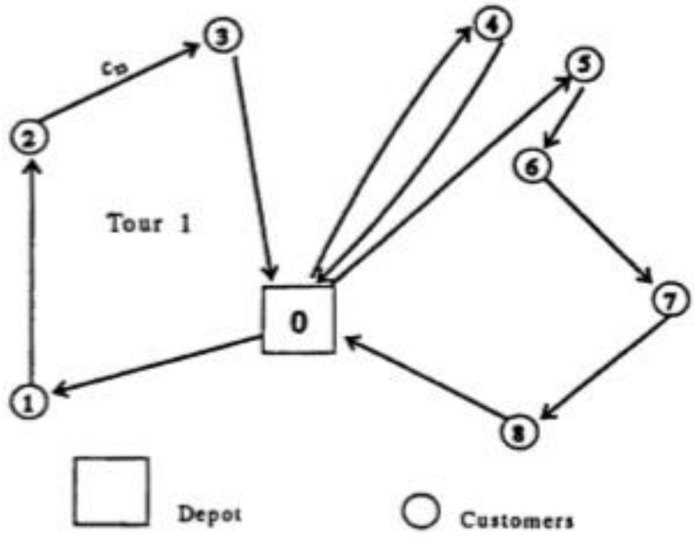

Figure 2.5 A Vehicle routing problem
Source: (Osman, 1993)

Figure 2.5 above shows an example of a vehicle routing problem aimed at finding an optimal solution that minimizes the total travel length and satisfies the conditions below:

$$\bigcup_{p=1}^{v} R_p = N, \qquad R_p \cap R_q = \emptyset, \forall p \neq q \in V;$$

$$C(R_p) = \sum_{i \in R_p \cup (0)} (c_{i\pi(i)} + \delta_i) \leq L, \qquad \forall p \in V;$$

$$\sum_{i \in R_p} \delta_i \leq Q, \qquad \forall p \in V;$$

$$C(S) = \sum_{p \in V} C(R_p),$$

Where;
n = the number of customers;
N = the set of customers, N= {1, ... n);
q_i= the demand of customer $i \in R_p$ (i = 0 denotes the depot, $(q_0 = 0)$
δ_i=the service time of customer $i \in N, (\delta_0 = 0)$;
c_{ij}=the travel time (distance) between customers i and j, $c_{ij} = c_{ji} \forall i,\ j \in N\ (c_{ii} = \infty, \forall i \in N$
v= the number of vehicles, which is a decision variable in our problem;
V= the set of vehicles, V = {1, ..., v};
Q= the vehicle capacity;
R_p=the set of customers serviced by vehicle p;
$C(R_p)$= Cost of the optimal travelling salesman tour π_p over the customers in $R_p \cup \{0\}$.
Cost includes the travel times (cii) and the service times (8i);
L=the prespecified upper bound on the maximum tour length;
S=the feasible solution defined as S = $\{R_1$, ..., $R_v\}$;
$C(S)$ =the total sum of each individual tour length $C(R_p)$ for all , $p \in V$. (Osman, 1993)

The VRP has been applied in a number of transportation and logistics problems. Laporte et al (2000) did a survey of heuristics for the VRP which they divided into classical and modern heuristics with the classical part containing the savings method, the sweep algorithm and various two-phase approaches while the modern part had the tabu search heuristics, one of the most successful metaheuristic approach (Laporte, Gendreau, & Semet, 2000). Xie et al designed a genetic algorithm for modelling vehicle routes for spreading de-icing salt by combining the road network structure, capacity constraints and load constraints (Xie, Li, & Jin, 2013). Saberi & Verba presented a paper that gives a model for the continuous approximation for the VRP for Emissions minimisation (EVRP) that demonstrates the application and usefulness of the model and the implementations of the Solomon test instances based on several studies. (Saberi & Verba)

Tlili et al demonstrated how to integrate GIS and the optimisation of routes using the VRP. They combined GIS with a metaheuristic to solve the VRP efficiently then come up with a geographical solution as an alternative to the numerical solution with a region in Tunisia studied for the test of the proposed approach (Tlili, Faiz, & Krichen, 2013). Keenan, P. (2008) also demonstrated how to model a VRP with GIS thus allowing a range of different routing problems to be modelled. He further suggested that the combining vehicle routing and GIS techniques in decision support system can significantly improve the modelling of VRP

(Keenan, 2008). Kůs (2015) in his masters' thesis also demonstrated how a GIS approach was used to for optimisation vehicle routes for residential recyclable collection. ArcGIS and its Network Analyst extension was used to analyse routing improvement and formulated an equation for the time required for recyclables collection (Kůs, 2015).

Erdogan (2017) formulated an open source spreadsheet solver for vehicle routing problems with two case studies for the applications of the solver from the healthcare and tourism sectors. He also provided computational results of the solution algorithm for the solver, and computational results benchmarked with literature and found that the solver is found that the solver can solve capacitated VRP and Distance-Constrained VRP instances with up to 200 customers within 1hour of CPU time (Erdogan, 2017). Other literature on VRP include a literature review on the vehicle routing problem with multiple depots by Montaya-Torres, Franco, Isaza, Jimenez, & Padila-Harazo (2015), an optimised cross over generic algorithm for capacitated vehicle routing problem by Lee & Nazif (2011), a simulated annealing heuristic for the hydrid of the vehicle routing problem by Yu, Redi, Hidayat, & Wibowo (2017), a new benchmark instances for the capacitated vehicle routing problem by Uchoa, Pecin, Pessoa, Poggi, & Vidal (2017) and the intelligent winter road maintenance management in Slovak conditions by Kociánová (2015).

Others include a bi-objective model of preventive maintenance planning in distributed systems considering vehicle routing problem by Rashidnejad, Ebrahimnejad, & Safari (2018), a model with a solution algorithm for the operational aircraft maintenance routing problem by Eltoukhy, Chan, Chung, & Niu (2018) and a report on snow and ice removal route optimization in Kentucky by Blandford, Lammers, & Green (2017

2.12.4. Solution Algorithm

Ant colony optimisation (ACO) is one of the many different methods that have been used to solve VRP and TSP. Other methods include generic algorithms like the Tabu search, harmony search, memetic algorithm, column generation and the branch and bound (Huang, Huang, Blazquez, A, & Paredes-Belmar, 2018). In the journal article, "Application of the ant colony optimization in the resolution of the bridge inspection problem, Huang et al (2018) presented a study of bridge inspection tasks where an inspection team departs from the depot, inspects the assigned bridges and returns to the depot but the problem requires more than a day to complete and therefore the inspectors must be lodged somewhere during the inspections after working hours and continue the task the next day.

The article studied two situations: one where one inspection team was studied and the second one where several inspection teams where considered, and the inspection time accessed (Huang, Huang, Blazquez, A, & Paredes-Belmar, 2018). The objective of Huang et al was to ascertain routes and accommodation with minimum total inspection cost using an ACO algorithm and suggested a local search method for improving the quality of the result. Papenhausen and Mueller (2018) proposed an Ants framework that uses an ACO for auto turning to find a series of code optimisation for GPU architecture (Papenhausen & Mueller, 2018).

3. METHODOLOGY

Any study requires that the work is carried out in an organised and systematic way and the process is called the methodology of the study. The steps involved include identifying a problem, finding out what has been done so far to solve the problem, find ways of solving the problem better using the knowledge acquired by formulating a hypothesis, collecting data and analyse the available data. This data analysis brings out a solution from which conclusions are drawn and the results compared with the available solutions. Dane (1990) says that the goal of a research is to formulate the problem and describe the problem with research questions and then find answers to these questions (Block, 2017). Thiel (2014) and Kothari (2009) describe engineering research as research that entail the implementation of the right and necessary methodologies and procedural steps to solve an engineering problem and that the methodological approach is the basis for the choice of tools for carrying out such a research (Famurewa, 2015).

In this study, two approaches were used. The first approach was the qualitative approach which was mainly literature review from which the model framework was developed. The second approach was the quantitative approach and involved model development as shown in figure 3.1 below. The qualitative approach also involved optimisation which was done in two stages i.e. route optimisation in ArcGIS using VRP network analyst tool and the cost optimisation in excel.

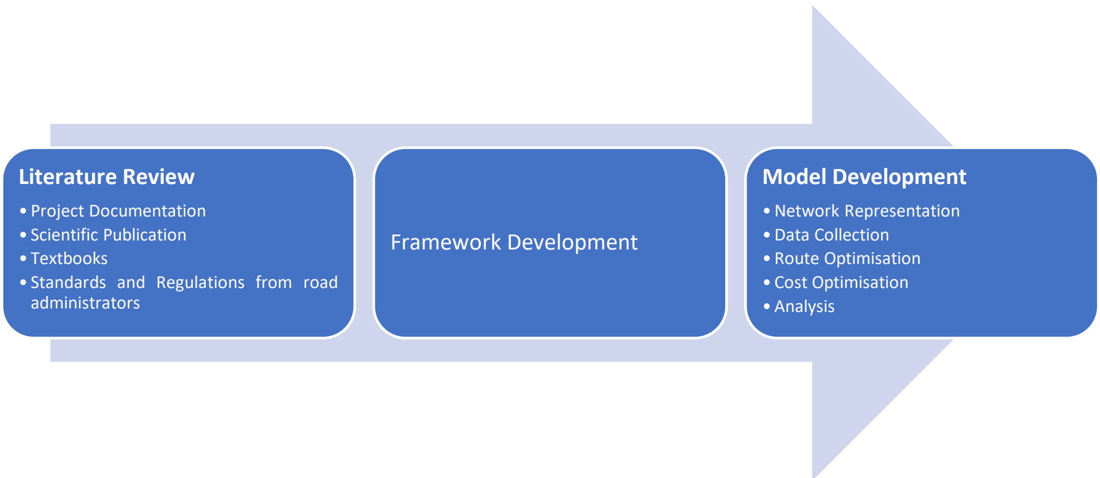

Figure 3.1 Research method

All steps of the research are summarised in the list below;

- After identifying the need from which the problem statement was drawn, the first step was literature review on maintenance frameworks and planning, winter road maintenance activities, Operation research methods for modelling and optimisation.
- The next step was theoretical process mapping, i.e. linking the problem to the theory from literature leading to the research purpose and objectives and finally, the research questions formulated
- Practical process mapping was done indirectly through observations and reading on how winter road maintenance is carried out in Luleå.
- This led to the problem description and came up with the maintenance framework for ploughing and sanding actions

- A model of the problem was created using ArcGIS VRP analysis and the results of the VRP exported into excel for cost optimisation. A solution algorithm was developed for the optimal maintenance cost and the optimal number of vehicles.
- A Single parameter deterministic sensitivity analysis was then performed to see how sensitive the total maintenance cost was to changes in any of the cost parameters while holding the other cost parameters constant for all the six-threshold penalty time.
- All the work was compiled in this master thesis report and the work defended in a master's thesis defence presentation.

3.1. Winter Road Maintenance Action Framework (ploughing and sanding)

One of the research questions is this project was how should the framework for carrying out a winter road maintenance action (sanding and ploughing) be to facilitate maintenance planning? The proposed framework is as shown in figure 3.2 below.

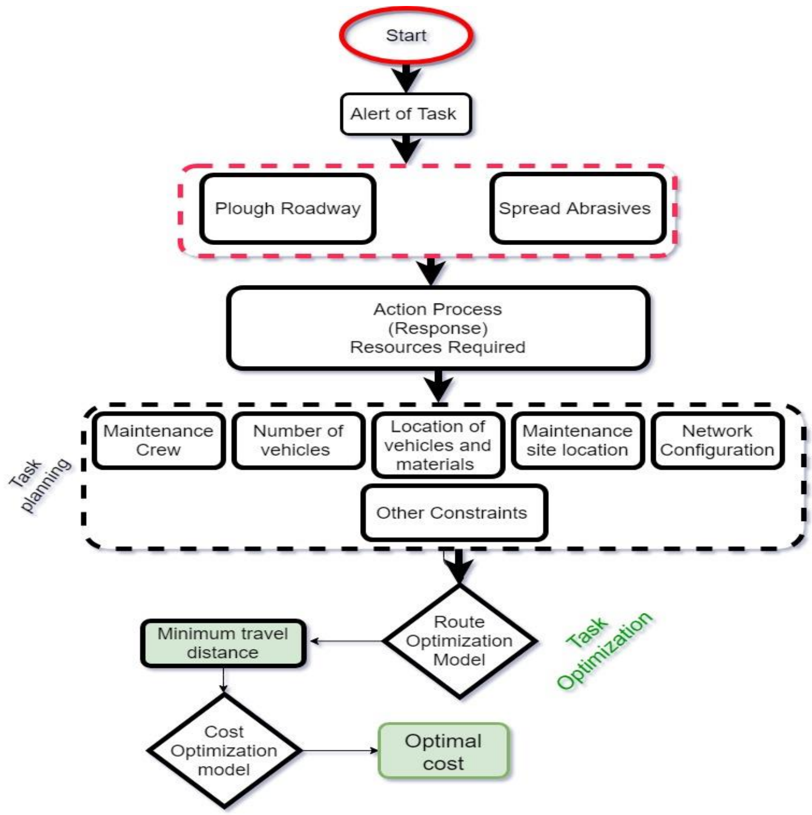

Figure 3.2 A Proposed Framework for Winter Road Maintenance

The proposed framework shows that after an alert of a maintenance action is received i.e. ploughing and sanding action, the response is determined by the resources available which include the number of vehicles and the operators, location of the vehicles and materials depot, other constraints like time required to complete the task before it attracts penalty charges and constraints on the road network configuration like roads barriers and restrictions. With these resources and constraints, the next step is an optimisation that gives the optimal total maintenance cost and the optimal required number of vehicles by minimising the total distance cover and in turn the total time taken to complete the task. The optimisation is in two stages, the route optimisation and the cost optimisation.

3.2. Road Network Digital representation

To formulate the problem of winter road maintenance for ploughing and sanding actions as a network problem, the road network of Luleå required to be digitally represented as nodes and edges with the nodes being where a road starts and ends, any junction where two roads meet, any point where there is a possibility of change of direction and depots for vehicles and materials. The edge is the distance between two successive nodes

Several support tools were considered with many not giving the desired outcomes. A software called Merkaartor was tried for digital representation but faced challenges to export the network for further analysis in MATLAB. ArcMap was a more suitable software for network representation and for the analysis of the routing of vehicles for efficient utilization of resources.

Figure 3.3 below shows the map with the roads in Luleå before digital representation using ArcGIS for network analysis.

Figure 3.3 Map of the roads in Luleå before digital representation

3.3. How to digitally represent a road network using ArcGIS

In this project, a property map of Luleå was downloaded from the Swedish cadastral services. All maps provided by the Swedish cadastral services contain road layers for vehicle transport, cycling and pedestrians. The road layer for vehicle transport was used in this project.

Figure 3.4 Vehicle Road Transport layer for Luleå before digital representation

Figure 3.3 above shows the vehicle road transport layer downloaded from the Swedish cadastral services and opened using ArcGIS. The property maps at the Swedish cadastral services and the other different digital maps are made by the Swedish University of Agricultural Sciences (SLU) as shapefiles and it is possible to add and removing lines from the network when opened in ArcGIS (SLU, 2018).

ArcGIS has an option to view the attributes of the network and for this project, another attribute to describe the cost of travelling on a road segment was added with the length of a segment used as a cost attribute. The geometry of the network was calculated after setting the length to kilometres. After the network properties and attributes were set, the next step was to represent the network digitally through an ArcGIS command to create the network dataset and modelled the turns and driving directions. The network dataset was now built, and feature classes added. The network was now ready for analysis with the different analysis tools i.e. shortest route, closed facility, new service area, vehicle routing problem and location allocation. In this project, only the shortest route and the vehicle routing problem tools were used.

Figure 3.5 below shows the vehicle road transport network digitally represented as nodes and edges with the distance between two successive nodes considered as a cost for using the road segment. The network was ready for network analysis using the vehicle routing problem analysis tool at this stage.

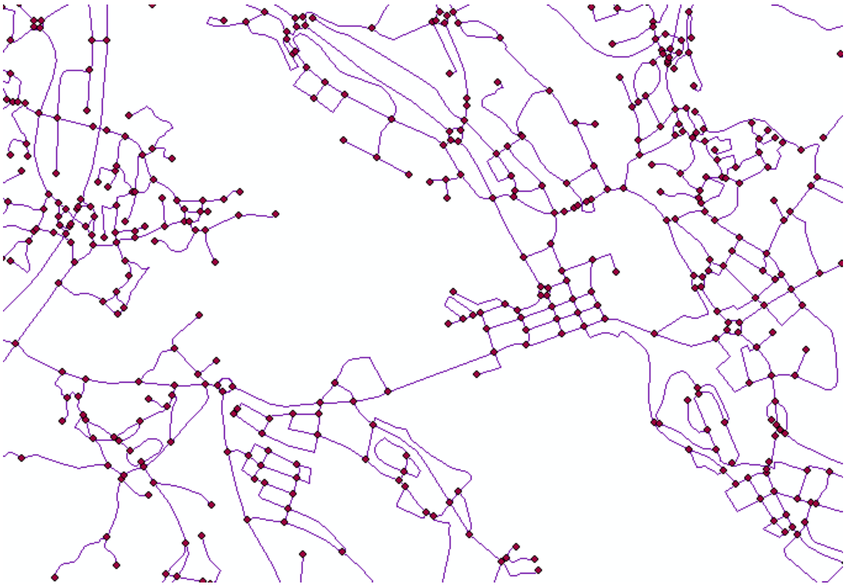

Figure 3.5 Vehicle Road Transport layer for Luleå after digital representation

3.4. Vehicle routing problem in ArcGIS

The problem of ploughing and sanding bus stops in Luleå was modelled as a Vehicle Routing Problem (VRP) with all the routes developed using Esri's Network Analyst. VRP determines the shortest routes for a fleet of vehicles to service many orders or deliveries of a product. In this project, and sand is treated as a product to be delivered to specific sites (bus stops) along roads.

3.4.1. Setting up of the Vehicle routing problem in ArcGIS

To set up the VRP of sanding and ploughing the bus stop, it was necessary to find the exact location of the bus stops which were the orders or the delivery points. The extraction, exporting and importing of the bus stops are explained in sections 3.3.2 and 3.3.3 below. Several assumptions were made for setting up the VRP which included;

- The speed of the vehicles was assumed constant throughout as the vehicle traverses a route travelling at 50km/hr.
- The vehicles are assured to have infinite capacity and therefore do not require reloading of sand.
- The service time of each order was assumed to be 2 minutes i.e. the time to plough and sand a bus stop.
- Each vehicle starts and ends at the depot. In this project, only one depot was considered for the vehicles.
- The vehicles are assumed to have enough fuel to go through all the orders assigned without any need to stop for refuelling.
- A bus stop could be serviced from either direction the vehicle approaches.

With these assumptions, the VRP was set up and the orders imported. When using more than one vehicle to service the orders, the orders were divided equally between the vehicles by restricting the maximum order count of each route. This is to have work divided equally between the operators and to ensure that at least each vehicle has some orders to service. The analysis was the run for 50 simulations to determine the shortest routes to services the orders varying the number of vehicles from 1 up to 50 vehicles.

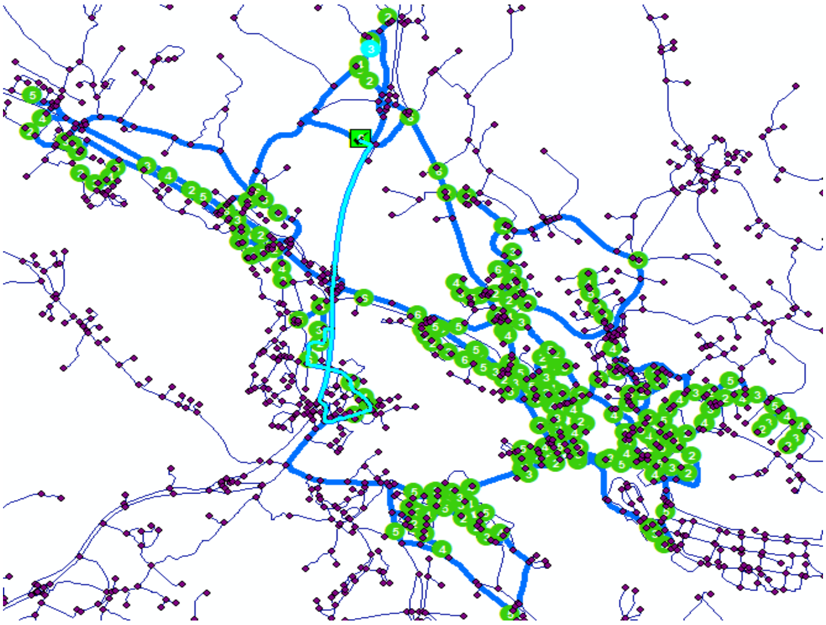

Figure 3.6 Result of one analysis

Figure 3.6 shows the result of a simulation to service the bus stops with 50 vehicles starting from one depot and end at the same depot. The route in light blue is one of the routes for one vehicle. The results for all the simulations were exported as attributes from ArcGIS to excel for cost optimisation.

Name	Description	ServiceTime	Vehicles	Sequence	PrevTravelTime	PrevDistance	CumulTravelTime	CumulDistance	CumulTime
Rutvisrevelen	Sanding and Ploughing	2	Vehicle_1	2	4.167136136	3.469479827	4.167136136	3.469479827	6.167136136
Björsbyvägen	Sanding and Ploughing	2	Vehicle_1	3	1.839648137	1.531639186	6.006784273	5.001119014	10.00678427
Porsö centrum	Sanding and Ploughing	2	Vehicle_1	4	2.041956445	1.700067692	8.048740719	6.701186705	14.04874072
Professorsvägen	Sanding and Ploughing	2	Vehicle_1	5	0.544309922	0.45317361	8.59305064	7.154360316	16.59305064
Universitetsentren	Sanding and Ploughing	2	Vehicle_1	6	0.636299085	0.529760965	9.229349725	7.684121281	19.22934972
Björkskataleden2	Sanding and Ploughing	2	Vehicle_1	7	0.656139921	0.546280811	9.885489646	8.230402092	21.88548965
Torpslingan	Sanding and Ploughing	2	Vehicle_1	8	0.616905905	0.513615169	10.50239555	8.744017261	24.50239555
Björkskataleden1	Sanding and Ploughing	2	Vehicle_1	9	0.56160548	0.467573967	11.06400103	9.211591228	27.06400103
Traktorvägen1	Sanding and Ploughing	2	Vehicle_1	10	0.187244929	0.155894249	11.25124596	9.367485476	29.25124596
Traktorvägen2	Sanding and Ploughing	2	Vehicle_1	11	0.020186489	0.01680665	11.27143245	9.384292126	31.27143245
Depävägen2	Sanding and Ploughing	2	Vehicle_1	12	0.561749842	0.467695007	11.83318229	9.851987133	33.83318229
Depävägen1	Sanding and Ploughing	2	Vehicle_1	13	0.162815833	0.135555186	11.99599813	9.987542319	35.99599813
Midgärdssvägen2	Sanding and Ploughing	2	Vehicle_1	14	0.788791133	0.656721816	12.78478926	10.64426413	38.78478926
Midgärdssvägen1	Sanding and Ploughing	2	Vehicle_1	15	0.115877941	0.096476173	12.9006672	10.74074031	40.9006672
Kräftgatan	Sanding and Ploughing	2	Vehicle_1	16	0.395498842	0.329278966	13.29616604	11.07001927	43.29616604
Samhall	Sanding and Ploughing	2	Vehicle_1	17	0.46574601	0.387763945	13.76191205	11.45778322	45.76191205

Table 3.1 Part of an extract of the result from ArcGIS

Table 3.1 above shows part of the results exported into excel for servicing the bus stops. The results give the name of each bus stop that each vehicle serves, the service time for each stop, the sequence in which these stops are services, the cumulative travel time, cumulative distance and cumulative time (travel plus service time) for each vehicle. The distances are in kilometres while time is in minutes.

3.4.2. Extracting and Exporting Bus Stops

A total of 213 bus stops in this project were extracted from google earth. The extracted bus stops are shown below from a map extracted from the LLT website. This was done by locating each of the stops and placing a placemark on each of them. After locating and placing a mark on each of the stops, the places were saved in a KML file format where the stops are saved as points.

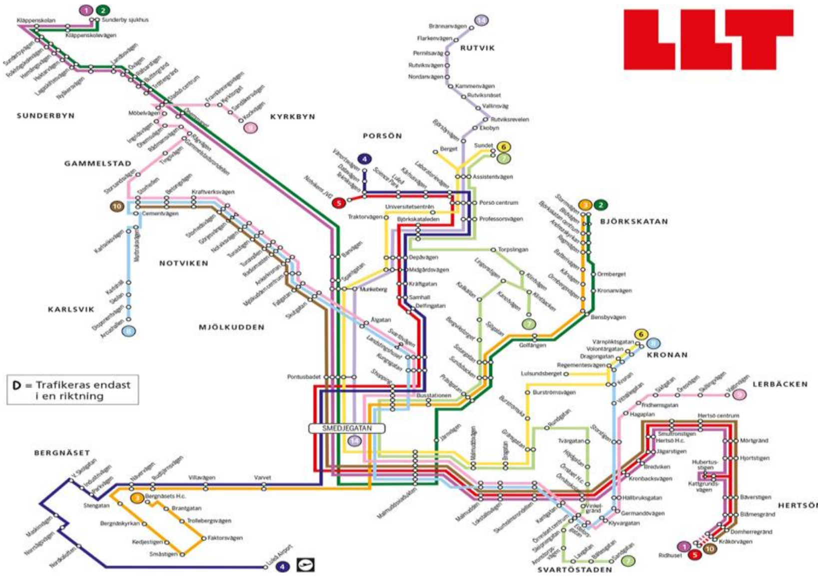

Figure 3.7 Bus stops that were extracted from google earth

Figure 3.8 below shows a google earth extract of the bus stops used in this project after placing a marker. The stops were then imported into ArcGIS as orders after converting the KML file in a shapefile. Section 3.3.3 gives a brief description of converting the KML file into a shapefile and loading the converted file as orders into ArcGIS for further network analysis.

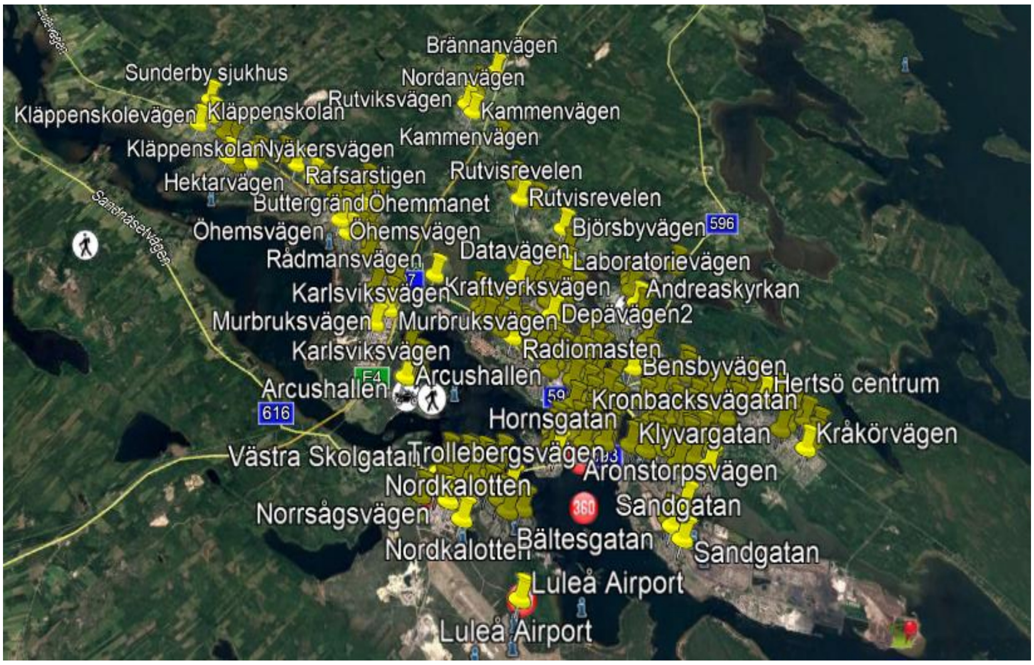

Figure 3.8 Extract of the bus stops after placing markers.

3.4.3. Importing Bus Stops in ArcGIS

After saving the bus stops from google earth as a KML the next step was to convert the KML file into a shapefile. The arc toolbar in ArcGIS has conversions tools that convert different file formats to shapefile so that they can be readable in ArcGIS. In this project, the KML file was converted to layers as shown in figure 3.8 below

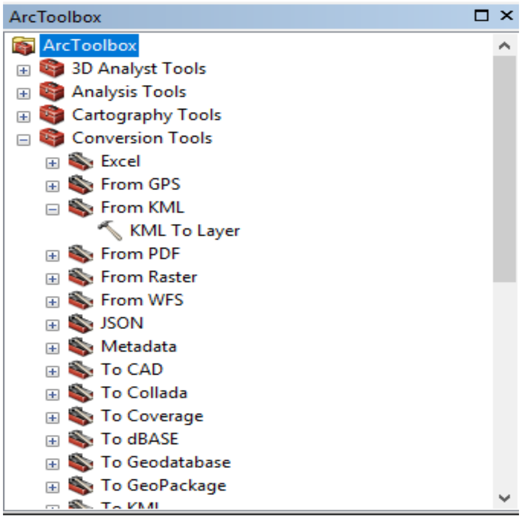

Figure 3.9 Converting a KML file to Layer

After converting the KLM to layer, the file opens in ArcGIS with the vehicle road network as shown in figure 3.9 below. The placemarks can then be changed to a more convenient one as shown in figure 3.10 below. Now the file was saved as a shapefile and the placemarks for the bus stops saved as points.

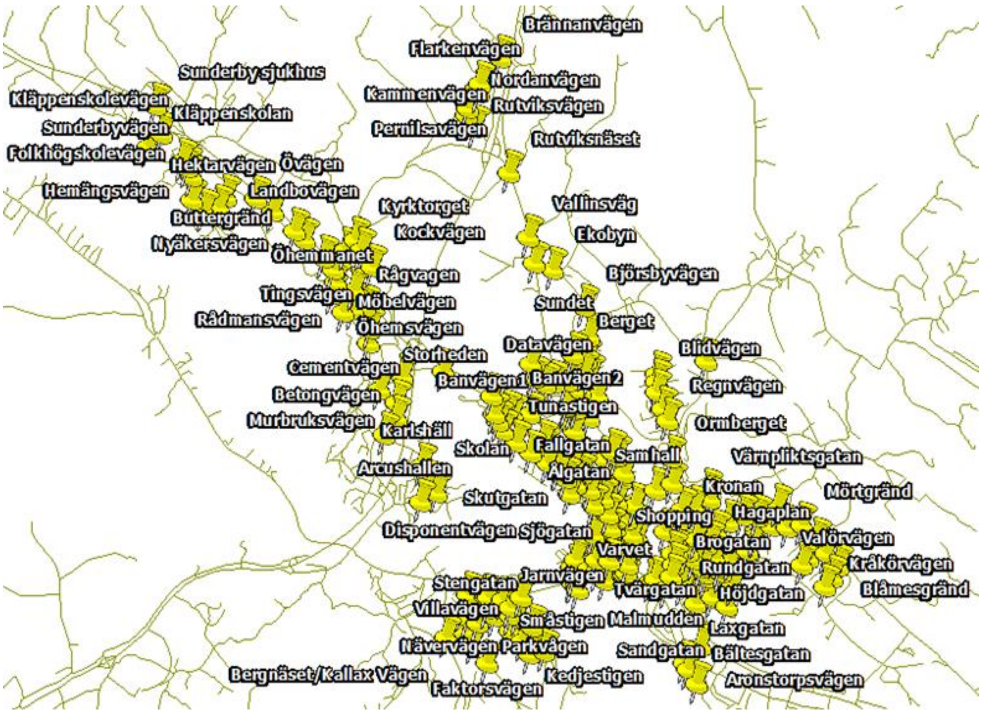

Figure 3.10 Bus stops imported into ArcGIS VRP analysis

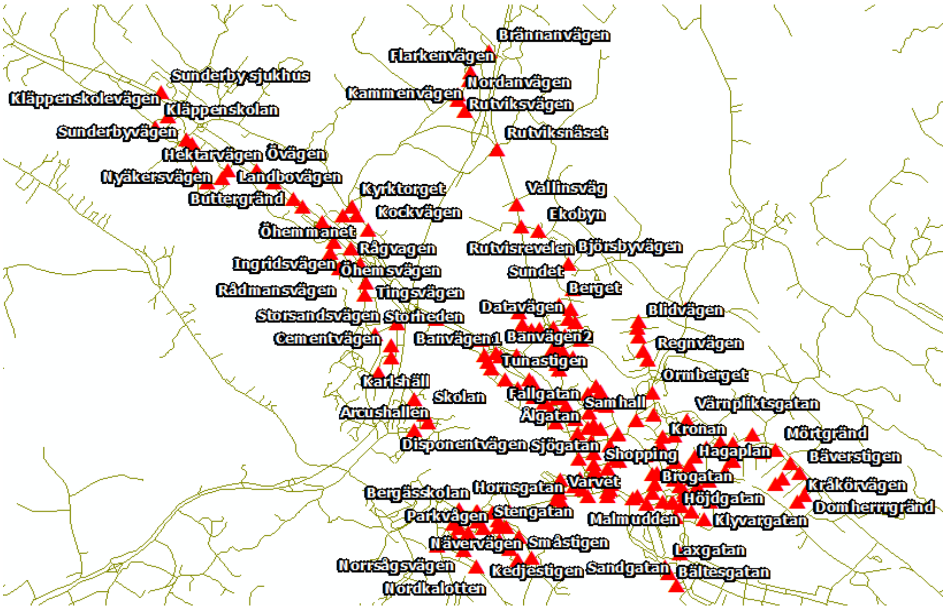

Figure 3.11 Place marks changed to triangular shapes in red colour

3.4.4. Vehicle routing problem optimal solution.

The optimal results i.e. the routes with the minimum distances to plough and sand all the bus stops were obtained for different scenarios, a scenario being the number of vehicles used to serve the orders. 50 simulations were run, and the results exported into excel for cost optimisation as shown in section four (4) of this report.

Table 3.2 below shows part of the results extracted from the attributes table of the routes from ArcGIS for using 50 vehicles. Each of the routes shows the total time that a vehicle in that route takes to travel from the vehicle depot and service the orders assigned to it and back to the depot and the total distance covered. These are the results that were used for cost optimisation.

Table

Routes

Name	Description	StartDepotName	EndDepotName	MaxOrderCount	OrderCount	TotalTime	TotalOrderServiceTime	TotalTravelTime	TotalDistance
Route_1	Sanding and Plou	Deport	Deport	5	5	18.116943	10	8.116943	6.758054
Route_2	Sanding and Plou	Deport	Deport	5	5	24.763304	10	14.763304	12.291581
Route_3	Sanding and Plou	Deport	Deport	5	5	26.518925	10	16.518925	13.753557
Route_4	Sanding and Plou	Deport	Deport	5	5	26.889912	10	16.889912	14.062517
Route_5	Sanding and Plou	Deport	Deport	5	5	27.094956	10	17.094956	14.233116
Route_6	Sanding and Plou	Deport	Deport	5	5	26.028378	10	16.028378	13.345191
Route_7	Sanding and Plou	Deport	Deport	5	5	26.344483	10	16.344483	13.608207
Route_8	Sanding and Plou	Deport	Deport	5	5	29.453393	10	19.453393	16.196732
Route_9	Sanding and Plou	Deport	Deport	5	5	27.175409	10	17.175409	14.299856
Route_10	Sanding and Plou	Deport	Deport	5	5	28.290485	10	18.290485	15.228195
Route_11	Sanding and Plou	Deport	Deport	5	5	30.253014	10	20.253014	16.862675
Route_12	Sanding and Plou	Deport	Deport	5	5	30.052313	10	20.052313	16.695243
Route_13	Sanding and Plou	Deport	Deport	5	5	28.440095	10	18.440095	15.352781
Route_14	Sanding and Plou	Deport	Deport	4	4	26.373621	8	18.373621	15.297524
Route_15	Sanding and Plou	Deport	Deport	4	4	27.491861	8	19.491861	16.228536
Route_16	Sanding and Plou	Deport	Deport	4	4	28.06254	8	20.06254	16.704237
Route_17	Sanding and Plou	Deport	Deport	4	4	30.159452	8	22.159452	18.449568
Route_18	Sanding and Plou	Deport	Deport	4	4	29.111945	8	21.111945	17.57726
Route_19	Sanding and Plou	Deport	Deport	4	4	31.464069	8	23.464069	19.535564
Route_20	Sanding and Plou	Deport	Deport	4	4	30.985822	8	22.985822	19.138256
Route_21	Sanding and Plou	Deport	Deport	4	4	34.649466	8	26.649466	22.187463

Table 3.2 Part of the results extracted from the attributes table from ArcGIS

On the other hand, table 3.3 below shows part of the results extracted from the attributes table of how the orders were serviced from ArcGIS for using 50 vehicles. Each route shows the name of the bus stops it serviced, the sequence in which the stops were serviced, the cumulative travel time and distance covered at the time a bus stop is serviced and the total time (total of the travel and service time) when a bus stop was serviced. Table 3.2 only gives the time up to when the last bus stop is serviced by a vehicle using a specific route. The total time the vehicle takes back to its depot is obtained from table 3.1 for each route.

Table

Orders

Name	Description	ServiceTime	RouteName	Sequence	FromPrevTravelTime	FromPrevDistance	CumulTravelTime	CumulDistance	CumulTime
Maskinvägen	<Null>	2	Route_40	2	14.488011	12.062595	14.488011	12.062595	16.488011
Västra Skolgatan	<Null>	2	Route_43	2	15.477549	12.88646	15.477549	12.88646	17.477549
Bergnäskyrkan	<Null>	2	Route_44	2	15.588048	12.978456	15.588048	12.978456	17.588048
Kedjestigen	<Null>	2	Route_46	2	16.007281	13.327498	16.007281	13.327498	18.007281
Nävervägen	<Null>	2	Route_36	2	14.689497	12.230344	14.689497	12.230344	16.689497
Rudtjärnsvägen	<Null>	2	Route_34	2	14.745295	12.2768	14.745295	12.2768	16.745295
Stadshuset	<Null>	2	Route_30	2	12.651889	10.533708	12.651889	10.533708	14.651889
Södra Hamn	<Null>	2	Route_28	2	12.832221	10.683844	12.832221	10.683844	14.832221
Jarnvägen	<Null>	2	Route_32	2	13.057037	10.870926	13.057037	10.870926	15.057037
Malmudden	<Null>	2	Route_35	2	13.872315	11.54969	13.872315	11.54969	15.872315
Kantgaten 2	<Null>	2	Route_38	2	14.408429	11.996005	14.408429	11.996005	16.408429
Laxgatan	<Null>	2	Route_47	2	16.365186	13.625135	16.365186	13.625135	18.365186
Vinkelgränd	<Null>	2	Route_33	2	14.252916	11.86653	14.252916	11.86653	16.252916
Klyvargatan	<Null>	2	Route_42	2	15.592792	12.982031	15.592792	12.982031	17.592792
Germandövägen	<Null>	2	Route_41	2	15.075343	12.551234	15.075343	12.551234	17.075343
Bredviken	<Null>	2	Route_45	2	14.855314	12.368051	14.855314	12.368051	16.855314
Hallonstigen	<Null>	2	Route_48	2	16.254097	13.532563	16.254097	13.532563	18.254097
Hubertusstigen	<Null>	2	Route_49	2	18.486008	15.390699	18.486008	15.390699	20.486008
Kråkörvägen	<Null>	2	Route_50	2	19.243257	16.021126	19.243257	16.021126	21.243257
Skillingvägen	<Null>	2	Route_39	2	15.495074	12.900648	15.495074	12.900648	17.495074
Rundgatan	<Null>	2	Route_27	2	13.392928	11.15055	13.392928	11.15055	15.392928

Table 3.3 Results of how orders were serviced by each route.

3.5. How results from ArcGIS Exported into Excel were analysed.

After exporting all the results from ArcGIS into excel i.e. for each simulation, the next step was finding the cost implication of using a certain number of vehicles.

3.5.1. Preliminary steps for calculating the Maintenance Costs

The following steps were followed in calculating the maintenance costs:

1. Results from table 3.2 were used to calculate the total distance covered by all the vehicles and the total time taken to cover the distance.

$$\text{Total Distance using N Vehicles} = \sum_{n=1}^{N} (\text{TDR}_n) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn 1}$$

$$\text{Total Time using N Vehicles} = \sum_{n=1}^{N} (\text{TTR}_n) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn 2}$$

Where:

- N = 1, 2, …., N
- N = The Number of Vehicles or routes in a scenario
- TDR_n = Travel Distance covered by Route_n
- TTR_n = Travel Time (travel plus service) taken to cover Route_n

2. Results from table 3.3 were used to calculate the penalty time by the vehicle to service bus stops. Six threshold time (30, 60, 90, 120, 150 and 180 minutes) to service all the bus stops without attracting a penalty was considered in this project. Each bus stop that is serviced after this threshold time attracts a penalty fee per hour of exceeded time. The sum of the exceeded time for each of the stops in each scenario was then calculated.

$$\text{Exceeded Time for using N Vehicles} = \sum_{x=1}^{X}(\text{Time of Service of Bus Stop}_x - \text{Threshold Time}) \ldots\ldots\ldots\ldots \text{Eqn 3}$$

Where:

- x = 1, 2, 3, ……., X
- X = The Number of bus stops, X=213 stops in this project
- Any value $(\text{Time of Service of Bus Stop}_n - \text{Threshold Time}) < 0$ is considered equal to zero no penalty
- N = The Number of Vehicles or routes in a scenario

3.5.2. Final calculations of the Maintenance Costs

With the total time, total distance and the exceeded time for each scenario of N vehicles calculated in as indicated in section 3.5.1 above, the next step was to calculate the direct and indirect cost of ploughing and sanding the bus stops for each scenario for all the six threshold service times.

The direct costs included the following:

1. The cost of fuel used by a vehicle as it travels from the depot and services the orders in its route and back to the depot.

$$\text{Cost of Fuel, } (C_f) = \sum_{n}^{N}(\text{TDR}_n \times \text{AFC} \times C_{f/\text{Ltr}}) \ldots\ldots\ldots\ldots \text{Eqn 4}$$

Where:

- AFC = Average fuel consumption of the vehicle in kilometre per Litre
- $C_{f/\text{Ltr}}$ = Cost of fuel per litre

2. The cost of personnel or operator per hour of operating a vehicle from the time he/she starts off from the depot to the time he/she returns after completing the orders assigned.

$$\text{Cost of Personnel, } (C_p) = \sum_{n}^{N}((\text{TTR}_n \times \text{HLR}) \ldots\ldots\ldots\ldots \text{Eqn 5}$$

Where HLR = Hourly Labour rate per personnel/operator.

3. The cost of hiring a vehicle per hour it is in operation from the time it starts off from the depot until it has serviced the bus stops in its assigned route and back to the depot.

$$\text{Cost of Vehicle Hire, } (C_{VH}) = \sum_{n}^{N}((\text{TTR}_n \times \text{HCVH}) \ldots\ldots\ldots\ldots \text{Eqn 6}$$

Where HCVH = Hourly Cost of Hiring a Vehicle.

The direct cost of maintenance is the sum of the cost of personnel, the cost of fuel and the cost of hiring a vehicle.

$$\text{Direct Cost} = C_f + C_p + C_{VH} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn 7}$$

Any stops serviced after the threshold time attracts a penalty fee per hour exceed

$$\text{Indirect Cost} = P_{fee} \times \text{Exceeded Time for using N Vehicles} \ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn 8}$$

By substituting Eqn 3 into Eqn 8 we obtain

$$\text{Indirect Cost} = \sum_{n=1}^{X} (\text{Time of Service of Bus Stop}_n - \text{Threshold Time}) \times P_{fee} \ldots\ldots \text{Eqn 9}$$

Where P_{fee} = Penalty fee for exceeding the threshold time.

The total maintenance is the sum of the direct and indirect costs i.e.

$$\text{Total Maintenance Cost} = \text{Direct Cost} + \text{Indirect Cost} \ldots\ldots\ldots\ldots\ldots\ldots \text{Eqn 10}$$

All the above calculations were made for each of the scenarios of N vehicles and for each of the six threshold service times.

3.5.3. Optimal Maintenance cost.

After all the maintenance costs were calculated, the next step was to find the optimal cost for each of the six different threshold service times and the respective number of vehicles required for the maintenance action. The optimal cost is the minimum total maintenance cost of all the scenarios and calculated for all the six threshold service times. A graphical approach was used to identify the optimal maintenance cost for each threshold service time, i.e. the number of vehicles that produces the minimum costs of each time threshold.

$$\text{Optimal Cost} = Min[\text{Total Maintenance Cost (from all scenarios)}] \ldots\ldots\ldots\ldots \text{Eqn 11}$$

Various graphs were then plotted to observe some trends in the results for decision making. The plots included:

- Latest and Earliest Arrival Time at the Depot Vs the Number of Vehicles
- Longest and Shortest Distance travelled Vs the Number of Vehicles
- Winter Road Maintenance Cost (SEK) for each of the six threshold service times Vs the Number of Vehicles
- Cumulative Distance Covered and the Cumulative time Vs the Number of Vehicles
- Penalty Delay Time for different threshold service times Vs Number of Vehicles

- Indirect Maintenance Costs for different threshold service times Vs Number of Vehicles
- Optimal Maintenance Cost and Required Number of Vehicles Vs Threshold Service Time

The costs used in the analysis are as shown in table 3.4 below.

Fuel Consumption (Ltrs/km)	0.4
Cost of Fuel/Ltr	15
Operator Cost (SEK/Hr)	500
Cost of Vehicle hire(SEK/Hr)	1500
Expected Latest Delivery Time(Minutes)	30
	60
	90
	120
	150
	180
Penalty on Late Delivery(SEK/Hr)	200

Table 3.4 Cost properties for maintenance cost calculations

3.5.4. Sensitivity Analysis of the results

Sensitivity analysis was carried out to observe the changes in the total maintenance cost with a change in one of the cost parameters. This was a single parameter deterministic sensitivity analysis where a single cost parameter is changed to determined values while keeping the other cost parameter constant. The cost parameters in this project where the unit price of fuel ($C_{f/Ltr}$), Hourly Labour rate per personnel/operator (HLR), Hourly Cost of Hiring a Vehicle (HLR) and the penalty fee for the time exceeded above the threshold (P_{fee}). The other sensitivity analysis was multiple parameters deterministic analysis where all the four cost parameters were changed to determined values and observing the change in the total maintenance cost.

Each of the cost parameters was increased at intervals of 10% up to 50% while keeping the other parameters constant for the single parameter sensitivity analysis and observed the trend in the total maintenance cost.

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4. RESULTS, ANALYSIS, AND DISCUSSION

Figure 4.1 and 4.2 below is a plot of the latest and earliest arrival time and a plot of the longest and shortest distance covered by the vehicles back to the depot for different scenarios.

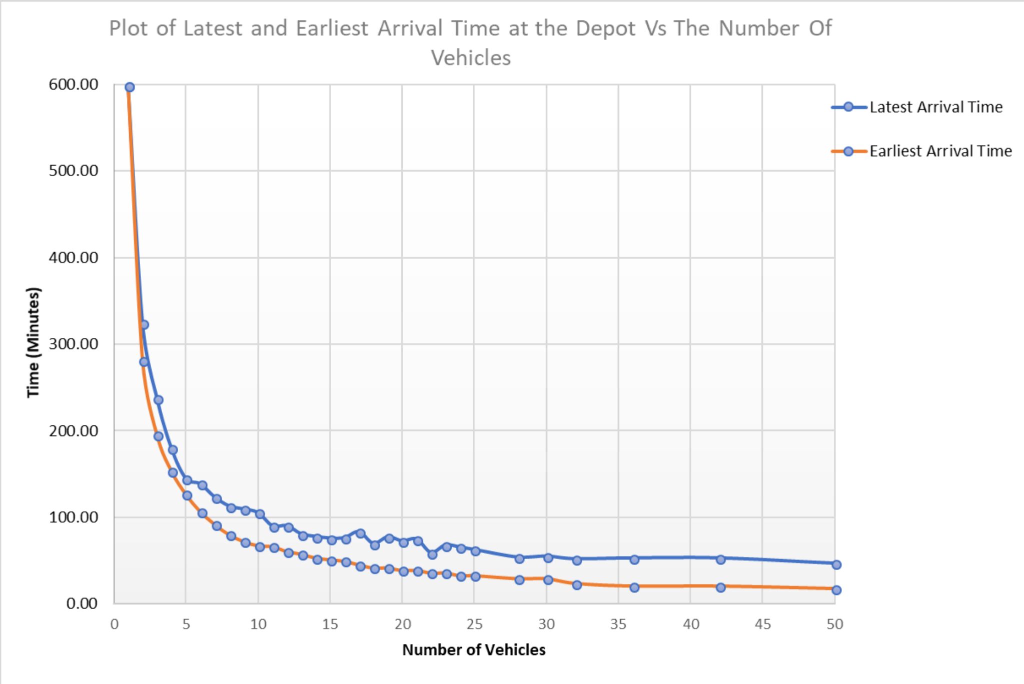

Figure 4.1 Latest and Earliest Arrival Time of Vehicles at the Depot

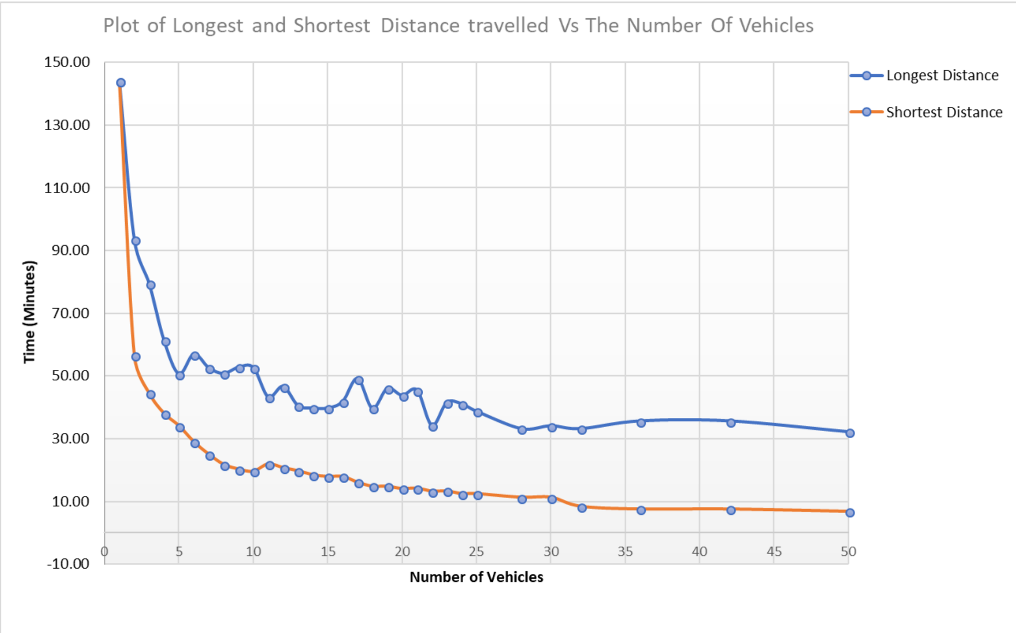

Figure 4.2 longest and shortest distance travelled by the Vehicles at the Depot

From the two plots (fig 4.1 and 4.2) it can be observed that the difference between the latest and earliest arrival times and the difference between the longest and shortest distance travelled by the vehicles decreases as the number of vehicles for winter road maintenance increase and becomes constant when the number of vehicles is increased from 25 vehicles up to 50 vehicles. This information can be used to model inter arrival of vehicles back to the depot and help to plan for quick checks, inspections, and cleaning of the vehicles after undertaking a task.

As the number of vehicles is increased, the completion time decrease and therefore reducing the penalty time.

Figure 4.3 below shows the cumulative distance and the cumulative time of the vehicles to and from the depot for each scenario.

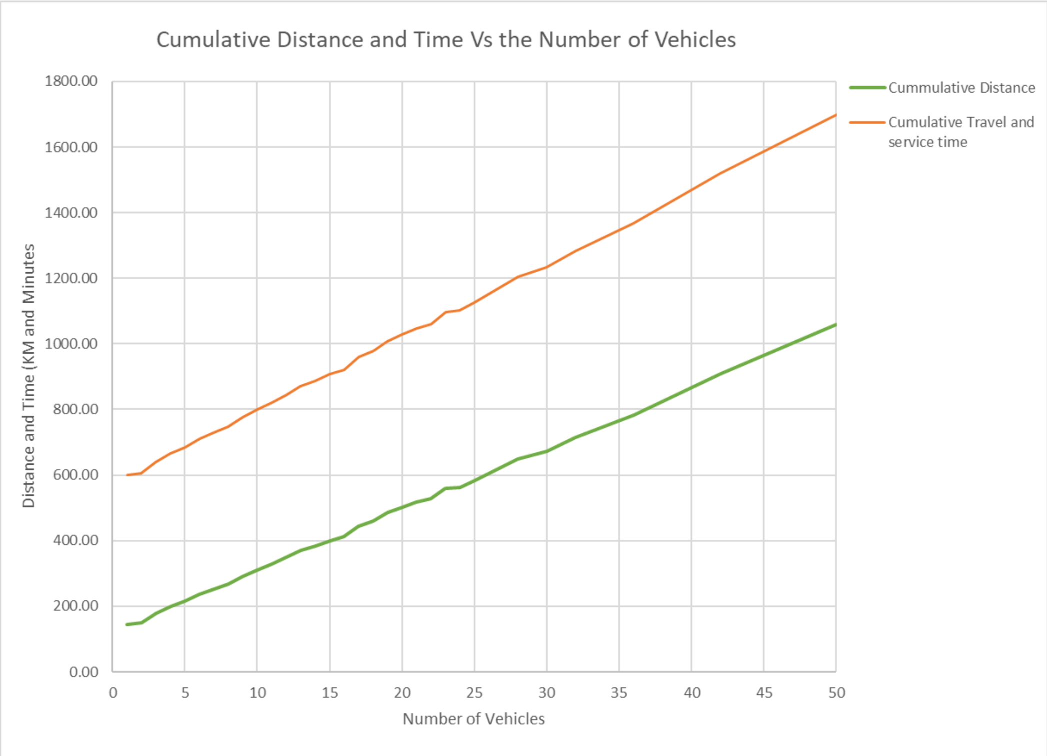

Figure 4.3 Cumulative Distance and Cumulative Time Vs Vehicles

From figure 4.3 above, it is shown that as the number of vehicles increases the cumulative distances and the cumulative time increases. This means an increase in the cost of vehicle hire, cost of fuel and cost of personnel. However, the penalty fee reduces because the operation of plough and sanding is completed faster and the penalty on each bus stops is reduced. The optimal maintenance cost is, therefore, the minimum of the sum of direct and indirect cost from the different scenarios

Figure 4.4 below shows plots of the cost of fuel, cost of vehicle hire, and the cost of personnel that makes up the direct cost of maintenance.

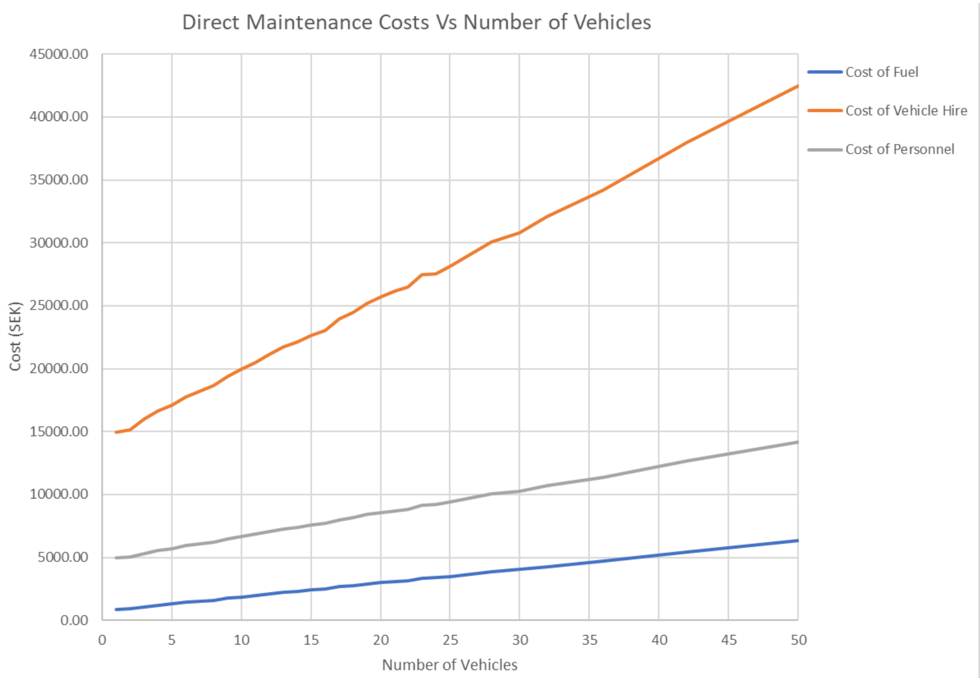

Figure 4.4 Direct Maintenance Costs

It can also be seen in the pie charts in figures 4.7, 4.8 and 4.9 that the cost of hiring vehicles takes up not less than 60% of the total maintenance cost. This can also be seen in the sensitivity of the three costs that the cost of vehicle hire is more sensitivity compared to the cost of personnel and the cost of fuel is the least sensitive.

Figure 4.5 below shows plots of the total winter road maintenance cost for the 90 and 150 minutes penalty thresholds. The Optimal maintenance cost for the 90 minutes threshold is about SEK26,000 and using 7 vehicles while the optimal cost for the 150 minutes penalty threshold is SEK 24,000 using 4 vehicles. As the penalty threshold is relaxed, the penalty fee reduces, and a maintenance contractor can use fewer vehicles to complete the sanding and ploughing of the bus stops. Reduction in the vehicles leads to a reduction in the cost of vehicle hire and cost of personnel.

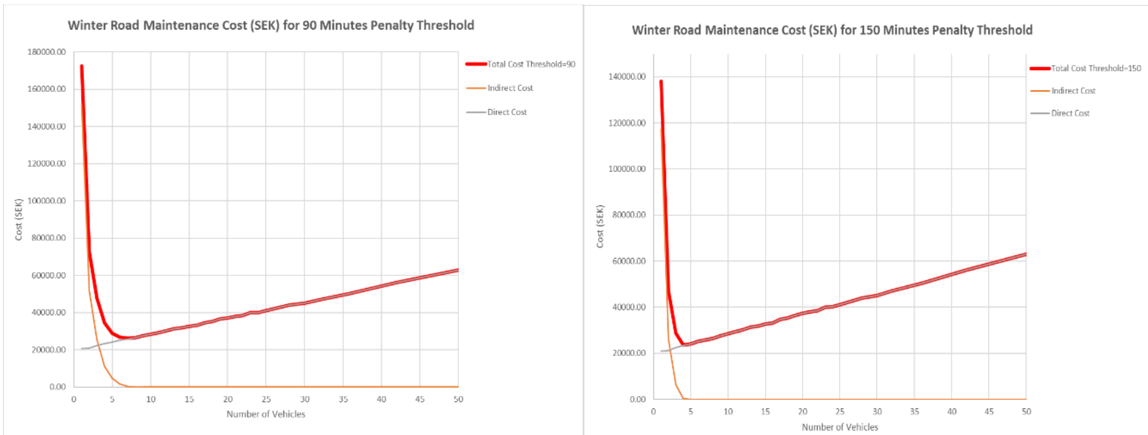

Figure 4.5 Winter Road Maintenance Cost for the 90 and 150 Minutes Penalty threshold

Table 4.1 below shows the optimal Maintenance cost and the required number of vehicles for the six different penalty threshold time.

Threshold Penalty	Optimal	
Time	Number of Vehicles	Total Maintenance Costs (SEK)
30	15	36,780.63
60	10	29,557.34
90	7	26,210.37
120	5	24,468.09
150	4	23,665.11
180	4	23,387.71

Table 4.1 Threshold Penalty Time, Optimal Number of Vehicles and Maintenance Cost

Figure 4.6 below shows the optimal total maintenance cost and the optimal number of vehicles with respect to the penalty thresholds.

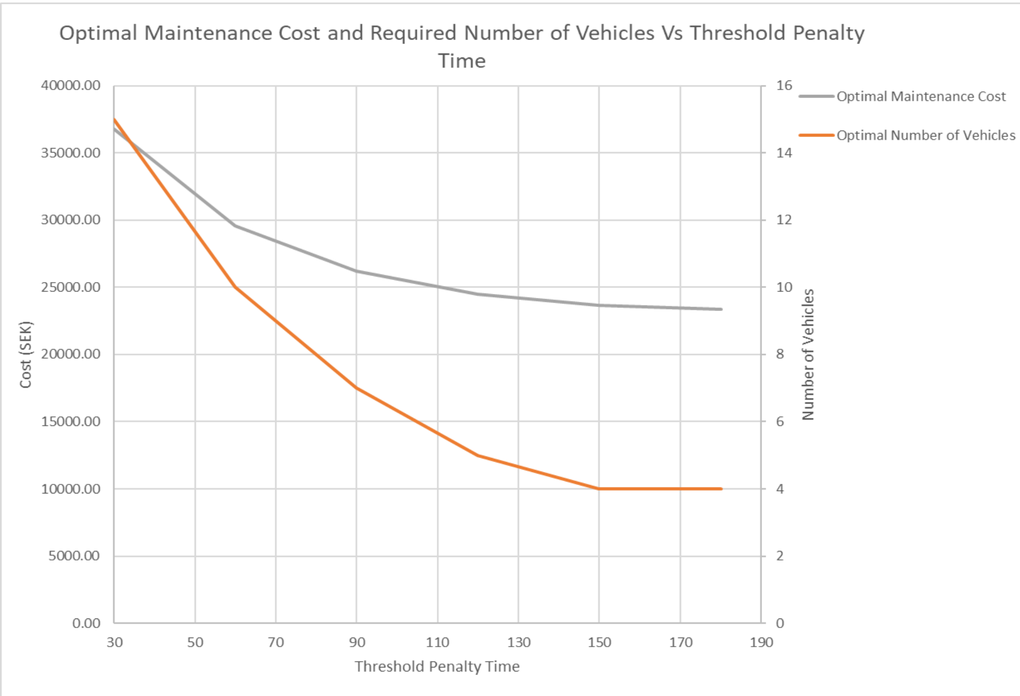

Figure 4.6 Optimal total maintenance cost and the Optimal number of Vehicles

It can be observed from table 4.2 and figure 4.6 that as the penalty threshold is relaxed, the maintenance cost reduces and the number of vehicles required also reduces. With reduced penalty threshold, more bus stops can be maintained before the penalty threshold is reached. This allows the model to choose an optimal cost that uses fewer vehicles and hence reduces the cost of vehicle hire and the cost of personnel. A maintenance contractor can use this result to negotiate for a penalty threshold that would be sustainable for there business considering that a more strict threshold (lower time limit) will require using more vehicles at an optimal maintenance cost than a lesser strict threshold. If relaxing the threshold would compromise the service level, then a better and more sustainable contract can be negotiated for in terms of how much the contract is worth.

The distribution of the direct (Cost of vehicle hire, cost of fuel, cost of personnel) and indirect (penalty cost) maintenance cost for the 30 minutes and 60 minutes threshold penalties are shown on figure 4.7 below.

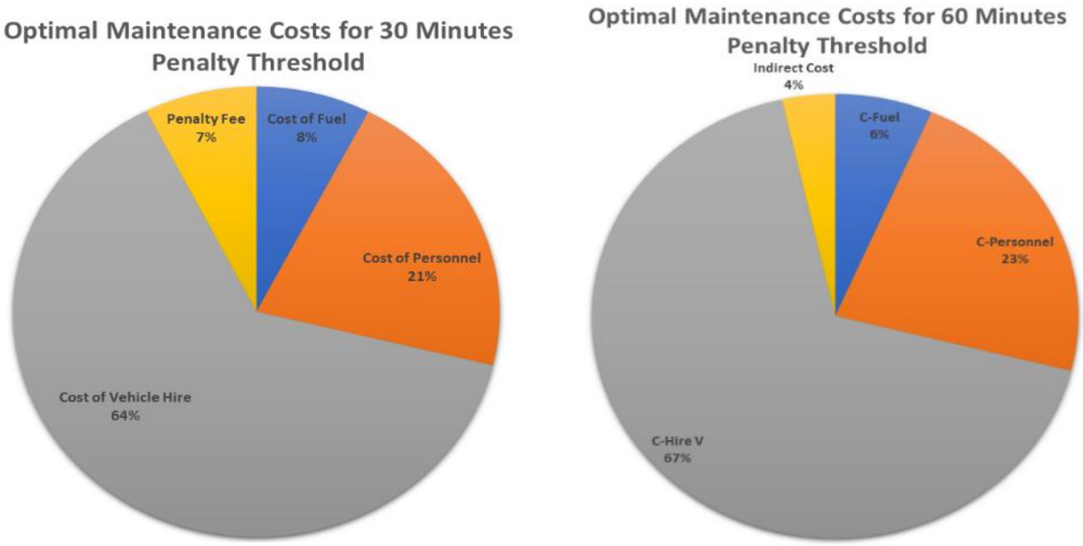

Figure 4.7 Direct and Indirect Maintenance costs for the 30 and 60 minutes thresholds

Figure 4.8 below shows the distribution of the direct and indirect maintenance cost for the 90 minutes and 120 minutes threshold penalties.

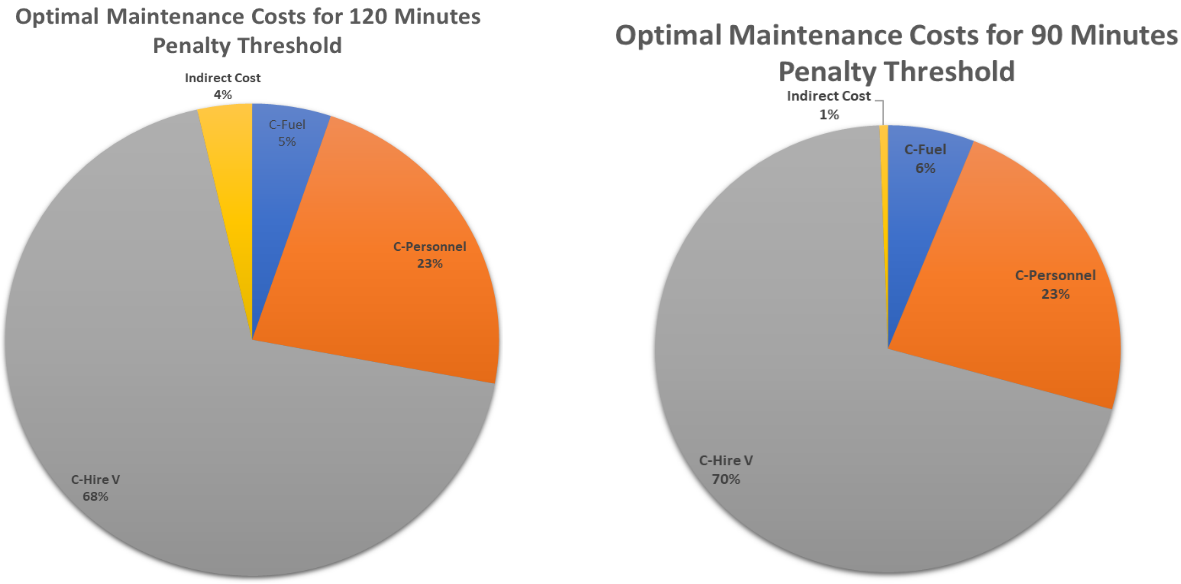

Figure 4.8 Direct and Indirect Maintenance costs for the 90 and 120 minutes thresholds

The distribution of direct and indirect maintenance cost for the 150 minutes and 180 minutes threshold penalties are shown in figure 4.9 below.

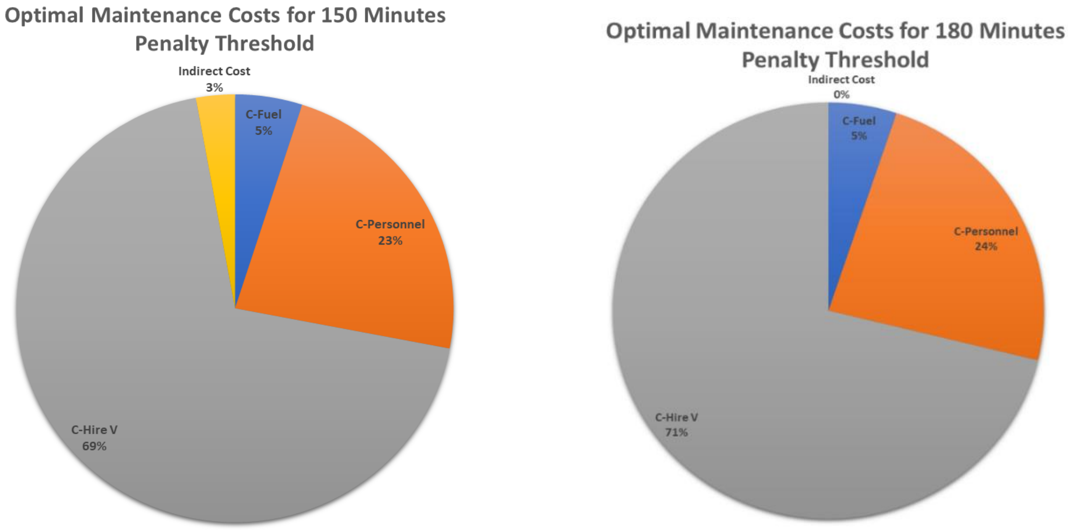

Figure 4.9 Direct and Indirect Maintenance costs for the 90 and 120 minutes thresholds

It can be seen from figures 4.7, 4.8 and 4.9 that direct cost take up over 90% of the maintenance costs. Vehicle hire makes up over 60% of the cost. The penalty cost is minimised and with a more relaxed penalty threshold time like 180 minutes, the penalty fee is 0% because all the bus stops are ploughed and sanded within 180 minutes at the optimal number of vehicles. The model chooses an optimal maintenance cost that minimises the total maintenance cost. If the cost of adding an extra vehicle is less than the reduction in the penalty fee due to the extra vehicle, the optimal number of vehicles will have an extra vehicle and the reverse is true.

Figure 4.10 below shows the graphs for the total maintenance cost for the different six penalty thresholds with respect to the number of vehicles. As the penalty threshold is relaxed, the optimal maintenance cost decreases and the optimal number of vehicles decreases too.

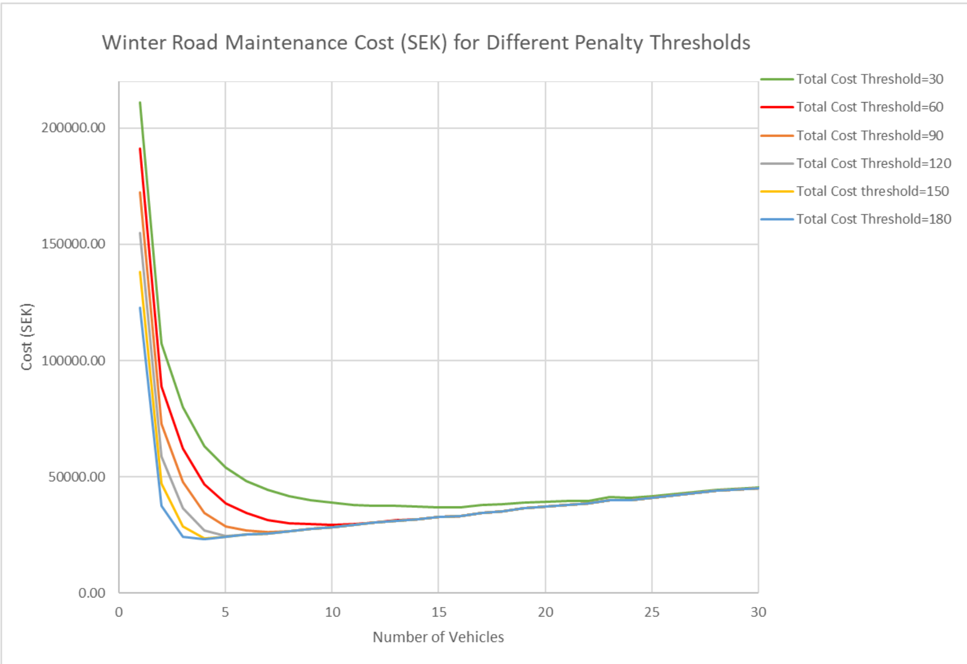

Figure 4.10 Winter road maintenance cost for the six penalty thresholds

Figure 4.11 below shows the penalty time for the six threshold times with respect to the number of vehicles. As the number of vehicles increases, the penalty time reduces because more vehicles can complete the task faster. The more relaxed penalty threshold times tend to approach zero penalty faster than the ones with a short threshold penalty time. For a threshold penalty time of 30 minutes, even with 30 vehicles, there is a penalty time of about 80 minutes while it only takes 10 vehicles to have no penalty for the 90 minutes threshold penalty time and 5 vehicles for the 150 minutes threshold penalty time.

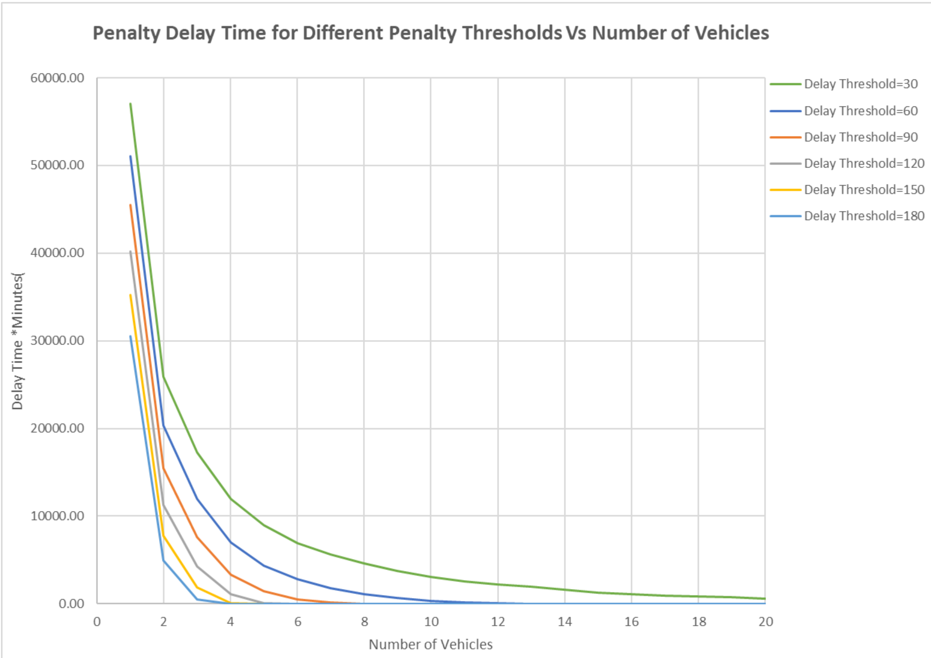

Figure 4.11 Penalty time vs the Number of Vehicles

This penalty times in figure 4.12 results in the indirect cost because of the penalty fee charged for the time some bus stops are maintained beyond the threshold penalty time. The indirect costs are as shown in figure 4.12 below.

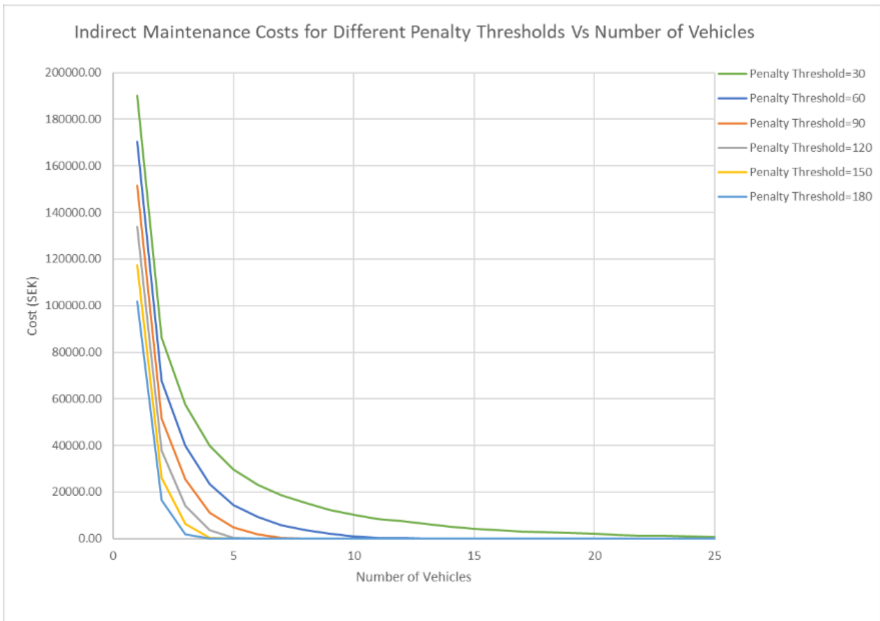

Figure 4.12 Indirect Maintenance Cost for the Six penalty thresholds

The optimal indirect costs for the 30, 60, 90, 120, 150 and 180 minutes penalty thresholds are as shown in table 4.2 below.

Threshold Penalty	Optimal	
Time	Number of Vehicles	Indirect Maintenance Costs (SEK)
30	22	3,106.74
60	11	1,071.90
90	8	158.24
120	5	894.58
150	4	693.50
180	4	0

Table 4.2 Threshold Penalty Time, Optimal Number of Vehicles and Indirect Maintenance Cost

Figures 4.13 and 4.14 show the sensitivity of the total optimal maintenance cost when the fuel price is adjusted.

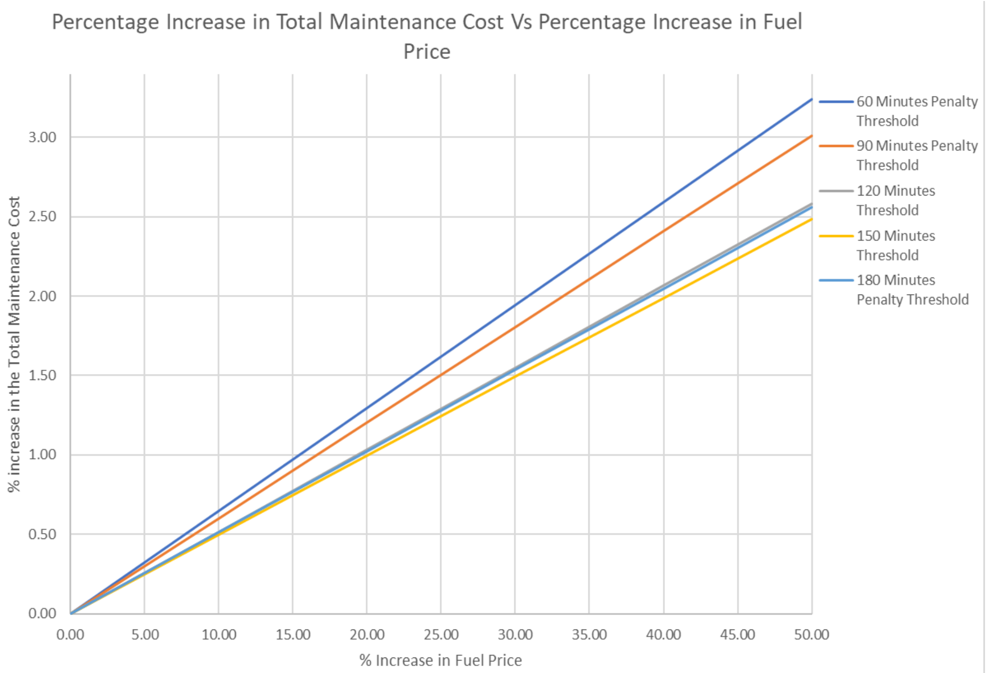

Figure 4.13 Increase in Total Optimal Maintenance cost with an increase in the cost of fuel

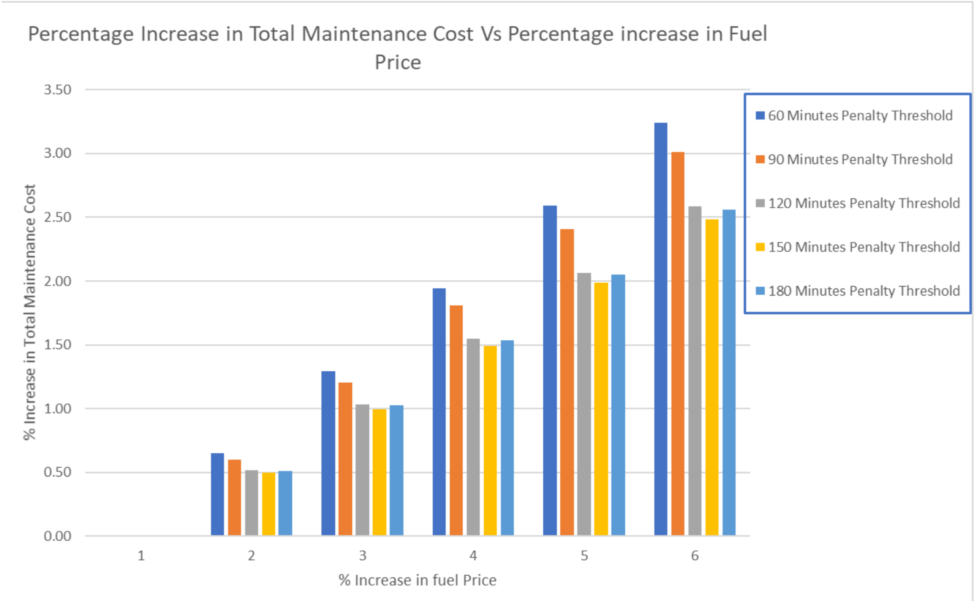

Figure 4.14 Increase in Total Maintenance cost with an increase in the cost of fuel

The 60 minutes penalty threshold is slightly more sensitive to increase in the fuel price. This is because a stricter penalty threshold requires more vehicles to complete the maintenance of the bus stops and therefore uses slightly more fuel than the less strict penalty thresholds. For every 10% increase in the fuel price, the total maintenance cost increases by about 0.5% to 0.65% in respect of the penalty threshold time. The same trend is also true for an increase in the operator cost.

Figure 4.15 below shows the sensitivity of the total maintenance cost with a change in the operator costs.

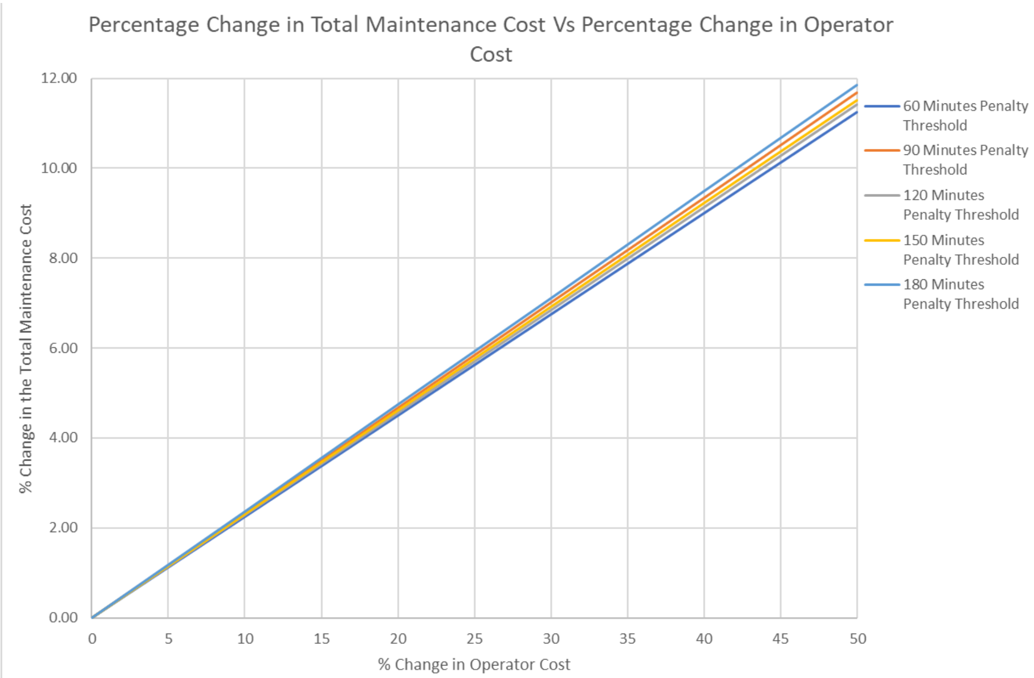

Figure 4.15 Sensitivity of Total Maintenance cost with an increase in the cost of personnel

Figure 4.16 below the increase in the total maintenance cost with an increase in the penalty fee. The sensitivity is based on the penalty minutes for the optimal maintenance cost and can be seen from the indirect maintenance cost in table 4.3.

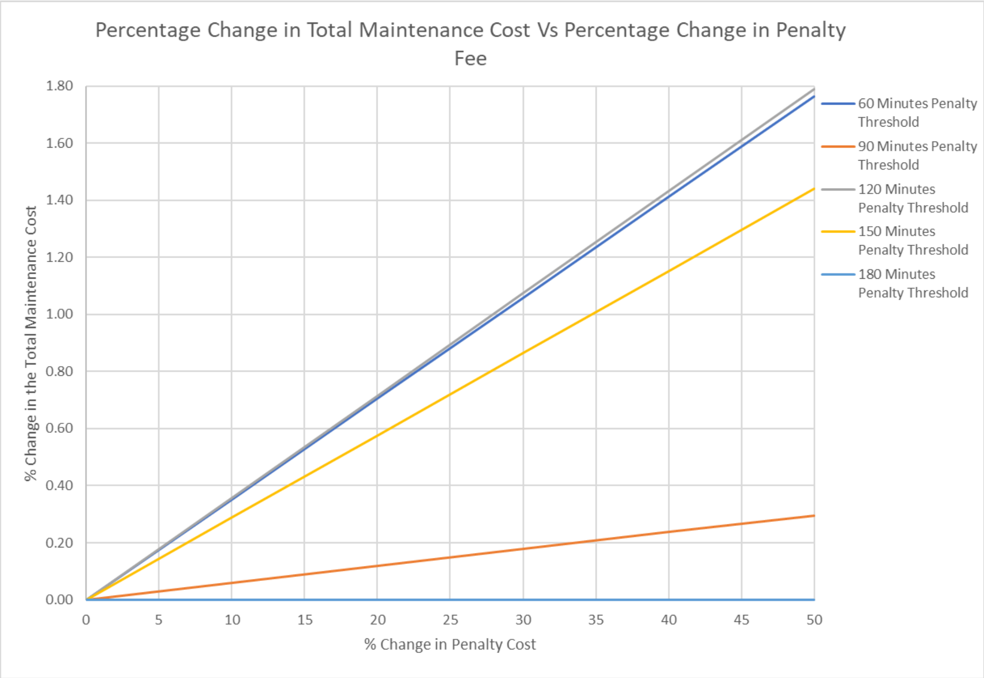

Figure 4.16 Sensitivity of Total Maintenance cost with an increase in the penalty fee

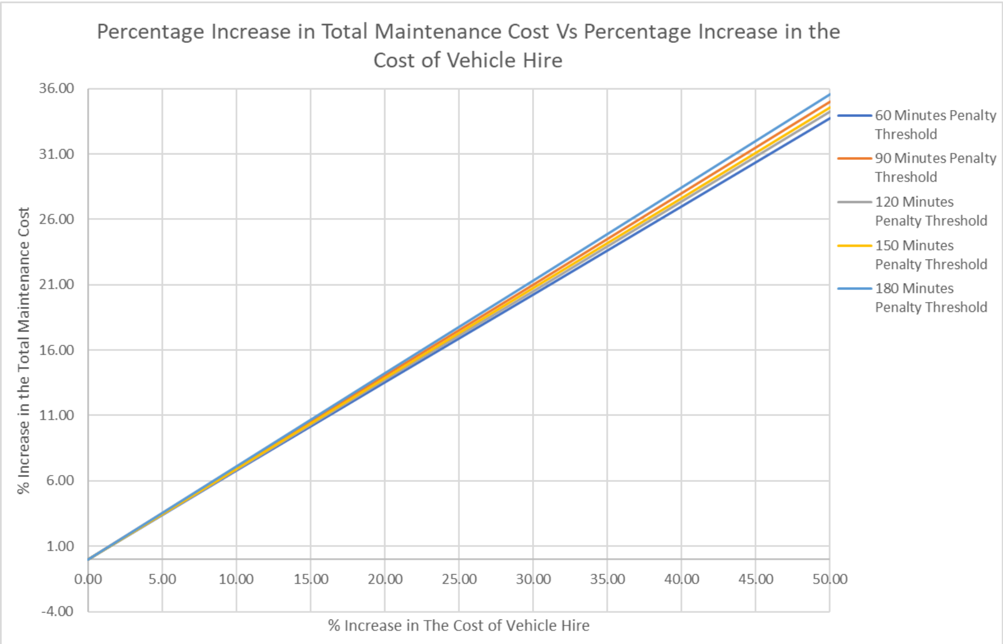

Figure 4.17 Sensitivity of Total Maintenance cost with an increase in the Vehicle hire fee

The sensitivity of the costs was now analysed for each penalty threshold time. The cost of vehicle hire is the most sensitivity as can be seen from figures 4.18 and 4.19 and the penalty fee is the least sensitive.

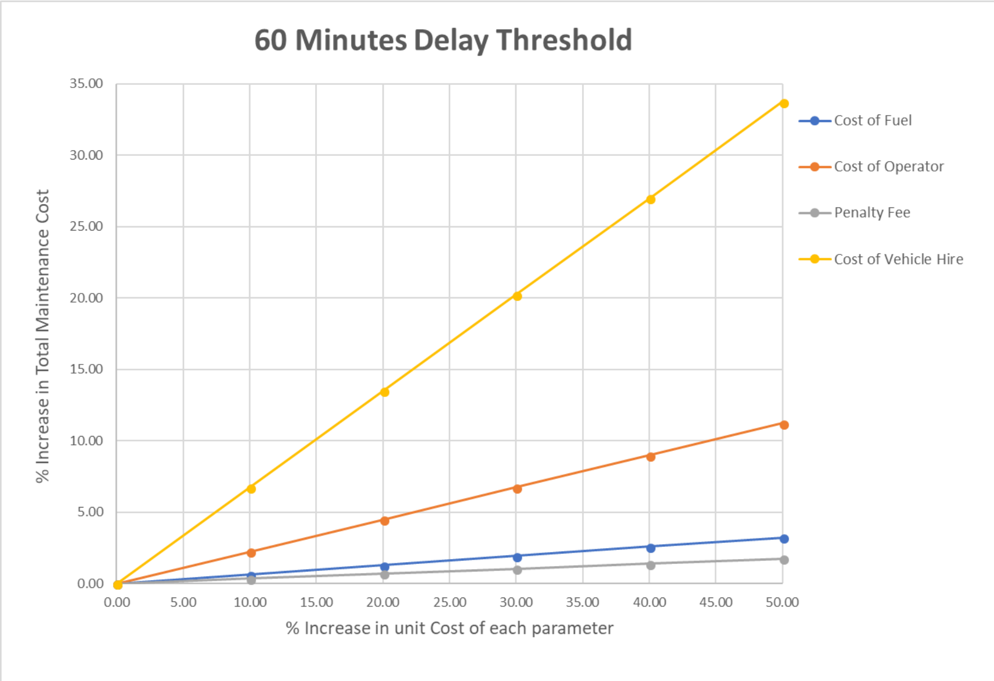

Figure 4.18 Sensitivity of costs for the 60 minutes penalty threshold for each parameter

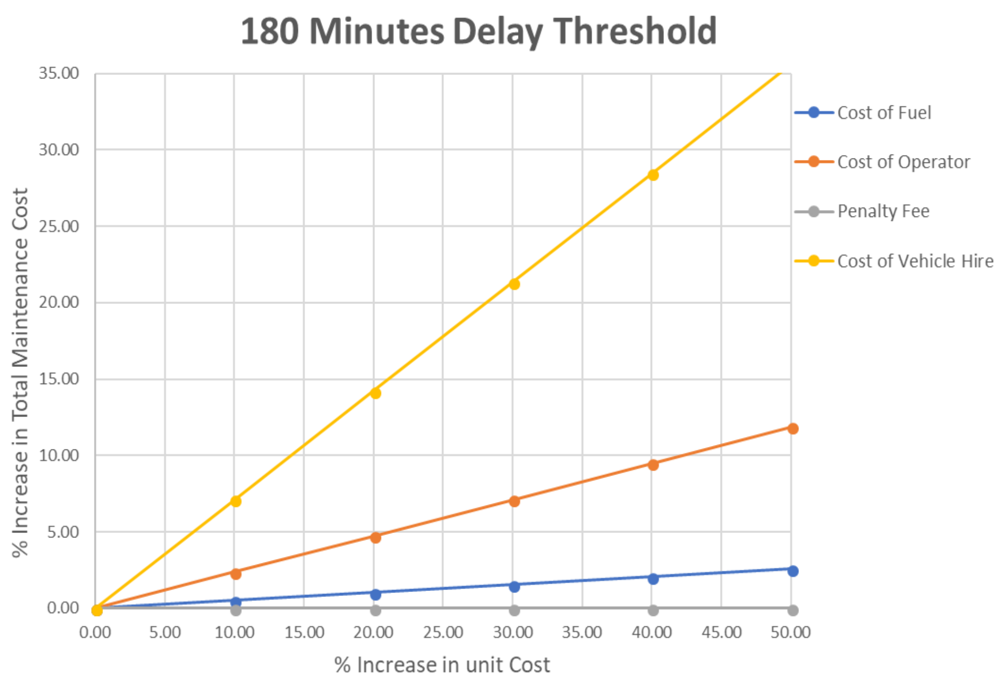

Figure 4.19 Sensitivity of costs for the 180 minutes penalty threshold for each parameter

The cost sensitivity can help maintenance contractor plan for an anticipated increase in the costs and adjust the plan for winter road maintenance accordingly.

4.1. Validation of Results obtained from ArcGIS

To validate the results obtained from ArcGIS, a simple network to calculate the shortest distance from Luleå University to Luleå airport was formulated and solved using TORA and an existing MATLAB code for finding the shortest distance. The results from MATLAB and TORA compared very well with the results obtained using the network analyst in ArcGIS for shortest distance. This result gave confidence that the results of the VRP in ArcGIS were indeed optimal solutions

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

5.1.1. Solutions to Research Questions

The first research question of digital representation of the motor vehicle transport road network of Luleå was solved with the help of a commercial software ArcGIS. It was the most suitable tool because it was also capable of preliminary analysis of the VRP. The shortest routes for the vehicles to plough and sand the bus stops was found for each scenario, i.e. varying the number of vehicles to perform the task and a maximum of 50 vehicles was the last scenario analysed.

The second research question was answered as shown in figure 3.1 which shows the proposed framework to support winter road maintenance. The framework shows that when an alert is received, available resources are optimised by using the best route which gives the shortest travel distance and in turn the least travel time. With the shortest travel distance and the least travel time, the direct cost is minimised while the indirect cost from penalty fees is minimised by the optimal number of vehicles to complete the task with the minimum penalty fee.

VRP was used as the optimisation approach which answers the third research question. VRP is a generalization of the Traveling Salesman Problem whose aim is to find the optimal solution for a fleet of vehicles to service a set of orders or deliveries. VRP was implemented using the network analyst of ArcGIS to determine the optimal routes and the cost optimisation model was developed in excel. The orders in this research project were the bus stops to be sanded and the deliveries was the sand that the vehicle must deliver to the bus stop as the material for sanding. The output of the VRP shows the order in which the bus stops are sanded, the time it will take and the travel distance. The cost optimisation model, on the other hand, determines the optimal total maintenance cost and the required number of vehicles for each penalty threshold time. Figure 4.5 shows the winter road maintenance cost for the 90 and 150 minutes penalty threshold with the optimal cost of SEK 26, 000 and SEK 23, 000 respectively and the required number of vehicles being 7 and 4 respectively.

5.1.2. Sensitivity Analysis

From the results for the optimal total maintenance cost and the optimal number of vehicles for the six penalty threshold times in table 4.2 and figure 4.5, stricter penalty threshold time required more vehicles for the optimal maintenance cost than the less strict one and also had a higher maintenance cost. It was also found that the cost of hiring vehicles took up over 60% of the total optimal maintenance.

The sensitivity analysis shows that if the price of fuel is adjusted, the stricter penalty threshold times are more sensitive to the change in fuel price than the less strict penalty times. This is because the stricter penalty times require more vehicles than the less strict ones and therefore using up more fuel because the more the number of vehicles the longer the cumulative distance as can be seen in figure 4.4. The same is also true for the cost of operators and the cost of hiring a vehicle because an increase in the number of vehicles results in increased cumulative time the vehicles take from the depot and back to the depot after performing a maintenance.

The sensitivity analysis of the direct (Fuel, Personnel, and Vehicle Hire) and indirect (Penalty fees) for each threshold penalty time shows that the cost of vehicle hire is the most sensitive and the penalty fee is the least sensitive as can be seen from figures 4.18, 4.19. 4.20, 4.21 and 4.22.

5.1.3. The significance of the results and the project

The results of this project could support the development of a maintenance plan to enhance vehicle fleet management and facilitate effective work schedules for maintenance personnel. The fuel requirements and other consumables needed for the operation can be reliably estimated and also planned. The results of the latest and earliest arrival time of the vehicles back to the depot could be used to plan for queuing of he the vehicles for quick checks and cleaning after performing a maintenance task.

With the optimal travel route for each vehicle and the total maintenance cost determined, maintenance contractors can determine the sustainability of their business and be able to negotiate for a better and more sustainable agreement (contract) or for the relaxation of the penalty threshold time if it does not affect the service level required i.e. the quality and safety requirements.

The approach used in this model could also be used to plan hauling and disposal of snow in cities. The optimal routes to the sites that require to be cleared of snow from the vehicle depot could be modelled and the routes to the disposal sites and back to the vehicle depot.

5.2. Recommendations for future works

The following future works are recommended:

1. A probabilistic sensitivity analysis of the total maintenance cost using Monte Carlo simulation to model various different situations.
2. A model that will be able to vary the speed of the vehicle considering traffic and the time of the day.
3. In this project, the vehicles were assumed to be able to be resupplied with sand if they run out of sand along their route. A model of the actual capacity of the vehicles is recommended with resupply from specific material depots.
4. Extending the approach used in this project to other winter road maintenance problems
5. Implementation of the results into the WiRMa platform

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APPENDICES

Appendix 1

S/N	Name of Bus Stop	S/N	Name of Bus Stop	S/N	Name of Bus Stop
1	Rutvisrevelen	72	Fallgatan	143	Dragongatan
2	Sundet	73	Mjölkdden centrum2	144	Storstigen
3	Porsö centrum	74	Mjölkudden centrum	145	Örnäset Vårdcentral
4	Professorsvägen	75	Ankarrkronan	146	Örnässkolan
5	Universitetsentren	76	Radiomasten	147	Vinkelgränd
6	Björkskataleden2	77	Tunavallen	148	Skurholmsrondellen
7	Björkskataleden1	78	Tunastigen	149	Kantgaten 1
8	Traktorvägen1	79	Notviksvägen	150	Kantgaten 2
9	Traktorvägen2	80	Görjesvängen	151	Örnnäset Centrum
10	Datavägen	81	Kraftverksvägen	152	Sleipnergatan
11	Vänortsvägen	82	Torpslingan	153	Edeforsgatan
12	Teknikvägen	83	Klintvägen	154	Klyvargatan
13	Luleå Science Park	84	Lingonstigen	155	Germandövägen
14	Kårhusvägen	85	Klintbacken	156	Hällbruksgatan
15	Laboratorievägen	86	Kallkällans äldreboende	157	Kronbacksvägatan
16	Assistentvägen	87	Kanotvägen	158	Bredviken
17	Berget	88	Golfängen2	159	Siktgatan
18	Björsbyvägen	89	Burströmsvägen	160	Fredhemsgatan
19	Ekobyn	90	Burströmska	161	Hagaplan
20	Vallinsväg	91	Rundgatan	162	Gränsgatan
21	Rutviksnäset	92	Höjdgatan	163	Brogatan
22	Brännanvägen	93	Tvärgatan	164	Mulmuddsvägen
23	Flarkenvägen	94	Vithällegatan	165	Lokstallsägen
24	Pernilsavägen	95	Kronan	166	Malmudden
25	Rutviksvägen	96	Regementesvägen	167	Hornsgatan
26	Nordanvägen	97	Volontärgatan	168	Varvet
27	Kammenvägen	98	Värnpliktsgatan	169	Luleå Varvet
28	Framlänningsvägen	99	Luleå Kronanvägen	170	Villavägen
29	Ingridsvägen	100	Bensbyvägen	171	Rudtjärnsvägen
30	Öhemsvägen	101	Golfängen1	172	Granuddsvägen
31	Rådmansvägen	102	Sotargatan	173	Bergnäsets Vårdcentral
32	Rågvagen	103	Bergvikstorget	174	Brantgatan
33	Tingsvägen	104	Sjögatan	175	Trollebergsvägen
34	Storsandsvägen	105	Kalikällan	176	Faktorsvägen
35	Arcushallen	106	Depävägen1	177	Småstigen
36	Disponentvägen	107	Depävägen2	178	Kedjestigen
37	Skolan	108	Notvikens JVG	179	Bergnäskyrkan
38	Karlshäll	109	Sunderby sjukhus	180	Stengatan

39	Karlsviksvägen	110	Kläppenskolevägen	181	Västra Skolgatan
40	Murbruksvägen	111	Kläppenskolan	182	Industrivågen
41	Cementvägen	112	Sunderbyvägen	183	Parkvågen
42	Betongvägen	113	Folkhögskolevägen	184	Nävervägen
43	Storheden	114	Hemängsvägen	185	Bergnäsvägen
44	Gammelstadsrondellen	115	Hektarvägen	186	Bergnäset Bergnässkolan
45	Buttergränd	116	Lagaskiftesvägen	187	Bergässkolan
46	Övägen	117	Nyäkersvägen	188	Bergnäset/Kallax Vägen
47	Rafsarstigen	118	Landbovägen	189	Maskinvägen
48	Tröttergränd	119	Smedjegatan	190	Norrsågsvägen
49	Stadsö centrum	120	Shopping	191	Nordkalotten
50	Möbelvägen	121	Sundsbacken	192	Luleå Airport
51	Öhemmanet	122	Sundsgärden	193	Laxgatan
52	Kockvägen	123	Prästgatan	194	Bältesgatan
53	Sandåkersvägen	124	Jarnvägen	195	Sandgatan
54	Kyrktorget	125	Luleå Mulmuddsviadukten	196	Aronstorpsvägen
55	Storhedsvägen	126	Mulmuddsviadukten	197	Jägarstigen1
56	Banvägen2	127	Småbåtsgatan	198	Jägarstigen2
57	Banvägen1	128	Södra Hamn	199	Hertsö Värdcentral2
58	Spantgatan2	129	Stationgatan	200	Hertsö Värdcentral1
59	Spantgatan	130	Stadshuset	201	Hallonstigen
60	Munkeberg1	131	Länsstyrelsen	202	Hertsö centrum
61	Munkeberg2	132	Residensgatan	203	Hubertusstigen
62	Midgärdssvägen1	133	Trädgårdsgatan	204	Kattgrundsvägen
63	Midgärdssvägen2	134	Norra Hamn	205	Kråkörvägen
64	Kräftgatan	135	Pontusbadet	206	Domherrrgränd
65	Samhall	136	Luleå Sinksundet	207	Blåmesgränd
66	Delfigatan	137	Andreaskyrkan	208	Bäverstigen
67	Kungsgatan	138	Stormvägen	209	Hjortstigen
68	Landstingshuset	139	Blidvägen	210	Mörtgränd
69	Svartövägen	140	Björkskatan centrum	211	Valörvägen
70	Ålgatan	141	Regnvägen	212	Skillingvägen
71	Skutgatan	142	Ormberget	213	Öresvägen

Table 0.1 List of the Bus Stops