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Route modelling for gritting vehicles

A GIS-based approach for the Municipality of Rotterdam

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Msc Thesis

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Summary

The municipality of Rotterdam is responsible for keeping local roads free from snow and ice to keep vehicles and pedestrians safe while travelling. This responsibility is primarily the prevention from roads becoming slippery, whereby specialized vehicles are being used for spreading salt on roadways. The expenditures involved in winter road maintenances are notable and exceed the 3 million Euros for an average winter. To decrease costs the municipality of Rotterdam is looking for the possibility to optimize gritting routes by means of a vehicle routing model. A vehicle routing model determines a set of routes, each performed by a vehicle that starts and ends at its own depot, such that all road segments are serviced. It is possible that these vehicle routing models may outperform own manual drawn routes, which are currently used for routing gritting vehicles. The first stages of digitizing routes and recalculate routing is important in the increasing use of ICT in winter service management.

The main research question of this thesis is: “To what extent can the adaptation of a routing model decrease the driving time of gritting vehicles in the municipality of Rotterdam?”. It must be noted that the main objective is not to endlessly optimize gritting routes, but rather to adopt a routing model within the municipal organisation of Rotterdam. Two contributes are made: (i) to formulate a process for acquiring, cleaning and manipulating network data, which are stored in a network dataset with network capabilities, and can be used as input for modelling gritting routes and (ii) to develop a process for generating, tweaking and adjusting a routing model, using a real network dataset based on driver distances.

A review of routing characteristics in the organisation show that the winter service organisation take care of all gritting responsibilities. The gritting vehicles start from one of two depots in Rotterdam and have to, in poor weather conditions, service all roads subject to gritting in a two-hour time window one the vehicles leave the depot. The two-hour requirement is held even when weather conditions are better. Salt capacity on vehicles is however not seen a constraining factor. In the literature review these characteristics are also indicated to be relevant and additional characteristics are added regarding the road network. That is, that a graph representation of a transportation network with one-way and two-way streets to be serviced and not every road segment traversed may need to be serviced. For the routing problem it is chosen to formulate it as a vehicle routing problem with a time-window. The vehicle routing problem is widely used and integrated within most commercial GIS applications.

A GIS routing model workflow is created with ESRI’s ArcGIS and used to recalculate two gritting routes of the Hoogvliet neighbourhood in Rotterdam. The GIS routing model consisted of thirteen phases. The routing model begins with a process for acquiring, cleaning and manipulation asset management network data, defined in data input and pre-processing stage of the GIS routing model workflow. At the core the routes are formulated using the vehicle routing solver of ArcGIS network analyst, which uses a meta-heuristic tabu search based algorithm. In the post-processing steps the route output is generated and the route reporting and route visualisations are made. The routing output is then generated and tweaked to represent arc traversals of winter service vehicles. In the routing model workflow, a possibility is added that some of the data input and parameters can be changed throughout the process.

To test the model on the gritting routes of Hoogvliet, first the current routing is loaded into the model. The results compared to three scenarios. The first scenario is the new routing scenario. This scenario does not impose any restrictions on any of the two vehicles or the sequence of routing. The algorithm is set to find the most efficient routing based on total vehicle travel time. The result found is that the total travel time increased by 5.4% in comparison to the current routing. The sectoring scenario creates a categorisation of service roads based on administrative districting to create more compact routing.

The model run had an increase of total vehicle travel time of 8.4%. The last scenario is the node reduction scenario, in which nodes are reduced between two gritting route junctions to reduce complexity. The node reduction scenario did outperform the current gritting routes by 5.3% but did leave some arcs ungritted and unconnected inside the routing.

The results shed light on the use of current GIS infrastructure to help in adopting a routing model for gritting vehicles. Although the routing model can be used to decrease driving time, it was tested at only two gritting roads in Hoogvliet. For implementation the routing calculations have to scale to 30 main gritting routes. To implement some issues remain on both technical and organisational issues. The algorithm is not specially designed for large arc routing problems and has poor performance both in speed & accuracy. Districting is necessary to account for these issues. Furthermore, the network dataset cannot be simplified to reduce model solving complexity. From an organisation perspective, routing is labour intensive and quite specific. If one wants to proceed in recalculate the routing just once, one may want to consider these points before adopting a GIS routing model within the organisation.

This thesis therefore makes four recommendations for adapting gritting routing within the municipality of Rotterdam. The first recommendation is to obtain or outsource the GIS software which is used to solve the formulated gritting routing problem. The current software which is available is not sufficient for solving large gritting routing problems. Secondly, it insists on the important notion that the routing must be closely created with the help of the winter service organisation. Route creation is an iterative process which require devoted attention by users. Thirdly, create a storage model for winter service asset management data and lastly make sure that the route creation is embedded in the organisation to ensure a sustainable routing solution.

Acknowledgements

This thesis is the final project of my master Geographical Information Management & Applications (GIMA). For my final thesis I wanted to tackle a problem which touched both the managerial side of geoinformation management, as well as the more technical side by using GIS applications. With the help of my internship position at the municipality of Rotterdam I found a topic in vehicle route modelling which satisfied both criteria. Being able to write my master thesis within the geo advisory team of the municipality greatly helped in finding both theoretical and practical gratification in completing my master thesis.

At first, I would like to thank my colleagues from the municipality of Rotterdam for their enthusiasm. A special thanks to Rob Poll- van Dasselaar, who introduced me within the municipality and Christian Veldhuis, who was a great support to me with his practical view on the organisational side of the project. Also, I would like to thank Willem Bouwmeester for our meetings regarding the WINTER project and his invitation to join the yearly test round for the staff routing for the upcoming winter.

Of course, thanks to my friends and family which were of great support. A special notification to my dad for his support and to Sietske Tjalma for proofreading my thesis.

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1. Introduction

1.1 Introduction

Ever since the establishment of public snow removal services in the late 19th century, local governments are dealing with the removal of snow and ice from urban roadways to keep vehicles and pedestrians safe while travelling (Campbell & Langevin, 2000: p. 390). In those days man and horse-powered vehicles were used to clear snow by putting it in their charts and dumping it in city rivers, lakes and sewer system. Later on, automobiles and trucks were increasingly used as they gained more prominence as a mode of transportation (Campbell & Langevin, 2000: p. 390). Today, municipalities in the Netherlands are still imposed with the task of keeping local roads and highways ramps accessible in winter. This responsibility is primarily the prevention from roads becoming slippery, whereby specialized vehicles are being used for spreading salt on roadways (Perrier et al., 2010).

The expenditures involved in winter road maintenances are notable. Whereas it is only necessary to sprinkle salt a few times, infrastructural components like depots for vehicle and salt storage must be available throughout the year (Gerlagh, 1998). Furthermore, equipment like gritting vehicles and sprinkling systems are bought or rented. Together with employing personnel and fuel/salt usage, this leads to significant costs (Gerlagh, 1998). And on top indirect costs, like environmental degradation, economic losses and mobility reductions are posed upon society (Perrier et al., 2010; O'Keefe & Shi, 2006). These indirect costs are thought to be several times larger than the direct costs involved (Nixon, 2009).

Municipalities are increasingly looking for ways to efficiently organise their salt spreading operations to save resources and minimize the environmental impact (Gerlagh, 1998; Perrier et al., 2010). A key theme in this field are the so-called 'vehicle routing models' (Perrier et al., 2007). A vehicle routing model consists of determining a set of routes, each performed by a vehicle that starts and ends at its own depot, such that all road segments are serviced, all the operational constraints are satisfied and the global costs are minimized (Perrier et al., 2007: p.215). Global costs for salt spreading are translated into objectives, such as minimize fleet size and a decrease of truck mileages (Xie et al., 2013; Perrier et al., 2007). However, the fleet size cannot be endlessly minimized due to basic operational constraints, including factors such as time windows, service levels and routing conditions.

Whereby vehicle routing models focus on operational context such as minimizing fleet size and operation time of the current routing, there are also winter decision-making processes which are more or less linked to the routing of trucks (Hajibabai & Ouyang, 2016; Jang et al., 2010; Noble et al., 2006). The latter include both strategical decisions (i.e. depot location) and tactical decisions (i.e. sector design). Depot location is needed to know how many depots are needed and where to place them within the network. The sector design indicates which roadways must be serviced and which ones are not. Evaluating strategic, tactical and operational decision-making processes in an integrated way enables an even more refined route assessment (Jang et al., 2010; Noble et al., 2006).

While the potential of vehicle routing is considerable, most municipalities still rely on hand-drafted maps based on field expertise instead to determine driving routes (Dowds, Novak & Scott, 2016; Hajibabai, 2014; Campbell & Langevin, 2000). The lack of implementing models could well be primarily due to the complexity of the operational environment (Bingham, 2008; Perrier et al., 2010). Differences in geographic location, weather conditions, legislatives, technological advancement and traffic regulations make it hard to adopt a generic approach (Perrier et al., 2010). Besides unique characterisations of the organisation comes into play. Local politicians may have a different view on strategic depot location decisions, fleet designing and deciding on operational constraints (Perrier et al., 2010). Decision-making for route optimization is thus a vigilant process which has to reckon with numerous and specific circumstances of both operation and organisation (Perrier et al., 2007).

To foster decision-making, the transportation sector is increasingly looking to Geographic Information Systems (GIS) for route optimization (Kuby et al., 2005; Fischer, 2004). GIS seems a promising technology which can overcome this ill-fit between the modelling of vehicle routing problem and its application for real-world problems (Keenan, 2008: p.202). Its strength is the possibility to create vehicle routing models and combine this with the ability to tweak settings and adjust routing outcomes manually. Facilitating this interaction between models and the skilled user can result in an effective decision support system (Keenan, 2008), but only if this fits the specifics of both the operational and organisational environment.

The aim of this thesis is therefore set to close the implementation gap of adopting a gritting routing model for Dutch local governments to decrease driving time. To contribute to this issue, this thesis aspires to develop a routing model for Rotterdam with the use of a GIS.

1.2 Problem statement

With around 640.000 inhabitants Rotterdam is the second largest municipality of the Netherlands (Municipality of Rotterdam, 2018). The municipality has 990 kilometres of roadways and 630 kilometres of bike lanes which are subject to gritting in winter times. These are divided into and serviced by 72 gritting routes (Municipality of Rotterdam, 2014). The winter maintenance division of the municipality of Rotterdam is responsible for the adequate handling of anti-slippery measurements during winter time. The executive team of this division consists of approximately 320 coordinators and members being standby 24/7 from November 1st till April 1st. As for the winter maintenance, for an average winter the operational costs exceed three million euros (Municipality of Rotterdam, 2014).

To guide the routing process of gritting vehicles hand-drawn maps are used, which are updated once a year mainly according to driver feedback and planned road maintenances. The latest origin of the map routes is dated to 1970 to be the latest. From therefore onwards, new city routes have been added to the existing gritting routes as well as new ones were developed. While the routes work fine in practice, the winter team is increasingly aware of the possibilities of ICT technologies within the sector to make the work process more professional and efficient.

During October 2016, the municipality of Rotterdam launched the project 'WINTER' to accompany this process of adding ICT applications to their gritting vehicles. Four main goals were formulated for the use of ICT applications, to achieve (i) an increase in the level of employer safety and other road users by adopting route guidance, (ii) more sustainable use of salt and less vehicle miles, (iii) a reduction of costs by decreasing man-hours while upholding the high service level and (iv) a diminished the pool of reserve drivers to decrease costs. To obtain these goals the deliverables of this project are partitioned into phases, from the digitalization of routes to the logging of the actual salt spread on roadways (table **1.1**).

Table **1.1** Phasing project WINTER

Phase	**Deliverables**
Phase 1	Digital availability of roadways and bike lanes which are subject to spreading
Phase 2	Digital distillation of optimal routing for salt spreading
Phase 3	Making the routing visible in the cabin of the gritting vehicles
Phase 4	Salt spreading equipment is integrated with the routing software and visible in the cabin
Phase 5	Routes are digitally logged and retrievable
Phase 6	Insight into salt usage per route

Within the municipality of Rotterdam the GIS advisory team is looked at to enable the project of coming up with solutions to recalculate routing. The focus here is on the first two phases: digital availability of roadways and bike lanes and the digital distillation of optimal routing. These deliverables are essential and used as input for the upcoming phases of the WINTER project.

1.3 Research relevance

The modelling of gritting routes and the underlying routing models are quite familiar and have been well researched (see for overview studies Mourão & Pinto, 2017; Perrier et al., 2006a; Golden & Wong, 1995). However, research did mostly address the formulation of mathematical models and appropriate heuristics for route optimization. What is researched to a lesser degree is how these models can be effectively applied within GIS systems and organisations. The publications on the development of GIS models (e.g. Keenan, 2001; Hajibabai, 2014; Krichen et al., 2014) did not share their models publicly and are not tailored to the specifics of routing problems (i.e. adding time windows). Therefore, these research outcomes have limited practical usage in this formulated problem. Instead, a routing workflow developed is built on top of commercially available routing models in GIS software, making it possible that the gathered data of asset management within GIS software can be used as input for routing solutions. It furthermore uses network data to formulate and evaluate routing outcomes. something that drastically increases practical applicability. Research of route optimization of gritting vehicles of the American Departments Of Transportation make little use of commercially available software, but rely on hand made routes or external route agencies instead (Dowds, Novak & Scott, 2016). Developing a Dutch GIS framework for handling asset management data and develop routing solutions can help municipalities and other affiliated parties in developing automated routing solutions within the organisation. And in doing so, provide organisation effective routing tools for the planning of gritting routes.

1.4 Research objectives

The research objectives are divided into theoretical, empirical and practical objectives. These objectives are used as a guideline for drafting the research questions. The theoretical objectives are for exploring the underpinning concepts and literature, as well to help structure the concepts into an integral framework. The empirical objectives give direction for the data collection, processing and analyses. The practical objectives are merely used to implement the results.

The first theoretical objective is to establish a knowledgebase about routing models and how these models can be used to decrease the driving time of gritting vehicles. This knowledgebase is twofold. First it describes the process from an organisational perspective. This concerns the current workflow of the winter service operations, as well as the different routing model requirements from the winter management team. The second theoretical objective is to link both the organisational and theoretical findings into a coherent framework, which can be used for designing the routing model.

The empirical objective is providing a GIS routing workflow which enables to decrease driving times of gritting vehicles within the operational and organisational environment. The model should be further explored and validated to ensure a correct translation of situational characteristics.

The practical objective is to advise on routing possibilities which decrease driving distances. Lastly, the procedure for calculating routing should be replicable within the organisation, in case when a revision is needed due to new roadway construction or organisational changes.

1.5 Research questions

After defining the objectives of this study the following main research question has been formulated:

To what extent can the adaptation of a routing model decrease the driving time of gritting vehicles in the municipality of Rotterdam?

The main question contains two main concepts: routing model and driving time. As explained in the introduction the routing model is taken in an integral way. Not only will the routing be optimized within a GIS, but also factors like depot location and sector design will be incorporated into the routing model. This holistic approach to a, what often seems, a narrow scope of route reconfiguration allows managers to make a more sophisticated strategic and tactical decision-making. Driving time is here defined as the total sum of driving minutes of gritting vehicles. This goal is first and foremost reached by reducing dead mileage/minutes, i.e. vehicles that drive on roads which have already been serviced. Subsequently, other relevant factors will be manipulated in order to find a balance between decreasing driving time and other relevant factors, like the compactness of routes.

To answer the main research question, five sub questions have been composed. The first sub question is designed to describe the current situation, whereby the next four sub questions are postulated based on the framework of Mitroff et al. (1974) on how to perform operational research based on quantitative modelling. The framework consists of four stages: conceptualisation, modelling, model solving and implementation. Each sub question respectively addresses one stage from the adopted framework.

1 <u>How is the current gritting of roads organised?</u>

First, a key objective is to get an understanding of the winter road maintenance organisation. What is the organisational structure of the winter gritting program and what is the decision-making process. Also, the current problems are described which can be used as input to elaborate on the system requirements for new routing.

2 <u>Which characteristics are considered relevant for modelling gritting routes?</u>

The second question deals with the conceptualisation for model routing. Which characteristics are used in routing models and which ones are considered relevant? Subsequently, different routing models and algorithmic solutions are examined which together construct the conceptual model.

3 <u>How can these characteristics be incorporated into a routing model?</u>

To answer this question a routing model workflow is developed which is capable to calculate routing based on the requirements which are set in the previous section.

4 <u>How does the routing model perform regarding the decrease of driving time?</u>

In question four the central theme is the performance of the model. This performance will be scenario based, in which each scenario reflects a strategic, tactical or operational decision. These scenarios are developed in close cooperation with the winter maintenance decision making team.

5 <u>To what extent can the GIS routing model be implemented within the organisation?</u>

This question gives an outlook to the implementation of outcome of the routing model and the different scenarios. To what extent can the results be used for reorganising gritting routes and what are the perceived effects of this reorganisation?

1.6 Research scope

The research scope is to delimitate certain aspects related to the object of study. The object of study is stated in the main- and sub research questions, this will be examined. The following topics will not be examined:

- This research only looks at salt spreading operations for winter service vehicles. Other operations snow hauling and manual labour are not considered. This does not imply that these operations are not performed within municipalities. During heavy snowfall these additional measures may take place but are outside the research scope.
- Furthermore, this research will not propose new algorithms and/or (meta)heuristics for solving this routing problem, as it relies on current computational practices. This research also does not conduct a benchmark for algorithmic solutions, nor is it a quest for the most optimal pathfinding. The objective is rather to translate the operational and organizational context into a model which enables the municipality with more efficient routing.
- This research is performed within the context of GIMA and the municipality of Rotterdam. A possible software solution will be within the limits of these organizations, respectively online available freeware. As a result, this software will more likely rely on a GIS infrastructure, rather than a mathematical software package.
- This research is conducted within the larger 'WINTER' project. Currently, the municipality is also looking for cooperation with external parties to enable the transition of ICT within the winter maintenance operations. These external parties deliver software modules and onboard sensors which automatically adjust the salt level of salt spreaders for weather conditions. Therefore, the thesis is not concerned with adopting real-time weather information sources within the routing model.

1.7 Contributions

The main contribution of this thesis is the development of a routing model in a GIS, including:

- A process for acquiring, cleaning and manipulating network data, which are stored in a network dataset with network capabilities, and can be used as input for modelling winter gritting.
- A process for generating, tweaking and adjusting a routing model, using a real network dataset based on driver distances.

The routing model will be tested in a real-life case of the municipality of Rotterdam. This ensures the fit of the model within the local context of a large-sized Dutch city.

1.8 Thesis report structure

The following chapters are structured as follows. Chapter 2 discusses the organisational framework within the municipality of Rotterdam. Chapter 3 provides a literature review about the salt spreading problem, different routing models and the implementation of these models within a GIS. At the end of the literature review the vehicle routing is synthesized in a conceptual model. The architecture of the routing model is presented in chapter 4. Chapter 5 analyses the results of the routing model, whereas chapter 6 discusses the possible implementation of the created model and suggests directions for further research. Chapter 7 contains the conclusion and provides policy recommendations.

2. The winter service section

This chapter provides an overview of the organisational management of gritting within the municipality of Rotterdam. The introduction included two prepositioned explanations for the lack of implementing a routing model: the operational environment (such as differences in geographic location, weather conditions, legislatives, technological advancement and traffic regulations) and the organisational environment with respect to decision-making. Both operational and organisational environment will be explored and serves as a foundation for the development of a routing model which fits and fulfils the needs of the municipality.

The chapter informs about the decision-making structure within the winter service section (section **2.1**). It is argued that the winter section can be represented as an organisation comparable to a Greek temple structure, with two pillars and a roof. The two pillars represent the departments of the winter service organisation and the road authority. To refine this model, both departments are separately dealt with in section **2.2** and **2.3**. Subsequently, the activities of both parties congregate in the determination of the gritting routes (section **2.4**). Within this section, both criteria for routing as well as updating are examined. In section **2.5** the roof of the temple is examined, in order to redefine the structure of determining gritting routes with the use of ICT. The chapter ends with concluding remarks in section **2.6**.

2.1 Winter road maintenance decision-making

System design in winter road maintenance is a complex process of decision-making. Several departments are responsible for different activities which interact with each other, sometimes even on different levels. To enable these organisational structures within the decision-making process, these have to be structured. The organisation within the winter service section will be enfolded using two components: the management planning level and management decision problem structure.

Management planning level

Decision-making problems occur at a variety of management planning levels. Keenan (2001) and Perrier et al. (2010) structure decision making at three levels: strategic, tactical and operational.

> The strategic level in an organization defines the strategy, or direction, and decision-making process on the acquisition and allocation of its resources which last over a long time period (Perrier et al., 2007). This time span can range over an extended period of time, even years.
>
> The tactical level emphases on medium-term and short-term decisions which are reviewed once every few months (Perrier et al., 2007). For salt spreading, activities on this particular level usually take place just after the winter season ended and when tactical preparations take place for the next season.
>
> The operational level points at controlling activities on a day-to-day basis, like the assignment of staff to routes (Keenan, 2001; Perrier et al., 2010). The operational level also deals with operational risks, like sudden break-downs of equipment or change is weather forecast and requires an adequate response within a time interval of minutes. Real-time management is also considered to fall within this category (Perrier et al., 2010).

Management decision problems

The winter road maintenance falls within the category of logistical problems and operational research. In classical logistics functions, four groups have been identified (Gutiérrez & Vidal, 2013):

Network design deals with the management of the transportation network and the sectoring of roadways into districts. The location of depots is also considered to be part of this area of network design (facility location problem).

Transportation management reflects transportation equipment, i.e. the need for specialized vehicles and equipment. The assignment of these vehicles to different parts of the transportation network fall within the responsibility of transportation management.

Staff management deals with human resources. This concerns both drivers of winter gritting vehicles, as well as management and controlling personnel.

Inventory control manages the stockpile and ensures it never will be empty. Primarily this implies both salt storage and replenishment. Both selections of suppliers and inventory policies are part of this inventory control.

While decisions take place at different planning levels and management decision problems, these categories must not be looked at as deterministic, but rather as complementary categories (Perrier et al., 2006). Problems may be addressed at different levels; fleet assignment can be seen as a tactical decision, usually updated every winter season. However, in case of heavy snowfall readjustments can be required monthly, and therefore be considered to the operational level.

There are numerous ways to incorporate decision making into an organisation. Traditionally each of the management decisions problems (i.e staffing) is strictly managed on different layers. Not the decision problem, but the duration and impact of a decision determines which body is responsible for the decision making. This corporate structure is denoted by a pyramid shaped model (figure **2.1**). The pyramid symbolized the strategic level from the top all the way to the operational level on the bottom. While pyramid structures are successfully implemented in hierarchal organisations, coordination may be difficult between levels. As an example, if the network design adds new roadways without sufficient communication this affects the strategic location of the depot and may lead to an overuse and drawback in resources (Gutiérrez & Vidal, 2013).

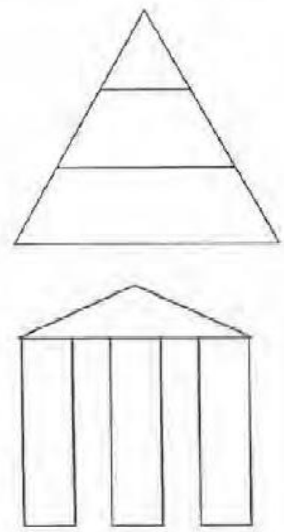

Figure **2.1** The Pyramid and Greek temple; used to structure management levels.

Instead, a more optimal model to organise resources could be a Greek temple structure. For this pillar structure many of the management decisions problems are taken within departments (pillars). Only at the strategic level, so at the top of the roof, different departments communicate (figure **2.1**).

The winter service section in Rotterdam has a tendency to follow the Greek temple structure. The core of this is located at the city management cluster (called: *stadsbeheer*). All tasks of transportation management, staff management and inventory control take place at this level. But network design falls within the responsibility of the road authority, being located within the cluster of city development (called: *stadsontwikkeling*). The roof of the temple represents the strategic collaborations between the different departments. For determining better routing, one could argue that the WINTER project team (as introduced in section **1.2**) symbolizes the roof of the temple. Within WINTER members from various departments communicate to detect IT-driven solutions, amongst them optimized routing. Before the strategy will be deployed, the winter service organisation is introduced.

2.2 The winter service organisation

In the Netherlands three levels of organisational bodies exist: national, provincial and local governmental bodies. For the local body of Rotterdam the winter service management is published in the gritting policy plan (*Beleidsplan Gladheidsbestrijding 2015-2020*). These have been approved by both the mayor and municipal executives and act as a guideline for further policy implementation. The daily operations are explained in the implementation plan (*Uitvoeringsplan Gladheidsbestrijding*).

The gritting team uses two main depot facilities, Giessenweg and Laagjes (term used to denounce the second depot at Karnisseland). Last summer, the Giessenweg depot has been renewed. The third depot at Hoogvliet is still closed for service during the upcoming year. All vehicles are scheduled to depart and arrive from the remaining two depots. Both Giessenweg and Laagjes depots are not scheduled to gritting only but are used for activities as vehicle storage for leaf sweepers as well.

The core team is constituted of four separate teams, existing of 91 employees each. They can be called 24/7 during the annual period of November 1st till April 1st (figure **2.2**). These four teams work in shifts which alternate weekly are composed of 82 drivers, each assigned to predefined routes. It also includes eight executive winter coordinators, responsible for mobilising and leading the driver staff from the depots. The core team is led by a central coordinator. The central coordinator makes the final decision when salt spreading is needed, in which area and which quantity. And on top, the Executive Manager is assigned during the whole season of leading all four teams and ensures that all facilities are available and manages training to personnel. These consist of schedules, vehicles, training, communicates i.e. Most of the employees have different tasks for their city, e.g. in the areas of cleaning waste collection and management included, which fits in the seasonal character and dynamic nature of existing jobs at hand.

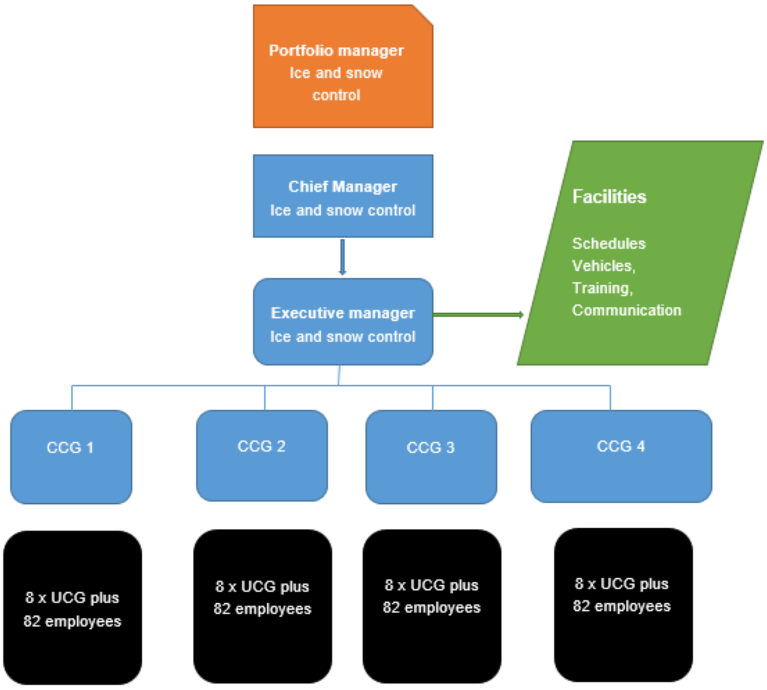

Figure **2.2** Organizational chart ice and snow control. On top the portfolio manager of the snow and ice control (orange), n blue the middle management of control functions and in black the operational forces of winter gritting vehicle drivers.

Due to the seasonal and dynamic nature of the job, the teams are not working 24/7. In a season there are usually a few turnouts per team. At the beginning of the day, between 12:00-13:00, the central coordinator sends out a message containing the 24-hour weather forecast. This forecast contains a colour code, ranging from green (all OK) to red (switching to 12 hours driving service). This code indicates fairly if teams can be called upon during an upcoming period of time.

Before the actual decision is taken to start spreading, different measurements took place. Rotterdam owns several measure stations, placed across the city and measuring different types of pavement (i.e. bridges, roadways, bike lanes, as well as some stations of surrounding municipalities). They are in close contact with Meteoconsult, which provides Rotterdam with weather information, delivered via an online platform. Based on these measurements, own experience and direct contact with a consultant from Meteoconsult, the decision whether to start spreading - or not - is made. When spreading is needed, the following sequence of actions take place (Municipality of Rotterdam, 2013: p.7):

- **Commanding**. The central winter service coordinator makes the decision on which moment what gritting program will be activated. Choice is between only gritting critical infrastructure or a complete regular routing procedure (section **2.4** will supply more details about different programs and determination of routes). This choice is affected by the current weather situation and weather forecasts. Different programs mean different routing which are enabled, level of salt usage and use of extra equipment (i.e. shovels for snow ploughing). Instructions are communicated towards both executive winter coordinators and external contractors. Actions are logged within the internal system.
- **Command processing**. The executive winter coordinators mobilise all personnel, subject to driving, and instruct them on salt usage and possible use of extra equipment.
- **Route driving**. Within one hour after commands went out, gritting begins. Drivers are riding the predetermined routes, based on instructions given. Furthermore, the driver notes down both the correct starting and finish times of the entire route as well as potential liabilities.
- **Route control**. The executive winter coordinators does control both time and liability input from all drivers. If defects occur to vehicles there will be taken notice of and implemented into the central system. Only thereafter the coordinator delivers administration forms.
- **Informing**. Next, executive winter coordinators inform the central coordinator about the gritting process. The central coordinator at his turn checks the available area of salt and logs this into the systems.
- **Logging**. The executive manager of the 'snow and ice program' checks the logging and makes sure that the level of salt remains at a necessary and strategic level. If needed, he himself makes the call to have the salt delivered.

This procedure is fixed, except when heavy snowfall occurs. When this happens, the team transits into a 12-hour service. This implies that two teams instead of one will drive the gritting routes, using rotating drivers. This process will continue until all roads are accessible and thus safe enough for traffic. This procedure is quite intense, partly due to restrictions on working hours and consecutive working days, in the Netherlands arranged in the working safety law (*arbeidsomstandighedenwet*). It also intervenes heavily with primary jobs of most employees. Winter gritting always has priority, meaning that other all other activities fall behind.

Next to the gritting teams, a key role is reserved for the road authority. This authority is responsible to provide the winter service organisation with adequate routing instructions. The next section describes this particular role.

2.3 The road authority

The municipality of Rotterdam embodies the road authority and is thus responsible for maintaining the local road network in an adequate way, according to Article 15 of the Dutch Road Law (*Wegenwet*). If this party fails to comply with the responsibility and damages occur, with respect to the road user, the road authority can be hold accountable. The possible liability for accidents due to substances on the road, amongst them sand and oil, but also snow, frost and ice has to be assessed finally and is based on Article 6:162 of the Dutch Civil Code (*Burgelijk Wetboek*).

In this liability claim a key point is till which degree the road authority is to blame for the actual situation. In principium the burden of proof is on the side of the plaintiff. However, due to the predictability of roads- icing the road authority should be able to proof that structural measures have been taken place to control complete road management. The municipality of Rotterdam takes the following actions to avoid liability claims, including (Municipality of Rotterdam, 2015: pp. 9-10):

- ➔ To establish a management- and execution plan for gritting, including a detailed presentation of routes and corresponding priority. This priority setting is based on hazardous analyses and previous complains which have been recorded in a ‘’complaint registration system’’.
- ➔ To keep administration of the times when gritting was executed and all actions as of a result of notifications of any kind.
- ➔ To control the effectiveness of gritting actions and to log all problems.
- ➔ To communicate to citizens (and other parties, red) about gritting management and what the citizens can expect from the municipality.

To maintain the entire road network the following actions are taken in diverse areas of snow removal. These actions will be discussed separately in terms of time management, preventive spreading and salt usage. Although the winter service organisation is advising on some of these measures as well, they ultimately fall within the responsibility of the road authority.

Time management
The most important rule which the road authority must follow is that all roads are subject to a time window in which the roads have to be gritted. This time window differs for the various types of roads (table **2.1**). The municipality agreed upon a time schedule of 2 hours which is in line with the national standard (Municipality of Rotterdam, 2013). Those timeframes are based on the so called ‘gritting times’ and taken from the moment the vehicle leaves the depot till the last square meters of the roads are actually sprinkled, and not when the command is being made by the central winter service coordinator.

Table **2.1** Time window gritting routes

Motorways	Max 1½ hours
Provincial roads	Max 1½ hours
Municipal main roads	**Max 2 hours**

(source: Municipality of Rotterdam, 2013: p.7)

The time windows are primarily meant for curative actions. Curative actions do take place when the roads are already subject to snow/ice. Preventive actions, on the other hand, are used to sprinkle salt on ‘’clear’ roads, based on the prediction that slipperiness will occur in the near future. With preventive actions it is possible to have more flexibility. However, in practice the municipality chooses to respect the time window for both curative and preventive actions. This is done because Rotterdam is an urbanized area (Municipality of Rotterdam, 2013: p.5) and to minimize risk due to vehicle/route switching within different scenarios. Experience learns that due to the constant switching scenarios (routing is available on paper map only) mistakes can be made easily. Small mistakes in gritting roads might lead to traffic jams and more importantly, create possible unsafe situations.

The fact that there are time windows for curative actions, does not mean that in every case everything is gritted within the two hour time period. In some cases a small violation of the two hour mark may save a vast share in the total routing time, or even make it possible to make cuts in the number of vehicles needed. Also, vehicles may get stuck in traffic jams. This is primarily the case when the gritting is used as a curative measure. Nowadays more and more municipalities try to avoid curative measures and actively steer to preventive spreading.

Preventive spreading

In the nota mobility of the ministry of traffic and water (*Verkeer en Waterstaat*) an integral vision is given for the accessibility, safety and flow of traffic until 2020. Within this vision the prevention of slipperiness, where is possible, has preference above curative spreading. The municipality embraces this vision (Municipality of Rotterdam, 2013: p.4). Of course, curative measures are taken when this is necessary.

Preventive spreading has a few advantages against curative spreading: (i) slippery roads are avoided, (ii) spreading can be done at a better time benefiting both the duration time (less traffic) and to make sure that the other daily activities of the workers can continue and (iii) less time pressure. The disadvantage is that it can happen that a preventive spreading has taken place which, in hindsight, was not needed (Municipality of Rotterdam, 2015: p.11).

Salt usage

Two different types of salt exist: dry and wet. The municipality is using wet salt already during a few years. Wet salt is a combination of a type of salt (in this case rock salt is used) with an additional 80% water (Municipality of Rotterdam, 2015: p.11). The advantage is that less salt is needed to achieve the same effect and thus cheaper. On top the wet substance binds better to the road surface, resulting due which it is less likely cars will redistribute the sprinkles elsewhere onto the road or into the road bank. A last advantage can be found in environmental protection; less salt is better for the environment, as it will distribute less into road banks and therefore damages less habitat and flora. The quantity of salt used per situation may vary (table **2.2**). Most common is the use of seven grams per square meter to salt. Not only the amount of salt is controlled, but also the width of spreading, which is currently done manually by the driver.

Table **2.2** Amount of salt used

Preventive	Wet	7 gram/m^2
Preventive	Dry	10 gram/m^2
Curative	Wet	10 gram/m^2
Curative	Dry	15 gram/m^2
Curative	Snow	20-30 gram/m^2

(source: Municipality of Rotterdam, 2013: p.7)

The introduction of wet salt decreased the total amount of salt used. Together with the previous discussed time window of two hours after leaving the depot, it nowadays rarely happens that a vehicle is running out of salt in service (Gerlagh, 1998).

2.4 Determining gritting routes

The municipality of Rotterdam has a total of 72 different routes throughout the entire city of Rotterdam. These routes are created and adjusted by the road authority and winter service organization, with the help of cartographers from the in-house GIS advisory team. For online publishment see the Rotterdam GISweb portal (*http://www.gis.rotterdam.nl/gisweb2/default.aspx*). The user can select both bike lanes, main motorways routes and corresponding vehicle which is subject to spreading.

All routes are subdivided into 2 categories and 3 subcategories. Firstly, a distinction is made between motorways (30 routes) and bike lanes (42 routes). Due to the vehicle width, different vehicles routes are needed. For motorways, another subdivision can be made between access routes and other main motorway routes. When Rijkswaterstaat and/or the official ''Province of Southern Holland'' decide to a preventive salt spread action, the central coordinator will be informed. Consultation with the meteorologist ends with the decision whether all routes are included, or only a subset, so called 'access routes'. This subjection consists of 8 out of a total of 30 routes which deal with critical infrastructures and frosty spots. These are primarily bridges and shadowy places, as those are subject to lower surface temperatures and make them more susceptible to frost.

Remaining main motorway routes are selected based on various selection criteria (Municipality of Rotterdam, 2015, p.6). Most important categories for selection are other area access roads, which can be identified by 2x1 or 2x2 lanes, which are separated from each other. The next category is regular routes of busses, which are crucial for both bus drivers and passengers. Park and Ride locations are also considered to have a high priority, in order to stimulate the use of public transport within the inner city. Along with these, calamity routes for hospitals, ambulance-, police, and fire stations are added together with other miscellaneous locations as schools, nursing homes, crematoriums and cemeteries. Lastly, motorways leading to business and shopping areas are considered of high importance, but only during business/opening hours.

Bike lanes are, likewise to bus routes, crucial in relieving car usage during winter times. Next to that, bikers tend to use car lanes instead of bike lanes if they are not taken care of properly. It is therefore in both car and bike users interest to give high priority to bike lanes. These are both separated bike lanes as bike lanes which are next to roadways. Apart from these routes, an additional category is marked as low priority. These are considered when there are long lasting poor weather conditions. This category contains neighbourhood access roads (*erftoegangswegen*), other parking facilities and pavements in residential areas. Both bike lanes and roads with low priority are excluded from this study. The focus is on main motorways.

Although the municipality has certain roads which are in need to be gritted, not all are scheduled for this service by the municipality. These are roads which are not serviced by the local winter service organisation. National and provincial roads are excluded in the overview. These constructions are threefold:

- ➔ The Gladheidsbestrijding Mainport Rotterdam, which is gritting the private terrain of the port of Rotterdam. This private service is the responsibility of the Rotterdam harbour.
- ➔ Trade-off roads with neighbourhood municipalities to increase efficiency.
- ➔ Contracting to private companies. These roads often are located within remote areas. This is the area of Rozenburg (detached to Gladheidsbestrijding MainPort Rotterdam) and Hoek van Holland (contracted to municipality of Westland).

At the start of each winter, a test drive is organized with involvement of all drivers active during the upcoming season. This test is used to inform the staff about new adjustments, but more importantly, to check whether routes are okay to drive. Any (i) access problems for vehicles, i.e. roads work, narrow streets, redesigned parking facilities (problem for the vehicles) are noticed, (ii) exchange of roads to third parties are tested, as well as (iii) newly build roads are added to the existing routes. Furthermore, (iv) strategic and operational changes can be a cause to create new gritting sector designs and gritting routes. All these events trigger the need for new and/or updated vehicle routing. Route amendments are carried out by cartographers within the GIS advisory team. While this solution is sufficient and works properly, management parties are looking for enhanced ICT solutions which enable even more refined and optimized routing.

2.5 Outlook: ICT in winter service management

In the winter service policy plan, 2015-2020, relevant developments within the field are introduced. Management of salt usage is important to ultimately reduce the amount. This can be achieved by using 'dynamic winter gritting' techniques, currently not yet used in Rotterdam. It consists of various measures to control salt usage, like correct gritting widths and the use of infrared measures to have a better salt dose precision (Municipality of Rotterdam, 2013: p.12).

The winter service department started the WINTER project in October 2016 to enhance the use of ICT applications within vehicles and the salt spreading machines. As noted in the introduction, four main goals were formulated for the use of ICT applications: (i) increase the safety of employees and other road users by adopting route guidance, (ii) more sustainable use of salt and less vehicle miles, (iii) reducing costs by a decrease of man-hours while upholding high service levels and (iv) aiming for less reserve drivers, again to decrease costs.

To obtain these goals the project is partitioned into several phases and deliverables, from the digitalization of routes to the logging of the actual salt spread on roadways (table **1.1,** page **4**). With respect to the routing of vehicles, the project should result in the availability of (i) digitised salt spreading lanes, (ii) optimized routing, (iii) route guidance for drivers within their cabin and (iv) automated salting and actual reporting about routing and salt usage. For this thesis the first two points are of interest, *digitised salt spreading lanes* and *optimized routing*. These are used as input for the remaining deliverables.

Routes can be optimized in two ways. optimize the current routing; drivers depart almost at the same time, but arrive at different times, and many of them arrive too early. Another item is the percentage of deadheaded kilometres, which should be reduced. But the main problem is more structural and is embedded into the design itself. The initial design is based on former municipality districts which are now outdated and lost their value. Recently the gritting system diminished, instead of three depots only two depots are active, but this transition has not been adapted. Second, routing and its combination with different scenarios are suboptimal. At present there are two scenarios: 1. grit only access routes or 2. grit everything. The scenarios themselves are acceptable, but routing for the access routing scenario is incorporated in the 'grit everything' scenario. And if one wants to specify further, a distinction can be made between using snow shovels or not. This allows a wider gritting width when sprinkling only, including a combination of gritted lanes. The adopted WINTER project encompasses both navigation and automatic width control of the salt spreader. This opens possibilities to recreate routing not only from a single route optimization perspective, but various routes for drivers while upholding high safety standard for drivers.

Theoretically it is possible to design several scenarios, but now only one scenario is used due to the fact that drivers only grit a few times a year. Many times, drivers are instantly being called upon for a night shift (3/4am) to clear the roads before the morning rush hour. Drivers operate in the middle of the night, only one person per vehicle, with a paper map navigation while driving on possibly slippery roads and in the meantime they have to manually adjust the width of their salt spreader. Subsequently, it has been calculated that if a turnout goes wrong, damage to society can be up to three times the annual budget (O'Keefe & Shi, 2006: p.5). Therefore, to temporarily keep the same routing for both scenarios to decrease the creation of human errors and to increase the safety of personnel by sticking to only one route per driver, is the first choice. However, one could choose to calculate multiple scenarios, after the first practical tests with the routing model seem promising.

2.6 Summary

This chapter introduced the main concepts of the winter service section, with a focus on its origin and creation. At the beginning of the chapter it is argued that the winter road maintenance decision making has comparable elements with a 'Greek temple organization'. Both operational and tactical decisions, and even strategic ones, are taken by the winter service organization and road authority departments, each holding responsibility for different parts in the logistical chain. The winter service organization primarily holds the responsibility for all gritting and related activities. Daily operations for routing, transportation management, staff management and inventory control belong to their responsibility. They themselves decide when to start gritting and following which scenario. The road authority acts as a party which is responsible for safe travel of road users. Several requirements are in place, such as a two-hour time restriction for municipal roads and policies on salt usage, but the salt capacity on vehicles is not seen as a constraining factor.

The determination of routes is primarily focused on the sector design: which route to grit and why. The gritting routes for motorways are divided into two categories: access routes and other main motorway routes. Access routes consist of critical infrastructure and frosty spots. For the other main motorway routes several criteria are outlined, amongst them main motorway roads, access roads, bus lanes, P&R locations, shopping areas and calamity routes for hospitals, ambulance-, police, and fire stations. Routes are gritted in only 'grit access routes' or' grit every route'. The weather forecast depicts which routing scenario is executed. One should note that routes may change due to the field experience of drivers and citizen complaints at the address of the winter service organization. Both activities trigger a response from the road authority for route adjustment, not to mention its own contribution to changes such as revisited sector design.

While these route adjustments are performed by in-house cartographers, management is exploring the possibility of automated and optimized routing solutions. Two possibilities are conceived for optimized routing. The first option is the current routing procedures by means of sharper time schedules and reducing deadheaded kilometres. There is, however, a more structural embedded call on route revising, such as outdated districting and a recent depot abolishment. The second option is to develop individual routing for both the 'grit access routes' as 'grit everything' scenario. This option will not yet be investigated in the short term but considered as a future option for vehicle routing.

3. Literature review

This chapter reviews the literature regarding spreading problems. After starting an initial exploration of the winter service section in chapter **2,** the spreading problem is defined in section **3.1**. The derived spreading operation characteristics are set out in section **3.2**. Section **3.3** presents several methods to incorporate the spreading problem into a routing model, as well as assessed that the vehicle routing model suits the problem best. In section **3.4** possible solution methods for this problem are given. As a next step section **3.5** considers the implementation of a vehicle routing model into a GIS environment. Section **3.6** syntheses the organisational framework (chapter **2**) and the proceedings of the literature review (chapter **3**) and merged these into a coherent conceptual model.

3.1 The spreading problem

Different problem sets and models exist and are described in literature on spreading operations. Before diving into these models, it is essential to understand those operations more in detail. Perrier et al. (2010) explain the spreading problem as follows:

"The routing of vehicles for spreading operations is the problem of designing a set of routes such that all required road segments of a transportation network are serviced by a fleet of spreaders, which may be heterogeneous vehicles (e.g., trucks of different capacities) based at multiple depots. The transportation network is generally described through a graph, whose arcs and edges represent the one-way streets and two-way streets to be serviced, respectively, and whose nodes correspond to the road junctions and to vehicle and materials depot locations. Not every road segment may need to be serviced and road segments with positive demands (amount of chemicals and abrasives) are called *required* road segments" (Perrier et al., 2010: p.3).

This small introduction contains four main elements which suit the problem as depicted in the previous chapter: (i) the possibility to include heterogeneous vehicles, (ii) multiple depot locations, (iii) transportation network, but represented as a graph with one-way and two-way streets to be serviced and (iv) not every road segment may need service. To fully grasp the spreading problem, a solution was made to decipher the problem set into problem characteristics. Little differences in the problem characteristics may easily lead to results which cannot be applied to real-life routing solutions.

3.2 Spreading operations characteristics

Numerous factors do exist in this spreading problem, which depict a part of the problem environment constraints and should be considered when embedding the solution (Perrier et al., 2010). Several studies have developed taxonomies to deal with both routing problems (see e.g. Bodin & Golden, 1981; Anbuudayasankar et al., 2014) and spreading problems (Perrier et al., 2007; Perrier et al., 2010; Xie et al., 2013). This thesis uses the taxonomy of Perrier et al (2007) for the problem set. The reader is referred to the study by Assad & Golden (1995), which specifically dive into characteristics different for spreading in comparison to other routing problems. For this moment, the main characteristics and sub characteristics are addressed and described in more detail.

3.2.1 Transportation network

Network models are used as an abstract representation of real-world components and therefore the basic component of vehicle routing. A network can be defined as "a set of interconnected linear features through which materials, goods and people are transported or along which communication of information is achieved" (Heywood et al., 2011: p.95). These interconnected linear features represent numerous different phenomena, such as transport-, utilities-, or hydrological networks. Our focus lies within a transport network design, but in an urban context. The components of a network can be divided into arcs (one-way flows), edges (two-way flows) and nodes (figure **3.1**). The nodes are used as vertices (to link arcs and edges), to account for the connectivity or may function as ending points or junctions. Besides this, turns are included, representing the transition from one arc or edge to another. Turns, arcs and edges are all represented as lines, whereas nodes are represented as points (dots) in this network data model (Heywood et al., 2011). The transportation network is also displayed as an UML diagram (figure **3.2**). This provides a more database overview and the relationship between the key aspects of network, manoeuvres and junctions.

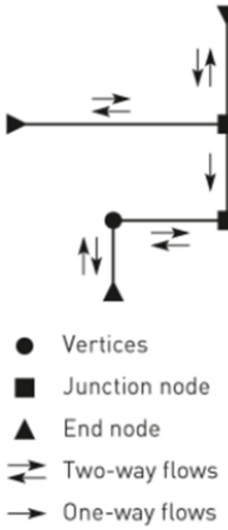

Figure **3.1** Network data model (source: Heywood et al., 2011: p. 96).

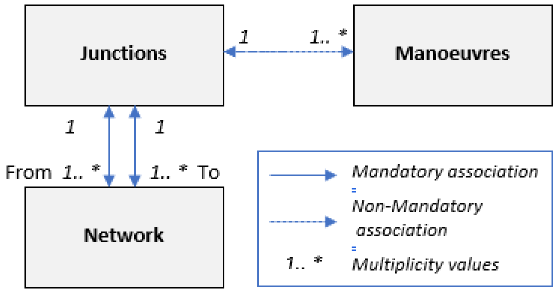

Figure **3.2** Transportation network UML class diagram. The relationship between network from and to directions to junctions and the possible relation between junctions and (vehicle) manoeuvres.

The representation of the network in a network data model is determinative for the functionalities which one can use. One of the modelling choices is between an undirected, directed or a mixed network. The undirected network only uses edges, the directed only arcs and the mixed network a combination of both edges and arcs. A mixed network is normally used in dense urban networks to represent the transportation network for gritting (Gerlagh, 1998). At first sight this seems an appropriate choice, but it may result in increasing computational complexity for modelling vehicle routing. This will further be elaborated upon in section **3.3**: vehicle routing models for spreading. Corresponding to the network data model is also the implication of a maximum time for spreading completion (Perrier et al., 2007). For Dutch municipal roads this time is set to two hours after leaving the depot for curative spreading; within this time slot all required roads in the network are treated.

3.2.2 Road segments

The transportation network consists of road segments. These are depicted as an individual asset which requires uniform treatment. First one should determine if a road segments needs to be traversed. Not all roads are subject to gritting. Road segments which are required to pass at least once are called required road segments (Perrier et al., 2007). Associated with required road segments are the costs of traversing in terms of length and three different traversal times: the required service time, the deadheading time if the road segments are not serviced yet and the deadheading time if the road segments are already serviced. (Perrier et al., 2007). Deadheading refers to passing a road segment without gritting it.

Consequently, note that not all road segments do have to be passed in exactly one time. Broad roads might require more than one passing, whereas multiple small adjacent roads or two-way roads (one lane each way) can be serviced in one go (Perrier et al., 2007). In todays practice salt spreading and snow ploughing is a single scenario. This means that due to the width and practical troubles of snow ploughing several lanes, the use of gritting multiple adjacent roads is ignored.

3.2.3 Sectoring

When winter road operations become too large to manage them effectively, a solution could be to separate both personnel and vehicles into smaller subareas. This sectoring or districting “involves the partitioning of a large geographical region into sub-areas … according to some criteria, to facilitate the organization of the operations to be performed within the region” (Muyldermans et al., 2002: p.521). Subareas are referred to as sectors. Sectoring criteria are often guided by a particular problem (Júnior, 2008), e.g. sectoring is applied successfully for primary school student distribution, voting districts or administrative districting; the last one is currently used for road sectoring (Júnior, 2008). While administrative districting is applied for managing winter service sectors, other criteria may fit better for sectoring design (Perrier et al., 2006). The design should preferably be based on the transportation network rather than administrative boundaries. Part of this transport network are network facilities such as vehicle depots and salt replenishment stations (Perrier et al., 2006).

Perrier et al. (2006) did set out three standard criteria for designing sectors: compactness, balance in workload, and continuity. Compactness depends on both the number of sectors and depots. If the number of sectors is equal to the number of the depots, those depots lie in the sector centre. If the number of sectors exceeds the depots, they are in general districted by means of an effective way of the type of winter road operations (Perrier et al., 2006). This number of sectors in which routing towards the sector and back to the depot in the leading design principle. The balance in workload trickles down to basic criteria, such as length of streets, travel time or expected snowfall. Perrier et al. (2006) note that if using the length of streets as a sector criterium, the computational time may become an issue. An option could look like choosing districts based on the continuity or a collection of street segments which include only adjacent streets. The strategy of continuity is effectively used when the percentage of deadhead within sectors is minimized and as a result the overall deadheading is minimized as well. One has to make sure that road continuity is respected with road segments and that they can be linked together. Some road segments might require a different treatment. Different characteristics such as priority levels, vehicle specifications or jurisdictional limitations may interfere with districting based on continuity (Assad & Golden, 1995; Perrier et al., 2006).

Sectoring can also be based on several administrative or transportation related factors. Choosing an appropriate sectoring model can therefore be difficult and rely on multiple practices. Anyhow, the end result should take into account the sector robustness (Perrier et al., 2006). Despite the fact that this is not a criterion for the initial design set up, for daily operations the outcome is necessary. Small changes in selecting gritting roads should fit into the initial design. From an organisational point of view, it would be unfavourable if the sectoring should be tossed yearly due to small changes in the operations. Ultimately sectoring should enable the organisation to deliver better work for both organisation and society.

3.2.4 Vehicles and depots

All vehicles start and end at multiple vehicle depots and the depot they start is where they end. Likewise depots have to be linked to the graph by adding a (depot) node. With each depot a number of vehicles are assigned, often different types. These vehicles use specific roads according truck width, spreading range and salt capacity. The number of vehicles of each type which it can store safely is limited. Within each vehicle depot salt is stored as well as additional vehicle equipment, such as shovels. Costs to maintain them are structural and high, especially when considering that it will be necessary to use them only several times a year for salt spreading, but in the mean time they have to be used for vehicle and salt storage all year round (Gerlagh, 1998). Also vehicles themselves are considered to be fixed costs, whereas fuel, materials and maintenance are considered variable costs (Gerlagh, 1998: Perrier et al., 2007).

3.2.5 Routes and drivers

All required road segments are divided into one or more routes. They were designed according to several constraints deriving from previous characteristics of the transportation network, as there are road segments, sectors, vehicles and depots. The start of the route is scheduled by the central coordinator, who assigns the starting time and sets the completion time. The workload of the drivers is scheduled within these two hours; itis also balanced, i.e. these workloads are approximately of equal length and duration (Perrier et al., 2007). Length is calculated in lane-kilometres, since roads may require multiple passes or being split into several lanes (Perrier et al., 2007).

As next item considering routing, and in particular salt spreading and ploughing, is the designing of routes with only a few special manoeuvres (Perrier et al., 2007). Manoeuvres like U-turns and turns which cross traffic lanes are undesired, due to the impact on both completion speed and hindering interrupting traffic flows. A well-designed route preferably should not contain too many special manoeuvres, long stretches of continuous serviced road segments. To accommodate for both special manoeuvres-, sectoring- and time violations the routing model can be incorporated in two different manners. First is to simply forbid certain moves, such as U-turns, or ban vehicles from districts. At second the action can be penalized. Additional costs can be added to the cost function for violation, which makes options only interesting when the savings are significantly higher. Time penalties mean that drivers have less time for completion, which brings additional costs and results in the use of additional (scheduled) drivers.

3.2.6 Objectives

Considering all aforementioned characteristics, one has to choose one or several objectives which they then strive to optimise. Typical objectives deal with minimising the (i) deadheading or total service time, (ii) number of vehicles used or (iii) a given penalty constraint such as left turns, U-turns and/or time violations. Associated with these objectives are monetary objectives as minimising (iv) global operation costs, (v) fixed costs and (vi) variable costs.

Minimizing objectives is a difficult task, as it contains a conflictive element (Perrier et al., 2006). For example, minimization of deadheading can result in an uneven work balance between team members. Or crossing too many small roads can lead to discontent amongst drivers. The main question here is: “Is it all about minimising the total deadheading or is there a small window for creating an even work balance and pleasurable routes to drive?” Trade-offs are hard to make and requires professional judgement instead of single minded optimisation (Keenan, 2001). Even more important for assessing good routes, is that optimal solutions are not found within the use of algorithms for most practical routing problems (Keenan, 2001). This notion, reaching a sub-optimal status quo within routing models will be explained in the next section using several routing problems.

3.3 Vehicle routing problems for spreading

Different routing problems are formulated for spreading operations. A vehicle routing problem can be defined as "the problem of designing optimal delivery or collection routes from one or several depots to a number of geographically scattered cities or customers, subject to side constraints" (Laporte, 1992: p.345). Different side constraints can be imposed, such as salt capacity and time windows. Vehicle routing problems can be divided into two categories: node routing and arc routing. In node routing problems the demand is on nodes (or vertices) on the graph (Han, 2015: p.350) Examples of a node routing problem are waste collection, internet-based grocery delivery or the distribution from warehouses to retailers (Eksioglu et al., 2009). In arc routing problems focus is on the route itself. The entire road segment, including the edge, is required to pass (Han, 2015: p.350). Practical examples are found in salt spreading, snowploughing and street sweeping, street inspection for maintenance, postal delivery and meter reading (Assad & Golden, 1995: p.375). All these examples emphasize the need to service these streets entirely. For postal delivery and meter reading density of potential customers can be high, whereas at that very moment a street segment is considered to be serviced. Therefore, a distinction between node and arc routing is merely a matter of representation of modelling (Assad & Golden, 1995: p.375).

Optimisation algorithms are used to solve both arc and node routing problems, whereby the vehicle routing problem relies on the mathematical discipline of combinatorial optimization problems (Garey & Johnson, 1979). These problems need a countably infinite set of solutions; this, in its turn, has to be minimized or maximizes on a given cost function (Michiels et al, 2007). Cost functions generally refer to an objective function, but for routing it is in most cases meant to minimize factors like driving time, fuel and operational costs (Perrier et al., 2006).

Within optimisation algorithms, an important distinction is made for computational complexity, defined as '*soft* and *hard'* problems (Michiels, 2007; Keenan, 2001). Soft problems are solved within polynomial (P) time: a maximum amount of time required for the algorithm to solve the problem. The notation used for algorithms is the capital O (Garey & Johnson, 1979). The O stands for 'order of growth' and is interested in the running time when the problem size increases. To create a more efficient algorithm the order of growth is limited, either by decreasing the problem size or its functional complexity. Hard problems, on the other hand, use exponential time algorithms instead of polynomial time algorithms to find the optimal solution. Where algorithms with the function O(n) are solved in polynomial time, functions of $O(cn)$ and c is larger than one, increase exponentially when the problem size n increases. An example of exponential parameters in a function is the number of nodes (n) or arcs in a network (Keenan, 2001). If n becomes too large computer running times can easily run into the aeons (table **3.1**, next page).

For some of NP-hard problems can be solved in non-deterministic polynomial time. This category of problems is known as NP-complete (Michiels, 2007). Little is currently unknown for this class if an algorithm exists which is able to solve these problems within polynomial (P) time. If yes, it can be validated in polynomial time, answers can be optimisation of algorithms are used checked immediately but there's currently no way to quickly find them as well.

Table **3.1** Comparison of polynomial and exponential time complexity functions. In vehicle routing problems the function is exponential. An increase in arcs or nodes to the vehicle routing problem has a significant impact on computation time (source: Garey & Johnson, 1979: p.7).

Time complexity function		Size *n*					
		10	20	30	40	50	60
Linear	*n*	.00001 second	.00002 second	.00003 second	.00004 second	.00005 second	.00006 second
Polynomial	n^2	.0001 second	.0004 second	.0009 second	.0016 second	.0025 second	.0036 second
	n^3	.001 second	.008 second	.027 second	.064 second	.125 second	.216 second
	n^5	.1 second	3.2 seconds	24.3 seconds	1.7 minutes	5.2 minutes	13.0 minutes
Exponential	2^n	.001 second	1.0 second	17.9 minutes	12.7 days	35.7 years	366 centuries
	3^n	.059 second	58 minutes	6.5 years	3855 centuries	2×10^8 centuries	1.3×10^{13} centuries

3.4.1 Arc routing problems

Last decades, definitions and solutions of several arc and node routing problems have been proposed. Some of the most prominent ones were introduced by Golden & Wong (1995). The arc routing problems are presented in terms of time complexity and how these routing problems are used in relation to salt spreading.

Undirected-, directed and mixed postman problem

One of the theoretical fundaments of arc routing is postulated by Leonhard Euler, mathematician. (Keenan, 2001). Euler visited the Prussian city of Köningsberg (nowadays called Kaliningrad, located within the Russian Federation) and formulated the 'Köningsberg bridge problem' (Eiselt et al., 1995). The question was if it is possible to traverse the seven bridges of the Pregel river within the city of Köningsberg exactly once and to return to the starting point (Keenan, 2001). Euler showed that this is only possible in a closed circuit if nodes consist of an even number of arcs, or if exactly two nodes have an odd number of arcs (Keenan, 2001). This closed circuit is known as 'Euler circuit' (Hertz, 2005).

Years later the postman problem, or so called the Chinese postman problem, was suggested by the Chinese mathematician Kwan Mai-Ko in 1962 (Eisselt et al., 1995). This problem states: a postman has to cover his assigned segments before returning to the post office but has to find the shortest walking distance (Keenan, 2001: p.101). Likewise to the formulation of Euler, the problem can be solved by means of a closed circuit. If not, edges must be covered more than once. These non-required traversals are unwanted deadheading arcs (Assad & Golden, 1995). When the graph is completely undirected or directed, the postman problem can be solved in polynomial time (Edmonds & Johnson, 1973). But when this problem exists of a mix of undirected and directed arcs, it becomes NP-complete (Assad & Golden, 1995).

In salt spreading operations Kramberger (2012) uses two formulations of the postman problem. In the first he uses the 'undirected postman problem'. In the second formulation priority nodes are added.

This is a possibility, but only if certain roads or areas have been given an increased interest to be serviced. This interest is expressed in terms of weight on edges onto the graph. If this weight is minimal, the change is likely that solution offered by the undirected postman problem in the first formulation will prevail (Kramberger, 2012: p.62). If the weight is considered different, tours may be constructed which is largely dependent on the amount of deadheaded edges being used. To divide vehicle and depots to certain districts makes the problem itself already NP-complete (Kramberger, 2012: pp.62-63), although the undirected postman problem can be solved in polynomial time. In practical situations, however, multiple vehicles and multiple depots are used.

Rural postman problem / Directed rural postman problem
The rural postman problem (RPP) attempts to find a single route of minimal length of a selection of edges in the network, whereby some edges in the network are visited and some edges are not but may be used in the solution. This problem is a variant of the Chinese postman problem (Gerlagh, 1998). The RPP is NP-complete, except when the required edges to serve are all passed once. In that case, the rural postman problem is reduced to the postman problem, which can be solved in polynomial time (Groves & Vuuren, 2005).

Additional deadline classes are used by Letchford and Eglese (1998) in order to solve the rural postman problem in salt spreading. Such classes can be useful, for reasons to prioritise roadways based on importance to the road network (Campbell, 2000). Recently Quirion-Blais et al (2016) made use of the rural postman problem in snow ploughing, instead of gritting, for solving it on a mixed graph with arc/edge hierarchy for a given k-number of vehicles. They further consider turn restrictions, route balancing and variable vehicle speeds on a real large-scale network (Quirion-Blais et al., 2016: p.1).

Stacker crane problem
The stacker crane problem is the mixed version of the rural postman problem. A set of directed arcs and a set of edges or undirected arcs have to be serviced (Assad & Golden, 1995). The name is derived from a stacker crane which must load containers onto a ship. A crane can only lift one container at a time and has to construct a route through a series of containers (demand) which should be minimized. The stacker crane problem is NP-complete (Frederickson, Hecht & Kim, 1978). To the best of the author's knowledge no studies exist in which the stacker crane problem is used to model gritting routes.

Windy postman problem
This problem is consistent with the postman problem, however the costs of traversing an arc are dependent on the direction in which it crosses (with or against the wind) (Assad & Golden, 1995). This cost function of the windy postman problem is therefore not symmetric (Dussault et al., 2013).

Dussault et al. (2013) used the windy postman problem to model snow ploughing operations. They proposed a scenario in where on some steep streets it is more difficult, or even impossible, to plough uphill. A notion is incorporated that deadheading costs over streets that have already been ploughed are significantly less than crossing deadheaded roads which have not been ploughed yet (Dussault et al, 2013: p.1047). They have developed a solution which can deal almost optimally with instances up to 200 nodes (Dussault et al., 2013).

Capacitated arc routing problem
The capacitated arc routing problem (CARP) starts from the central depot, in which it should obtain a collection of routes of minimum total length, in which the routes themselves have an individual demand. The most important restriction is the capacity of the vehicles (Gerlagh, 1998). The CARP is a special case of the Rural Postman Problem (RPP) and it is shown to be NP-complete (Assad & Golden, 1995; Gerlagh, 1998). This implies that only a subset of the required arcs must be served (Gerlagh, 1998). The CARP can be studied on mixed graphs (Gaspar & Benze, 2016).

3.4.2 Node routing problems

All arc routing problems mentioned can be deduced to node routing problems. Both postman and stacker crane problems are enriched examples of the node routing problem of the travelling salesman problem (Assad & Golden, 1995). For the travelling salesperson a salesperson has to travel to each city within a territory, stopping only once at each location before returning to the location of origin (Curtin et al., 2014). The TSP is not of that much importance but could be used to set an initial solution (as done by e.g. Hajibabai, 2014). More interesting is the vehicle routing problem (VPR), especially when constraints are added such as time windows.

Vehicle Routing Problem

The VRP can be defined as to define optimal routing for a number of orders to deliver to a set of customers which have to be retrieved from a central depot. Due to constraints such as load, distance and/or time, one vehicle is unable to deliver these goods from a single depot. The problem is then to determine the vehicles needed to serve all customers (Benjamin, 2011: p.8). This involves the number of vehicles, minimizing distance and/or distance travelled by the fleet of vehicles. Several variations of the VRP exist. This included adding time windows (VRP-TW) or a VRP with limited vehicle capacity (CVRP). There are many variations which are developed for the vehicle routing problem (Toth & Vigo, 2002). These constraints and features that are subject for adding make up the specifics of the vehicle routing problem, if desired to be used. These constraints that make up the model choice will now be discussed for our specific routing problem.

3.3.3 Model choice: vehicle routing problem

All problems set have both strengths and weaknesses. The practical situation, however, is the most important item to choose the best fitting model. In chapter 2: organisational framework, three points were considered of importance for this choice of a suitable routing model: (i) mixed graph, (ii) limitation of U-turns and (iii) introduction of a time-window. The actual action needs (iv) multiple heterogonous vehicles and (v) multiple depots, whereby (vi) not every street needs servicing.

A polynomial algorithm cannot be used for the problem solving if using a mixed graph. At least this problem is considered NP-complete, and therefore optimal solutions cannot be guaranteed. Remaining considerations seem to formulate that our routing problem is either the rural postman problem on a mixed graph with deadline classes or a vehicle routing problem with time windows. Preference goes to model the problem as a VRP-TW, because the algorithms for node routing are more advanced (Assad & Golden, 1995; Gerlagh, 1998) and the number of tools and software applications are more integrated within node routing problems (Tagmouti et al., 2011; Corberán & Prins, 2010).

Now that the routing problem is defined, the methods in which the problem can be solved are considered.

3.4 Solution approaches for VRP

The solution approaches for the VRP are usually broken down into two types: exact methods and heuristics/metaheuristic (Curtin et al., 2014). Exact methods “obtain optimal solutions and guarantee their optimality” (Talbi, 2009: p.18). Examples of exact methods are pure optimization problems, such as mathematical programming, or classical algorithms such as dynamic programming (which breaks it down into more simple sub problems) and branch-and-bound or branch-and-cut algorithms (Caceres-Cruz et al., 2014; Tabli, 2009). They are used to solve small size routing problems (around 75-100 visiting nodes) with simple constraints (Caceres-Cruz et al., 2014)

Heuristics and metaheuristics provide near-optimal solutions for medium and large-sized problems with optional more complex constraints (Caceres-Cruz et al., 2014). Using (meta)heuristic can be beneficial for three reasons: faster problem solving, solving larger problems, and obtaining more robust algorithms (Caceres-Cruz et al., 2014: p.7). In general, these heuristics are designed to solve a specific problem or instance, whereby metaheuristics are used as a framework for almost all optimisation problems (Talbi, 2009). Discussing all (meta)heuristics for the vehicle routing will go beyond the scope of this thesis. For overview studies the reader is referred to reviews studies of e.g. Anbuudayasankar et al. (2014) and Cordeau et al. (2002). Here the focus is on three types of operations with appropriate heuristics: the configuration of an initial solution with a constructive heuristic (nearest neighbour), improvement procedure by means of local search (2-opt, 3-opt) and the short memory-based metaheuristic of tabu search.

Before optimising it is necessary to start with an initial solution. One way of achieving this is using the nearest neighbour algorithm. It starts with any node at the beginning (e.g. depot) and adds the closest node to the route. This continues until all the nodes are allocated. It is one of the first examples to construct a tour for the travelling salesman problem (Caceres-Cruz et al., 2014). Although it creates a quick solution, it does generally not lead to optimal results. The solution may be feasible, but it does not have to. In routing the initial solution may violate constraints such as time restrictions (Caceres-Cruz et al., 2014).

Improvement procedures take an initial solution and try to improve it. This can be achieved using the locally available search space, that is, moving nodes between routes. Doing this for two nodes in the same route is called 2-opt (figure **3.3**). More of these local improvements are used. Examples are 3-opt moves whereby one node is replaced by two other nodes in the tour and a shift move, whereby one node is removed from a route and replaced in another route. If the move is only used when the newly generate route is an improvement on the current variant it is called an iterative improvement (Han, 2016). The problem with these improvement procedures is that they are trapped in a so called local optimum. A local optimum is achieved when in the current solution no iterative improvements can be made within the local search space. Global optima is the optimum of the entire function (Luke, 2015: p.14). If an algorithm gets stuck in a local optimum, the only way out is to accept deteriorations of the objective function under certain conditions. These strategies can all be achieved with the use of metaheuristics.

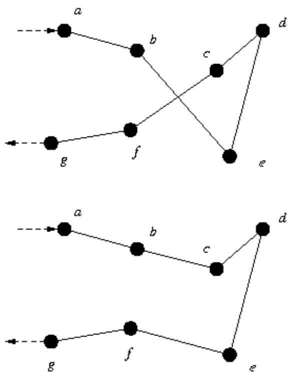

Figure **3.3** 2-opt move whereby orders the frequency b-e and e-f is opted to b-c and e-f.

Metaheuristics are used as a framework for almost all optimisation problems (Talbi, 2009). Luke (2015) describes the use of metaheuristics: “Metaheuristics are applied to *I know it when I see it* problems. They’re algorithms used to find answers to problems when you have very little to help you: you don’t know beforehand what the optimal solution looks like, you don’t know how to go about finding it in a principled way, you have very little heuristic information to go on, and brute-force search is out of the question because the space is too large. But if you’re given a candidate solution to your problem, you can test it and assess how good it is. That is, you know a good one when you see it” (Luke, 2015: p.9). The vehicle routing problem fits perfectly within this description. Many metaheuristics exist (i.e. simulated annealing, genetic algorithms, ant colony optimisation). This study particularly focuses on the metaheuristic of tabu search.

Tabu search is considered a suitable approach to solve large vehicle routing problems (Curtin et al., 2014). These are also used in a special way by vehicle routing problem with additional constraints, such as time windows and capacity problems. Tabu search keeps a history of recently considered candidate solutions which is called a tabu list. If candidate solutions for the next iteration is on the tabu list, they are refused until they’re sufficiently far in the past (Luke, 2015). This means if candidate solutions perform worse than current solutions, these are still accepted and the algorithm is not permitted to hold on the current solution. How long moves do remain in the tabu list is dependent on the iteration settings (Krichen et al., 2014).

Next to the tabu list, the best overall score is kept and stored. Several criteria can override the tabu list, called aspiration criteria (Luke, 2015). The most common one is the allowance of a move if results are better objective value (Curtin et al., 2014). Because of its overall good performance, well documented literature and easy implementation for users, tabu search based algorithms are widely employed in GIS (Curtin et al., 2014; Cordeau et al., 2002).

3.5 Implementation of vehicle routing models in geographic information systems

Geographic information systems (GIS) are of utmost importance in transportation network modelling (Kuby et al., 2005; Fischer, 2004). A GIS can be defined as "computer-based systems for the capture, storage, manipulation, display, and analysis of geographic information" (Thrill, 2000: p.4). The ability of GIS to integrate these multiple functionalities into one working structure is key to bring different technologies onto one platform (Thill, 2000). Loidt et al. (2015) reported three analytical components of transportation GIS: modelling, analysis and simulation (2015: p.2). These analytical components generate new information with consideration of the spatial nature of transportation. In regard to vehicle routing, the modelling aspects within the analytical components are important, but analysis and simulation of transportation related data within salt spreading can also benefit from GIS.

Implementing vehicle routing models into a GIS may generate several benefits in comparison to other approaches, like transport modelling software product or mathematical optimisation studios. Assad & Golden (1995) note that GIS can handle network data sufficiently, whereby other attempts try to bypass the obstacles of obtaining and using detailed geographic data (Assad & Golden, 1995). Euclidean distances instead of network distances are used, and travel times were estimated using regressions to fit the actual travel distances based on i.e. linear or Euclidean norms (Assad & Golden, 1995; Levinson & El-Geneidy, 2007; Keenan, 2008). This is especially relevant for intra-city and urban street networks (Assad & Golden, 1995). Subsequently, information about which side of the street network is used and the driver actions of turn restriction and penalties greatly help the translation from a modelling representation into the actual use of real street networks. This creates feasible paths which can be used in real routing and increase the acceptability of final routing (Assad & Golden, 1995: p.382-383).

Besides handling network data, additional data sources can easily be stored by means of a GIS environment. These data can be conveniently manipulated by the same system when adjustments are required (Assad & Golden, 1995). And different data sources can be linked to this routing information to provide greater insights such as demographics or weather data (Assad & Golden, 1995). These overlays with both transportation and non-transportation data can improve insights in transportation policy and land-use interaction (Kuby et al., 2005: p.15).

A special role for combining transportation and non-transportation data does exist for zoning or route districting. If multiple vehicles are able to service an area, GIS can be used very effectively to restrict vehicles to certain areas, based on depot location or other reasons. Dividing an area of interest into districts can be based on pre-set boundaries, such as neighbourhood, census blocks or different traffic analysed zones (Kuby et al., 2005: p.15). A GIS enables users to quickly change zoning systems and rerunning the analysis, whereas complexity of zoning can be better understood (Kuby et al., 2005). Partitioning different transportation zones cannot be executed in a 'correct way' but understanding how zoning has an impact on transportation decisions is a main feature of a GIS (Kuby et al., 2005).

Next, the interaction from the user with the routing algorithms is a strong feature within the GIS environment (Assad & Golden, 1995). This is particularly possible due to mapping and display features of a GIS, which serves as a feedback loop to data integration and tweaking of parameters within routing models (Loidt et al., 2015). Keenan (2001: 2008) mentions spatial decision support systems (SDSS) rather than GIS. Here a GIS is used for decision-makers to redefine the problem and generate alternative solutions rather than focussing on one answer (Kuby et al., 2005). Keenan (2001) notes "... the value of [a] SDSS is not determined by its innovative use of technology. Rather the contribution of these applications will be determined how well they support the need for a spatial component in decision-making" (Keenan, 2001: p.52).

While on the one hand this is true for decision making, the innovative use of technology is the weak spot of many GIS-T applications on the other hand. Many software programs may be used to analyse location problems, but they end up working as a 'black box' (Mapa & Lima, 2014: p.845) and do not clearly state which solution methods they use in transportation modelling (Mapa & Lima, 2014: p.845; Curtin et al., 2014). Some do not even admit using heuristics and occasionally state that optimal routing is provided using their software (Curtin et al., 2014: p.292). Therefore users need to be aware of the algorithmic performance of the various routing software available.

One way of unravelling the output performance of these black boxes is thoroughly testing the accuracy of the heuristic implemented. Accuracy measures the degree of suboptimality of a heuristic solution from the original value (Cordeau et al, 2002: p.513). One way of doing this is by comparing heuristic implementation with exact solutions. While this procedure is not done yet with vehicle routing algorithms, comparative studies about algorithms of travelling salesman problems and location problem analyses in comparison to exact heuristics show that GIS-T applications perform suboptimally (Curtin et al., 2014; Mapa & Lima, 2014). Mapa & Lima (2014) look at facility location and transportation problem and compare the heuristics of TransCAD with exact mathematical models based on Mixed Integer Linear Programming, finding suboptimal solutions up to 37%. Curtin et al (2014) show that for several GIS packages (ArcView 3.2, ArcGIS 9.1, ArcLogsitics Route and Integraph Geomedia) that the TSP solvers perform suboptimal (on average ~15% above optimality) on problems ranging from 10-20 stops (Curtin et al., 2014: p.297). However, the percentage of suboptimality decreases with an increase of the number of stops. Instances of larger than 25 stops are not compared to exact heuristics, because it takes a too long computational time. This is unfortunate, because it provides a limited sample on optimization problem on large-scale networks.

The only study which describes the algorithmic side on vehicle routing problems and GIS is by Kim & Bea (2016). They looked at a vehicle routing problem for delivering packages of a big online retailer in South-Korea. They collected 337 delivery vehicle operations in the month of February. They compared these data to compare two metaheuristic algorithms on their performance: a tabu search algorithm of ArcGIS 10.1 with a genetic algorithm built in MATLAB. In almost every instance the tabu search algorithm performed better: an average of 12.8% decrease in driving minutes. As this result is compared with one metaheuristic, performed on a small instance (6 vehicles, each with a few deliveries) and without the use of time windows, no conclusions can be drawn.

In summary, GIS-(T) has many advantages to offer when developing an integral routing model. It can well handle network data, as well as manipulating network data input and interacting with routing algorithms. This interaction is mostly limited to setting input parameters of different routing scenarios. The algorithm itself remains a black box, and often leads to misinterpretation of solutions. Only a few studies have actually compared these GIS black boxes to ILP/MILP models and show suboptimal results. Kim & Bea (2016) have compared metaheuristics within a GIS environment and shown sufficient results, but large comparison studies remain scarce till today.

3.6 Conceptual model

Based on the exploration of both the organisational and theoretical perspective on salt spreading a conceptual model is established (figure **3.4**). Both organisational decision-making and routing characteristics are brought together in this model and are interlinked with relationships either on directional or bi-directional level. At the bottom characteristics that collectively influence the staff routing are visualised. The concept as presented here is a modified version based on the work of Gutiérrez & Vidal (2013) on health care logistics and was redesigned for salt spreading problems.

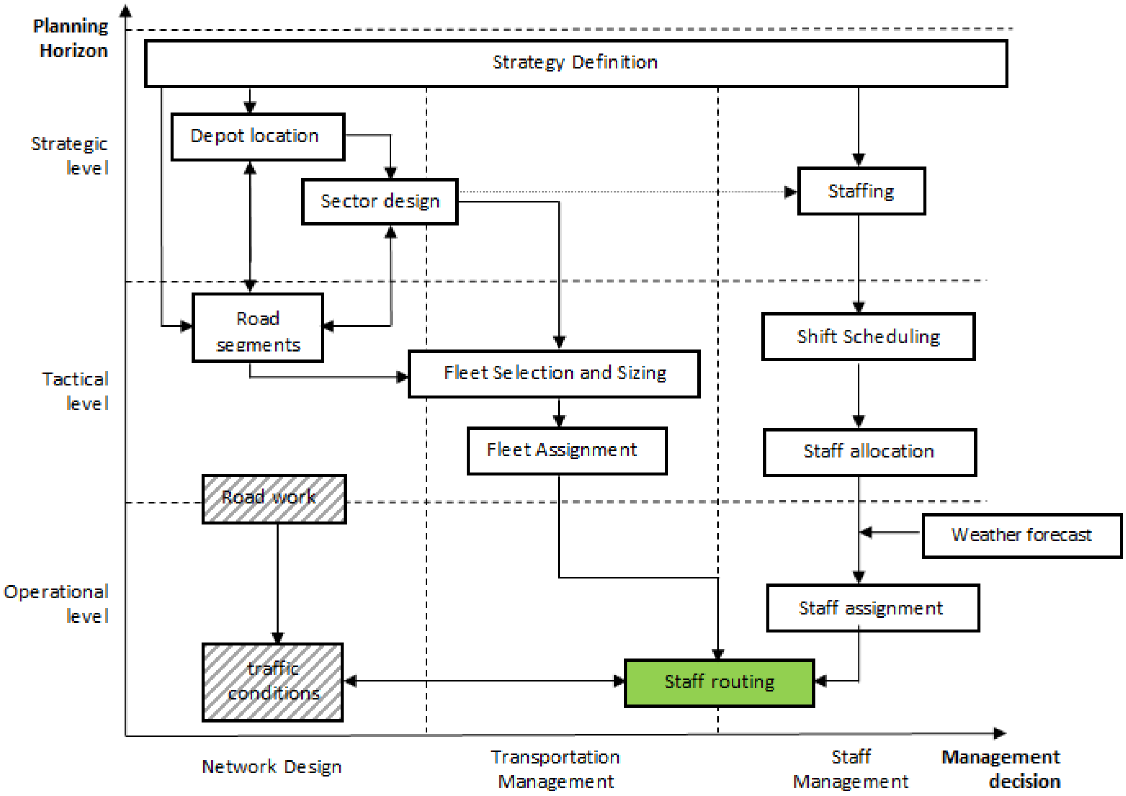

Figure **3.4** Conceptual model. Representing characteristics and underlying relations resulting in staff routing (in *green*)

The X and Y axis represent the decision-making structure of the organisation. The winter service section divided into the winter service organisation and road authority; the first manages the transportation and staff management and second the network design. Planning horizons determine that both departments are responsible for operational, tactical and sometimes strategic decisions. The strategy definition is however taken in a higher management level and directs and steers individual characteristics on their behalf. The WINTER project is of a certain strategic importance, whereby the strategic used ICT technologies trickle down via strategic and tactical decisions to the core of the operational model and staff routing. The X and Y axis of the model, together with the strategy definition is depicted as Greek temple organisation structure. Communication between the departments and the project team is vital for adequately designing and implementing routing.

The boxes represent the spreading operation characteristics, placed within decision making structures, which details the management decision and planning horizon. Note the reciprocal relation between the strategy definition, (required) road segments, sector design and depot location. A change in one of these four characteristics leads to a tactical and strategic revaluation of the design of the entire network. The outcome of this process has severe impacts on all other elements in the logistical chain up to the staff routing. In the left-down corner of the model two grey boxes of traffic condition and road work are crossed out. These characteristics are excluded from research but should not be forgotten during the actual planning process of daily routing.

Many routing models exists to generate staff routing which are highlighted in green. Exploration of different vehicle routing models and their application to salt spreading, combined with the practical and operational issues, led to the choice of a vehicle routing model. For this purpose, arcs and edges will be transformed into nodes. Staff routing will be solved using the metaheuristic procedure of tabu search, which will be incorporated into a geographical information system.

4. Methodology

This chapter provides both methodological aspects and a description of the routing model. The first part explains the research method of choice (section **4.1**), study area (section **4.2**) and software (section **4.3**). The entire model is introduced in section **4.5** which is documented in section **4.6** and **4.7**. Concluding remarks finish the chapter (section **4.8**).

4.1 Research method

The research structure of problem solving is based on the system view of Mitroff et al. (1974). It ensures to follow a proper structure with corresponding research steps of this thesis. The systemic perspective is created to study science from a holistic approach. Disregarding a whole system perspective and a holistic view may lead to a miss of essential characteristics of this set of problems (Mitroff et al., 1974: p.46). The structure consists of four phases: conceptualisation, modelling, model solving and implementation (figure **4.1**).

The conceptualisation (1) retrieves both the routing model factors found in practices as well as the literature brought together in a conceptual model. Here, the routing model was built in the modelling phase (2) and defines the relationships and modelling steps, as well as GIS architecture. This will lead to prepare input data and the creation of the routing model itself. The model solving phase (3) proposed different routing scenarios which will be solved using this model. The implementation phase (4), unfortunately, is hard to quantify since the routing project is still in the exploration phase. To fill in the void and get an understanding on how the implementation can be beneficial within the organisation, the model and solutions are being reviewed. Phase four consists of discussing implementation possibilities of the model within the organisation. As described in the introduction, research questions (RQs) are based on both structure and sequence of the system view problem solving.

1. Conceptualisation	Factors retrieved from current practices	**RQ1**
	Retrieve factors from literature	**RQ2**
	Create conceptual model	
2. Modelling	Data input	**RQ3**
	Create routing workflow	
3. Model solving	Scenario analyses	**RQ4**
	Scenario overview	
4. Implementation	Routing workflow discussion	**RQ5**
	Possible implementation within organisation	

Figure **4.1** A four-step framework of the systems view of problem-solving. Each of the four-steps is linked to a specific research question which are formulated in the thesis's introduction.

4.2 Study area: Hoogvliet

The municipality of Rotterdam counted a total of 629 606 inhabitants on January first, 2016, which makes it the second largest city in the Netherlands (Municipality of Rotterdam, 2018). Currently the municipality services by means of gritting routes 990 km of roads and 630 km of bike lanes (Municipality of Rotterdam, 2014). This is carried out from two central depots (figure **4.2**). For this gritting operation, they use 22 big gritting vehicles and 42 medium gritting vehicles (Municipality of Rotterdam, 2014). This study focuses on a part of Rotterdam and our routing model is initially developed and tested for this part only. This allows the author to develop a GIS prototype and to provide a concept. In a later phase, this concept can be expanded to remaining roads in the city of Rotterdam and completes the entire gritting service system.

The area of Hoogvliet is chosen in order to set up an initial model (figure **4.2**). Rotterdam annexed Hoogvliet in 1934, as well as the city of Pernis. The area consists mainly of residential areas built during the 1960's of the last century (HGH, 2018). Hoogvliet is located in the southern part of Rotterdam and comprises of two main gritting routes: HR_044 and HR_045 (appendix **A**). Gritting route HR_045 is approximately 43 km in length[1] and is routing in the neighbourhoods of Zalmplaat, Boomgaardshoek, Meeuwenplaat, Middengebied, Centrum, Westpunt and Nieuw-Engeland. Gritting route HR_044 is around 27 km in length and routed in the neighbourhoods of Oudeland and Tussenwater. Also, the access route to the small residential area of Pernis (North-East of Hoogvliet) is serviced by the current routing. The number of deadheaded kilometres is estimated to be around 8% for route HR_044 and 28% for HR_044[2] respectively.

To develop a GIS routing prototype, the Hoogvliet is suitable as a study area for several reasons. The area (i) is relatively small, but compact for routing, is largely surrounded by the river Oude Maas on the south and west, motorway A15 in the North and agricultural fields in the east. Also, Hoogvliet (ii) consists actually of more than one route, which allows us to use districting to group routes. These routes (iii) have a high amount of deadheading, probably resulting in promising solutions. Also (iv) the workload of the routes (27 km against 43km in length) is unbalanced and on top (v) the depot is not located within the area itself. This forces to include several starting points, both from highways and local roads. It also is (vi) not too large to solve for routing algorithms. At last, (vi) the winter service organisation uses also Hoogvliet when experimenting in new techniques, such as applying different kinds of salt.

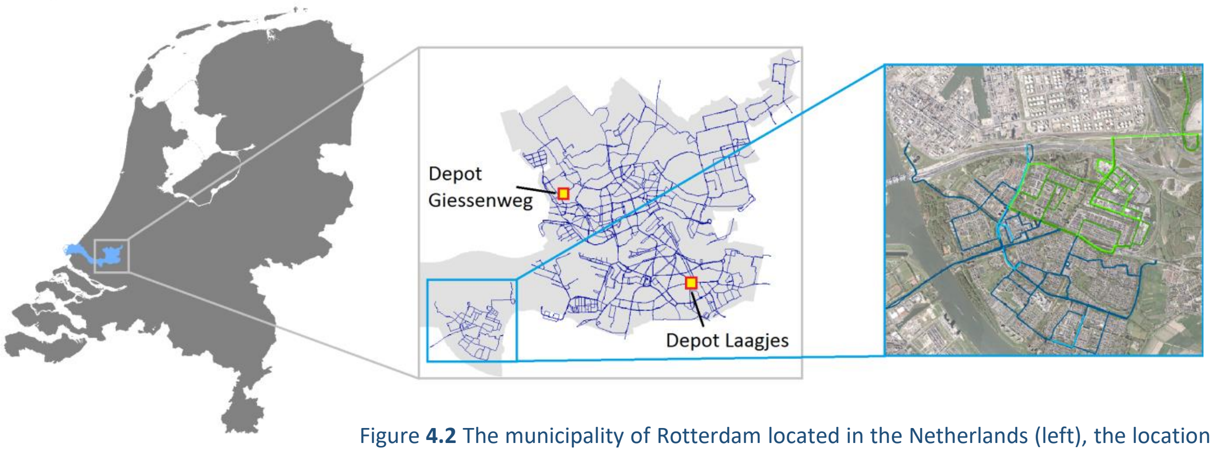

Figure **4.2** The municipality of Rotterdam located in the Netherlands (left), the location of the of Giessenweg & Laagjes depot (middle) and the gritting routes of Hoogvliet

[1] This estimation is based on initial assumption of the current digitised gritting routes and does not incorporate the travel kilometres from thSce depot to the start location and from the end point back to the depot.
[2] The estimation of deadhead kilometres is within the servicing time (i.e. between the first and last road serviced), travel kilometres from and to the depot are excluded. Taken the last remark into account the percentage of deadheading is even larger than the current estimation.

4.3 Software

The choice of GIS routing software is the most important choice to make for routing model creation. Different GIS software packages are available, with pros and cons for route modelling. Three points have been summarised within the organisational framework al considered important for choosing the most suitable routing model. These are, again, (i) mixed graph, (ii) limitation of U-turns or other special manoeuvres and (iii) introduction of a time-window. The situation takes place with (iv) multiple heterogonous vehicles, (v) multiple depots and (vi) not every street needs servicing. Next to these routing issues, attention has been given to organisational applicability in terms of software, data and knowledge of GIS systems. This to ensure that the developed routing model can be implemented sustainably within the municipality of Rotterdam. Several alternatives, including QGIS, TransCAD, Open Source Projects and ArcGIS. will be discussed.

QGIS is an open source GIS program to support geospatial information editing and analyses. The most known routing application which relied on QGIS is PG Routing. PG routing is an open source project which extends the PostGIS / PostgreSQL geospatial database to create geospatial routing and functionalities. Data and attributes can be easily changed using GIS clients like QGIS but also uDig (PG Routing, 2018). The project contains several routing algorithms, e.g. the Floyd-Warshall Algorithm for all pairs shortest path, Travelling Sales Person and Turn Restriction Shortest Path (TRSP). The project does not include solutions for vehicle problems or arc routing problems. On the website of QGIS a plugin of the Chinese postman plugin is available[3], but this does not account for the wish to use only a certain amount of the network (rural postman problem) and time-window implementation. Therefore no current available plugins for QGIS are preferred to accomplish our route optimization.

TransCAD is a state-of-the-art GIS program and designed to help transportation professionals store, display, manage, and analyse transportation data. It offers several routing functionalities, amongst which the vehicle routing problem and even solutions for arc routing problems. It does seem to include many of the preferred options, such as time windows, multiple depots and even the possibilities to use non-homogenous vehicle fleets (TransCAD, 2018). The downside of TransCAD is that the municipality of Rotterdam doesn't own a license yet. Licenses are quite expensive, being $12.000/year for a single licence (TransCAD, 2018). Also, the knowledge of these software packages within the municipality of Rotterdam is limited. And on top, it is unknown if the used TomTom Multinet dataset can be correctly loaded into TransCAD. Ranging these potential organisational and financial drawbacks, this option is therefore not preferred.

For arc and vehicle routing some open source projects are available. Mourão & Pinto (2017) made an overview of open source software for solving various arc routing problems and instances. Most notable of this list is the work of Oliver Lum (2017) on creating an Open-source Arc Routing Library (OAR Lib). In this library several heuristics have been deployed for instances on the Chinese postman problem, directed rural postman problem and the windy rural postman problem. It works with Open StreetMap data and visualization utilities have been built-in. All these formulations of the arc routing problem do not fit the specific wishes of the rather complicated demands of adding time windows, multiple depots and multiple vehicles. Adding these features to a programming environment is considered too difficult and out of scope of this research. Next to these issues, these programs are more designed to be IT optimization tools rather than a GIS-based approach.

And at last ArcGIS, a widely used corporate GIS program developed by ESRI inc. For routing applications the user is directed to an extension of ArcGIS, called network analyst (ESRI, 2018). This offers the user several routing functionalities, such as the travelling salesman person and vehicle routing problems. For the vehicle routing problems, many specifications can be added, such as time windows, multiple

[3] https://plugins.qgis.org/plugins/chinesepostman/

vehicles and depots and even penalties and restrictions on certain vehicle manoeuvres. ESRI does not provide solutions for arc routing, but they deliver a plugin for arc routing developed by the company of RouteSmart. This plugin is not free to use; licensing prices are upon request.

Having considered all options, the vehicle routing problem solver of ArcGIS network analyst was the software of choice to accompany the gritting route process. The choice for the ArcGIS network analyst is based on:

- Availability within the context of the municipality of Rotterdam
- Within the organisation it is known how to use ArcGIS, and to a lesser extent also the network analyst extension
- Allowance of choice towards the user amongst many specific problems, such as different vehicle types, districting and time windows
- The software has developed adequate documentation
- Allows input from shapefiles and is able to parse network data
- Can correctly deal with network data, network distances and network restrictions

Although the advantages are considerable, the software shows some drawbacks, and were partly discussed with the implementation part of routing model in GISs. The biggest drawback is that the heuristics used by ArcGIS network analyst are propriety and therefore working as a black box. They do not state which solution methods they use in transportation modelling, which usually leads to users believing in the efficiency of the output (Mapa & Lima, 2014: p.845; Curtin et al., 2014). Also, the model is solved for nodes as a vehicle routing problem. The solution of this model has to be translated into arcs. The routing model output should be transformed and critically examined before deciding upon rerouting decisions. In the next section the routing workflow will be discussed, as well as the establishment of this routing model is introduced.

4.4 The routing workflow

The calculation of routes is incorporated into a comprehensive workflow. This workflow consists of thirteen phases, ranging from the creation of the network dataset to visualise the staff routing output (table **4.1**). The model is a translation from the conceptual model (section **3.6**), where the parameter input (depicted with a **P**) corresponds to the routing characteristics. The orange boxes state that these steps rely on data input whereas the green box represents the final output of staff routing. All grey boxes indicate intermediate steps within the data preparation routing processes (figure **4.3**).

The start of the model initializes various data inputs. This consists of road data sources such as current routing in the form of digitized lines, TOP10NL road segments and TomTom network data. Also, data considers frost spots to be loaded into the model; neighbourhood districts are imported as well. At last the location of the depots is added. During pre-processing various data inputs are prepared to be imported within the vehicle routing model. The network is created and the roads subject to gritting are extracted and manipulated to be correctly imported. Subsequently, the districting is created, and depots are added. This is finalised, as the remaining parameter settings are formulated, as setting the strategy & objectives and the fleet & staff assignment.

At the core of the routing workflow is the creation and optimization of routes. This is achieved using ESRI's vehicle routing solver, which uses an in-house developed tabu search algorithm. The output of the vehicle routing model is the entire route but amongst various input nodes. Next this primary data output is transformed from node routing to arc routing statistics, during the post-processing phase. Also maps are created using data visualisation techniques. Both route report and route map are presented to the user.

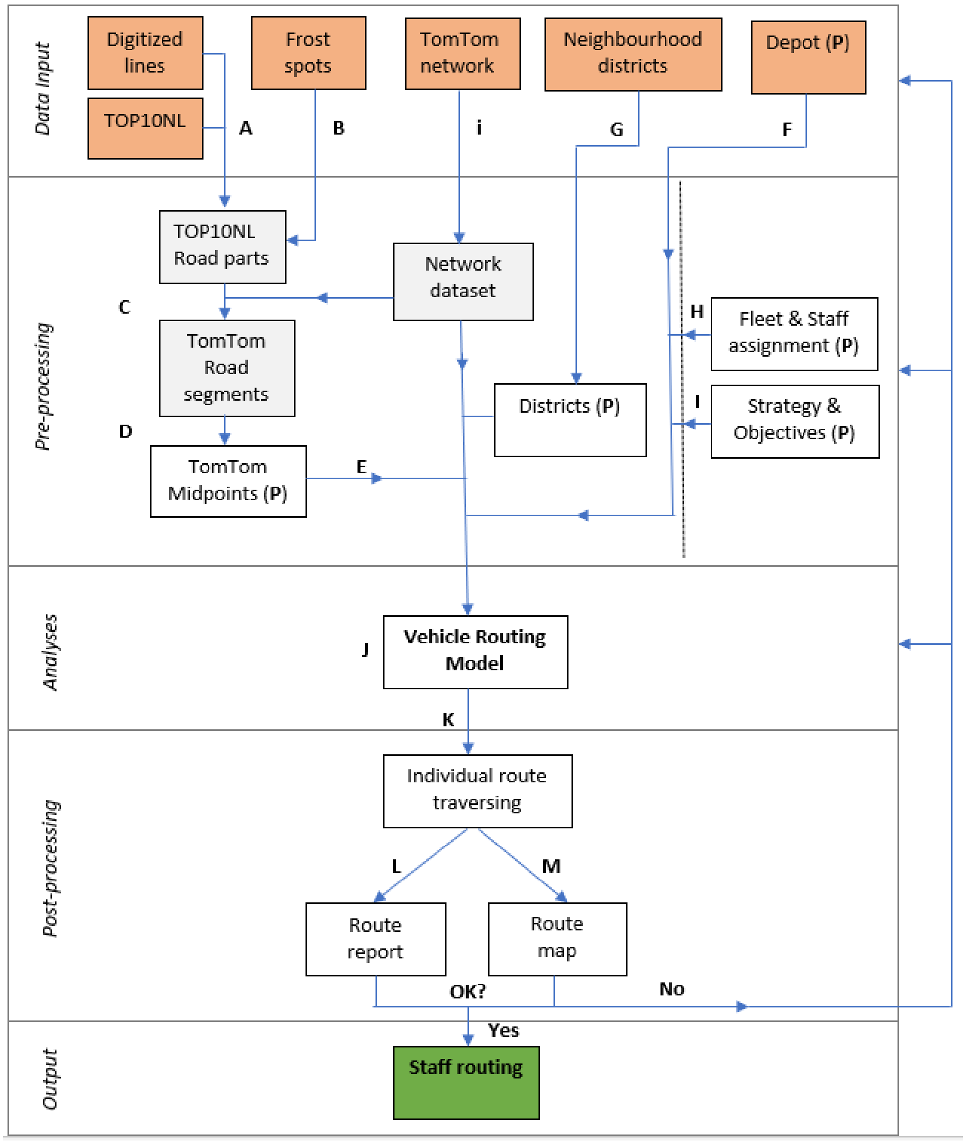

Figure **4.3** Routing model workflow. Depicting all fourteen steps of the routing model workflow. If the routing is considered OK the routing output is final. If the created route report and route map is not satisfactory, the user can change one of the parameters or change the data input of the model and redo the remaining phases until the user is satisfied with the routing.

Table **4.1** Phases of the routing workflow

i	Create network dataset	Adding TomTom network in ArcGIS network dataset format
A	Digitisation	The translation from digitised lines into TOP10NL road parts
B	Adding attribute data	Adding critical frost spots to the TOP10NL road parts
C	Transformation	Transforming the TOP10NL road parts to (TomTom) road segments
D	Arc to node routing	Creating nodes from arcs
E	Snapping & directionality	Correctly placing nodes to the network
F	Adding depots	Adding depots and characteristics
G	Sectoring	Adding and constructing routing districts
H	Fleet & staff assignment	Adding vehicles
I	Objective function	Objective function and general model parameter setting
J	Create OD matrix & Solve	Route model solving using ESRI's in-house tabu search algorithm
K	Route traversing	Create additional individual route dataset
L	Route reporting	Routing model output with arc statistics
M	Route mapping	Routing visualisation techniques

It is up to the user to decide if the formulated routing is considered good. If it is considered sub-optimal, and the user wishes a different outcome, one can go back to one of the earlier stages of the routing workflow. Three options are depicted in the routing workflow to reconsider. Firstly, the vehicle routing model can be re-run. The probabilistic set-up of tabu search based algorithms can possibly create different routing outcomes if the model is re-run. Second, one of the parameter inputs can be changed. Different districting, starting depot and/or gritting roads can be inserted to see if this creates a better routing. Thirdly, data input can be changed. Different districts, network datasets and other base data may result in more robust routing output. If the user is satisfied with the route reporting, then the staff routing is as final.

The following sections describe the routing workflow more in detail. Section **4.5** describes the data input, section **4.6** dives into each of the phases of the routing workflow, whereby section **4.7** looks at the initial vehicle routing model parameter settings.

4.5 Data description

Three road data sources are used during the modelling process: (i) the current routing, (ii) the TOP10NL road segments and (iii) the TomTom Multinet road data. Besides these three datasets three additional datasets are available. This is an (iv) depot dataset, an (v) additionally created asset management dataset describing critical frost spots, which is built on top of the TOP10NL road segment dataset. Lastly, a (vi) neighbourhood dataset, which includes the municipal districts of Rotterdam and is used for road segment sectoring. Every one of these datasets contains information and capabilities which are needed in the process of route making and will be briefly introduced.

Routing dataset: current routing

The current routing consists of routes, which are shaped as digitised lines; they contain information about route number and category (e.g. access route, main motorway route). Multiple digitised lines exist per route; each line segment indicates if this route part is used as a salt spreading route, or as a connection route. Both begin and endpoints of routes are given, together with the ID of the line segments they can be used to discover and reconstruct individual trails.

For now, the current routing serves the purpose of generating routing instructions on A3 printed maps. Both data structure and layout, serving the paper map production are not designed for maintaining the road assets, nor for creating automated routing. However, the current routing contains important data about the actual roads requiring service and type of vehicle. This information can be of value for creating new routing Taking a closer look at the distinction between a salt spreading route and connection route reveals many small digitisation errors. This implies that the roads subject to spreading, the direction and road passing have to be manually checked before routing calculations will be activated.

Asset management dataset: TOP10NL road parts

The TOP10NL is the 1:10,000 topographic map of the Netherlands. It consists of various object classes, each representing a topographic object of roads, buildings but also an area classified by a theme. Many public organisations, including the municipality of Rotterdam, are obliged to have their part of the TOP10NL in place and keep them up-to-date. For our purpose the interest lies within the road parts object class of the TOP10NL, which always contains multiple geometric aspects (figure **4.5**). As a next step to the road surface, lines, point, centre point and centre lines can be constructed, where only the road surface geometry is used. When it is referred to road parts, road surface geometry is meant. Furthermore road parts object class contains several interesting attributes, as at the other side road type and main traffic use may help in the digitisation process and prevent selection of wrong road parts. Other attributes such as infrastructure type and separated roadways may help in the translation from road part into a network dataset.

Using the TOP10NL as an asset management dataset has several advantages. First, the TOP10NL is one of 12 key registers of the national Dutch key register system, which was implemented to have Dutch governments organize (and use) their data more efficiently. In daily practise this implies that the TOP10NL is well documented and knowledge of using and maintaining the dataset is guaranteed within the organisation. These benefits lead to a more efficient and sustainable use of gritting route data. . Second, the polygons can be modified if this is wished upon. Third, other road asset management data can be stored on the same polygons. This makes it easier for the road authority to have an integral approach for road maintenance. Fourth, in the future the TOP10NL is planned to be linked to other key registry systems in order to reach an even more refined asset management. A link with the Key Register Large scale topography (basisregistratie grootschalige topografie) would lead to better geometric properties of road parts. In a next phase this can be of interest for extracting road width and road surface properties, which allow asset managers for even more precise estimations of salt usage. Fifth, the data is owned by the municipality. Storing asset management on the network dataset would imply that the municipality is attached to the network dataset supplier. If one would like to terminate the contract or share the data for public usage, problems might occur. Sixth, having a way to link asset management datasets to a network dataset might be interesting for other applications within the municipality which require routing, e.g. the routing for street sweeping and/or visual road inspections. Also, other datasets could be linked, like the tree dataset for routing tree trimming.

Figure **4.4** Wrong digitized routing. The red line indicates a connection route which is correctly depicted, while the other connection (2x blue line) on the right is not highlighted in red.

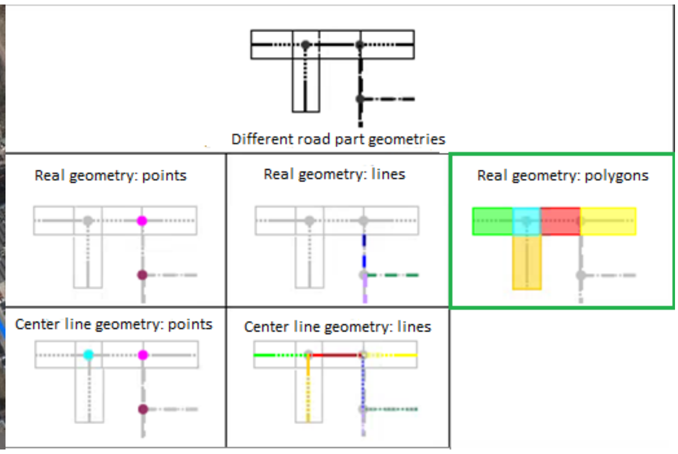

Figure **4.5** Different geometries of the TOP10NL road part. This thesis only uses real geometry: polygons, highlighted in green (source: PDOK, 2017).

Asset management dataset: critical frost spots

Although the TOP10NL road part data were introduced as the asset management dataset, it is sheer impossible to add every attribute of interest directly into the road parts. One of these attributes is critical frost spots. Critical frost spots are those places which could need high priority due to slipperiness. Infrastructure like bridges, shadowy places and spots where earlier accidents have taken place, are the basis for this category. Owing a dataset which describes the exact positions of these places is of great importance, because they are used to prioritize links in existing routes. Not obtaining precise information may result in data generalisation or location errors, failing to take adequate preventive measures. Thus, registration should be correctly organized, maintained and applied to the routing calculations. Critical frost spots here are used as an example how data can be linked to the main asset management dataset, the TOP10NL. In daily practice however, many other datasets can be linked as well, e.g. weather information, temperature sensors and/or additional road information.

Asset management dataset: Depots

All depot locations are created and stored in a point shapefile and snapped to the network dataset. Already created depots do get additional attribute data which is inserted in the routing problem, such as maximum vehicle capacity and time window settings. These are used to set the vehicle routing problem within the vehicle routing workflow. The depots are used as start and as endpoint of the route for vehicles (figure **4.6**).

Figure **4.6** Depot Giessenweg [author's own picture]

Network dataset: TomTom Multinet

Both routing and asset management dataset are not suitable to analyse networks. To enable network analyses a third type of dataset is needed, i.e. a network dataset. Network datasets consist of edges, arcs and junctions. Together with attributes, which control the navigation over the network and other attributes they establish a network dataset (ESRI, 2017b). They contain information about the network, such as length, speed limit, road hierarchy and travel time. Additional information is given about junctions, like junction type and turn restrictions. Several of these datasets exists, both from open source and commercial providers. Familiar open source network datasets are for example OpenStreetMap, or the Dutch National Roadfile (Nationaal Wegen Bestand). Popular commercial datasets can be found within TomTom Multinet and NAVTEQ NAVSTREETS.

The municipality of Rotterdam owns a license in order to use the TomTom Multinet dataset, which is their network dataset of choice. The reason for using the TomTom Multinet is that, unlike open source alternatives like the Dutch National Roadfile, which contains information about estimated travel times. These are of importance to route vehicles within the two-hour time limit. Over- or underestimation of travel times can lead to violation of the time windows or inefficient use of vehicle time capacity. Secondly, the TomTom dataset contains additional tables which provide in special driving manoeuvres as well as restrictions. Having these additional data geometrically joined benefits the providence of realistic driver routes. Finally, a licensing contract enables contractors to receive reliable up-to-date routing when needed. Additional products can be bought if needed, like more accurate and real-time speed profile updates. For the detailed data model behind TomTom Multinet, in which the relationship between the shape files and attribute data is described, the reader is referred to appendix **B**.

Sectoring dataset: Neighbourhood districts

There are several ways to sector links for routing. One way is the use administrative areas. In the Netherlands these administrative areas are dealt with on different spatial levels. Mostly used is the CBS neighbourhood classification. But for sectoring purposes, the classification seemed too large and therefore the more detailed administrative areas of sub neighbourhood districts are used (figure **4.7**). An industrial area just above the Oudeland and Tussenwater is not depicted in the map. A district name for this industrial area was created, being Nieuwe Gardering. Furthermore, there are some roads which lie outside of the districts. These are joined into a new district called Pernis.

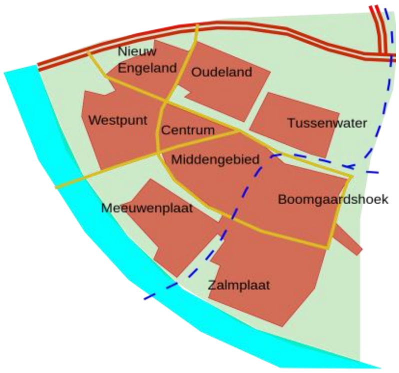

Figure **4.7** Neighbourhood districts Hoogvliet.

4.6 Modelling phases

The workflow as shortly introduced in section **4.4** consists of thirteen phases. The first four phases consist of correctly translating current routing dataset to an asset management dataset and finally to a network dataset. For technical details regarding these steps taken in ArcMap the reader is referred to appendix **C**. The next six phases consist of setting up the routing model. The last two phases deal with validation and visualisation of the staff routing.

Phase i: Creating network dataset

To be able to use commercially available street data within the calculations of ArcGIS Network Analyst, a network dataset must be created. This process can be time-consuming and requires a thorough understanding of network creation. For this reason, ESRI has released a street data processing tool on GitHub, which allows popular street products of TomTom Multinet to be automatically built into a network dataset. The tool processes shapefile data from TomTom Multinet by importing the street feature classes into a file geodatabase and adding fields for modelling overpasses/underpasses, one-way streets, travel times, hierarchy, and driving directions. Also feature classes for modelling turn restrictions and signpost guidance are created. The output of the procedure delivers a network dataset with edges and junctions. All three line datasets are provided with streets, signpost information and restricted turns.

After its creation the network can be used in ArcGIS, this does not mean that it is final. There are several occasions conceivable in which one would wish to (manually) adjust the network. Reasons like adding yet non-existent roads, removing roads and changing road attributes such as directionality, turn features and/or travel times. The most important reason however is to simplify the network. If the number of visiting arcs increase, vehicle routing problems do become more complex to solve. This step needs to gather all arcs in need of gritting before one can start with simplifying the network in a later phase. Due to commercial street data and complex network building functionalities, it was not possible to adjust the network. This means that the basic network is used as-it-is. No features are added, changed or simplified. Although this gives no direct problems, it does have practical implications for adopting the routing workflow.

Phase A: Digitisation

The first phase consists of digitizing the current route into the TOP10NL road parts, for which there are two main aspects: the selection of the correct TOP10NL road parts (false positives or false negatives will have to be manually added or deleted) and the ´correct translation´ of information about the road parts in the form of attribute data. For the road parts several attributes can be of interest to add.

The first phase consists of digitizing the current route into the TOP10NL road parts. For perfect fitting of the two datasets a commonality is required. This’’ join'' can be made on different aspects of the dataset, like spatial, attribute or unique field characteristics. Exploring the dataset revealed that the combination of a spatial join with attribute characteristics filtering led to the best overall result. Used attribute filters are those for the fields of motorized traffic and parking places. With this method not all required road parts could be selected. A total of 15 road parts are manually removed and 5 are added, approximately a 2% error rate. The total process resulted in a total of 999 selected road parts (table **4.2**).

The second phase adds attribute data to the TOP10NL road parts, of which several can be of interest, such as (i) the gritting class (main route, biking route), (ii) how many passing times does the road part needs to be gritted (ii) what is the original route number, (iv) how many times is the road used in the original connection routes (v) what are the sequence numbers of a road part inf the original route. Attributes (i) and (ii) are needed for the newest route model whereby the last three attributes are needed to calculate the efficiency of the current routing.

Table **4.2** Digitisation road parts

	Action	Count
Spatial join	Add	1064
		1064
Attribute: Main road usage		
Bicycles, mopeds	Remove	37
Motorized traffic	Remove	15
Pedestrians	Remove	1
		1011
Attribute: Road type		
Parking area	Remove	2
		1009
Manually edited		
Should not be spatial joined	Remove	15
Not within spatial join	Add	5
Total remaining road parts		**999***

*Consisting of 512 links and 487 junctions

Unfortunately only the first attribute (gritting class) could be digitised from the original lines. This resulted in the manual adding of the gritting passing times for roadways. The remaining three attributes are relevant for calculating current gritting times and they will be added but only in phase D.

Phase B: Critical frost spots
The TOP10NL road part data layer is used as the main asset layer as digitised in phase A. It contains two additional attributes: the gritting class (main route, biking route etc) and how many passes are needed for gritting. In this stage supporting datasets can be linked onto the road part dataset. One dataset of interest to be linked is critical frost spots, due to their high priority, due to slipperiness. Infrastructures as bridges, shadow places and spots were earlier accidents have taken place may also fall within this category.

To account for the critical frost spots a new dataset layer has to be created. New objects can be created either by adding a polygon, line or point object (figure **4.10**, next page). These can be linked to the TOP10NL road parts via a spatial join. Adding the spots directly to the road part would result in inaccurate and generalized data, and these spots cannot be adequately recognized.

Phase C: Transformation
The main objective in phase C is to select the right components of the underlying TomTom network dataset. This starts with creating a spatial join between the TOP10NL road parts and the TomTom street network and resulted in a selection of 1144 links (table **4.3**). At this moment, there are no criteria in either TOP10NL nor TomTom dataset to make a finer selection. Therefore, all selected TomTom links which are not correct have to be manually selected and deleted. Over 400 links were removed easily, after detection wrong. During this transformation, it was possible to select all junctions of the TomTom dataset, represented here as points. This step is not done in this moment, whereas selecting all junctions serviced for gritting and adding them into the routing model would create a much bigger routing problem and thus harder to solve. For this reason only links are used in the routing model. For big intersections however links are used between multiple TomTom junctions. These links were joined to the nearest TOP10NL links. The spatial join also missed 26 TomTom links, and were added to the dataset, which in the end resulted in a total of 758 links.

Table **4.3** Digitisation TomTom road links

	Action	Count
Spatial join	Add	1144
		1144
Manually edited		
Should not be spatial joined	Remove	412
Not within spatial join	Add	26
Total remaining TomTom links		**758**

Phase D: Arc to Node Routing

After selecting all TOP10NL road parts (phase A) and all relevant TomTom links (phase C), the attributes from the TOP10NL road parts will be linked to the TomTom dataset. From the TOP10NL road parts only those parts which represent links are used; road parts which represent junctions are neglected. Joining the road part junctions to TomTom links will result in many digitalization errors and ultimately in wrongly addressed routing. The joining of TOP10NL road part links to TomTom links is not straightforward: some TOP10NL road part links represent several TomTom links, or the other way around. This concept of a 'many-to-many join' is illustrated by means of an association (figure **4.8**).

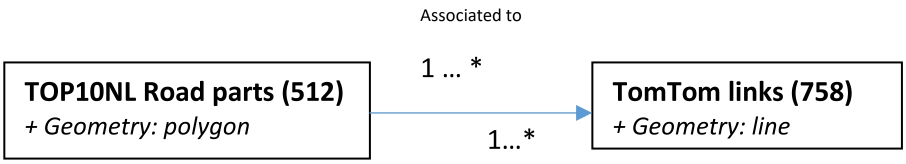

Figure **4.8** Association between TOP10NL Road parts and TomTom Links

One-to-many road parts are associated to one-to-many links. This illustrates by design that it is not possible to have road parts which are not associated to any TomTom links. Furthermore any road part is always associated to a TomTom link, whereby all TomTom links represent one-to-many road parts. This ensures that all selected links are incorporated into the routing model. Testing to apply this association led to many digitisation errors, and the geometry of both the road part and TomTom links is changed into points for better digitisation results (figure **4.9**). Next to the advantage of a better fit for attribute transfer, the TomTom links had to be converted to points anyway. This is due the fact that the model uses nodes (points) instead of links (lines) as input for routing calculation.

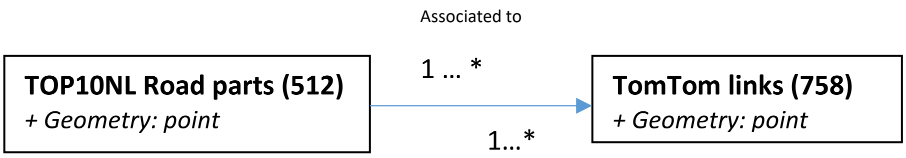

Figure **4.9** Reconfigured association between TOP10NL Road parts and TomTom Links

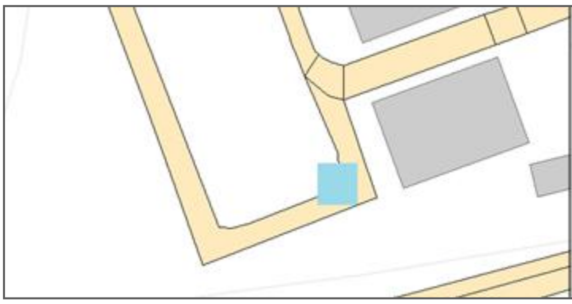

Figure **4.10** Adding critical frost spots (blue polygon) for phase B.

Figure **4.11** Manual checking if the centre of the TOP10NL road parts (red points) connect to the centre of the TomTom lines (green points) via the black plotted line.

The transfer of attributes of the TOP10NL road parts to the TomTom links is performed by multiple sessions; all 758 TomTom links are connected to the nearest TOP10NL road part as well as their connection. The latter is manually checked by means of a visual inspection (figure **4.11**, previous page). Nine TomTom links were wrongly connected and therefore coupled to a different TOP10NL Road part. All remaining TOP10NL road parts, not coupled yet, are identified and selected, and linked to the nearest TomTom link. Again, this connection between the remaining TOP10NL road parts and the TomTom links is manually checked for digitisation errors. Of the 96 remaining TOP10NL road parts, 26 were manually edited to link to another TomTom link.

As a next step both datasets are linked to each other. For all TomTom points the correct TOP10NL road part is added as an attribute to the TomTom link table. To join the table containing the TomTom links to the TOP10NL road parts, one has to be sure that all attributes of the TOP10NL road parts are transferred into TomTom links (figure **4.12**). For the 1:1 relationship (green) and *-1 relationship (blue) this is effectuated by means of an attribute join. The TOP10NL not being joined yet have been collected in a third database and joined via a related relationship database, ensuring the 1-* cardinality (orange). As a result, all TomTom links have the correct attribute information of the link itself and the corresponding TOP10NL road part.

TOP10NL road parts

ID	Attributes
top10nl.117157263	...
top10nl.117157264	...
top10nl.117157265	...
top10nl.117157266	...
top10nl.117157267	...
top10nl.117157268	...
	...
	...

TomTom links

ID	Foreign key
15280049880249	...7263
15280049880250	...
15280049880251	...7265
15280049880252	...7265
15280049880253	...7265
15280049880254	...
15280049880255	... 7268
15280049880256	...

Remaining TOP10NL road parts

ID	Foreign key
top10nl.117157269	...
top10nl.117157280	...
top10nl.117157280	...
top10nl.117157286	...
top10nl.117157297	... 0255
top10nl.117157298	...
top10nl.117157299	...
top10nl.117157300	...

Figure **4.12** Data structure between TOP10NL road parts and TomTom links tables

Phase E: Snapping & directionality

After converting all TomTom links into points and connecting them to the significant TOP10NL road part, TomTom midpoints can be snapped to the network. This snapping cannot be carried out directly onto the network. The network representation is a simplification of the reality and features within the network are represented in different ways (figure **4.13**). Currently one node has to be placed onto the network. This is fine for simple roads, which has to be serviced only once, via either a positive, or negative direction. Roads which require positive and negative passing, represented as a simple line features, require special treatment (figure **4.13c**). To deal with this two instead of one TomTom midpoint is placed. One midpoint is serviced on the right side and the other on the left side of the road. This makes the road being serviced in both directions.

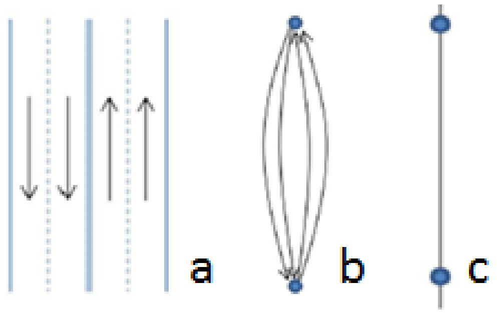

Figure **4.13** Network representations (a) in reality, (b) in the underlying TomTom data structure and (c) in the feature representation within the GIS environment

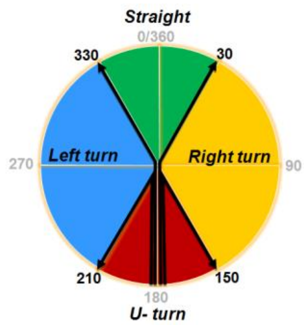

Figure **4.14** Global turn evaluator.

To account for this, there is again, no general rule or attribute in the dataset which can account for this. Streets may need treatment in both positive and negative directions. Again, the solution of this problem is manual labour. The current routing is loaded into ArcMap and looked through the current classification of gritting and connection roads. From this classification, those links are selected (by means of the TomTom midpoint) which needs treatment in both positive and negative direction. The result of this analyses are documented in maps and can be found in appendix **D**. In total 109 nodes have been duplicated, bringing the total up to 906 nodes. Creating additional nodes comes with an ever increase in the computational complexity of the combinatorial optimisation problem. This results in an increased processing time for solving. One last action before snapping the nodes to the network, is to set a time window. All the roads must be serviced within two hours, which is thus inserted for all nodes. Vehicles cannot add any nodes after the two hour time window. Lastly, in the input phase the nodes could not be added due to that some nodes did share a common identifier. To solve this the OBJECTID of left, right and both way nodes are recalculated. For right nodes 10000 is added and left nodes 20000 is added. Result is an OBJECTID2 class which contains unique object ID's for insertion into the routing model.

Phase G: Depot
The depots are represented by points, which are snapped to the network. The depot starting time is added as an attribute value of 00:00:00. Any time can be used, since the network dataset does not contain spatiotemporal traffic data and/or dynamic historic travel data.

Phase H: Fleet & Staff assignment
The fleet & staff assignment is quite straightforward. Two members of the team are assigned to the two vehicles. The vehicles start at the Giessenweg depot and they also finish there. The time is set on zero and starts running when the driver leaves the depot. Then the time window is set on the service nodes to be served in a 2-hour time window. This means that no end time is needed to set on the vehicles. ArcGIS Network analyst also requires you to set the number of nodes which can be serviced, with is set to the maximum of a thousand nodes.

The fleet and staff assignment also incorporate some kind of view on the time it takes for the driver to perform manoeuvres. For this purpose the global turn evaluator is used to penalise different types of turns. The straight turn and U-turn have a 60 degree turn angle range, whereas the left and right both have a 120 degree turn range (figure **4.14**, previous page). The standard values are set a 3 second turn penalty on right turns, 5 seconds on left turns, 30 seconds on U-turns and 2 second for crossing straight lanes which is considered a normal to high penalty (O'Connor, 2013; Price, 2008). A few remarks on the settings on these values: left turns are given a higher penalty than right turns, because they are more difficult to make and create more interference with the traffic. A 30 second penalty is given on U-turns because of the large length and width of the salt spreading vehicles. U-turns are therefore only allowed to be taken at intersections or dead ends, not on the middle of the road. When the vehicle drives straightforward on an road junction only a 2 second penalty is rewarded. Intersections or road crossing with different road hierarchies require alertness from the driver and possibly slow down the actual driving time in case other traffic inserts into lanes.

Phase G: Sectoring
Now that all the nodes have been placed on the network, it is time to assign the nodes to different vehicles. The standard option is to not predefine sectors. In this case, nodes are inserted and replaced between vehicles by the tabu search algorithm. Sectoring can replace this process by predefining which nodes are serviced by which vehicle, either by hard or by soft boundaries. Hard boundaries do not allow nodes to be replaced between vehicles; the vehicle is bounded by the sector it is assigned to. Soft boundaries allow vehicles to service nodes outside the initial district. Servicing outer nodes however comes with an additional cost which is put on top of the cost function, which is based on

Euclidean distance from the route district (ESRI, 2017b). The further away nodes are from the vehicle district, the less chance it has on being assigned to the specific vehicle routing.

Sectors are based on administrative or transportation relative factors. As input, the administrative areas of the Hoogvliet sub-neighbourhoods are chosen. These consist of nine subareas and one area which falls outside of Hoogvliet. Because there are only two vehicles available for serving ten areas, the areas have to be merged into two coherent blocks. Merging these areas is based on the adjacency of administrative districts, but also transportation related factors are taken into account. Sectoring can have a significant impact on the quality of routing and the workload balance between routes. To account for this, not one but two different sectoring outlines are made, making it possible to compare different sectoring and get a better understanding on how sectoring influences routing. For comparison to the manual drafted routes districts are formed which match closest to the original routing.

Phase I: Strategy & Objectives

The main strategy of the municipality of Rotterdam is set to reduce driving minutes. This does not mean other factors to be irrelevant. The municipality would also like to see a reduction in the total vehicle mileage. This variable will also be tracked and noted in the results, to see if there is a balance. However, the objective is not minimised by the routing algorithm. Rotterdam also would like to explore the use of less vehicles and drivers, but for Hoogvliet no viable solution is found, due to the two-hour time window.

To incorporate the strategy of reducing driving minutes into the routing model an objective function is used. This allows the model to minimise driving minutes for a given input. For evaluating the routing solution the follow model is established:

$$TT_m = TT_{start} + TT_{end} + \sum_{i=1}^{n}(\mathrm{TT}_{\mathrm{SRSi}} + \mathrm{TT}_{\mathrm{NSRSi}}) + \sum_{i=1}^{NLt} t_{Lturns\mathrm{i}} + \sum_{i=1}^{NRt} t_{Rturns\mathrm{i}} + \sum_{i=1}^{NUt} t_{Uturns\mathrm{i}} + \sum_{i=1}^{NSt} t_{Sturns\mathrm{i}} \quad (4.1)$$

Where:

TT_m	Total travel time in minutes
TT_{start}	Travel time from the depot to the first service road
TT_{end}	Travel time from the last service road to the depot
$TT_{\mathrm{SRS}i}$	Travel time for the *i*-th service road segment
$TT_{\mathrm{NSRS}i}$	Travel time for the *i*-th non-required service road segments
n	Total number of road segments in the route
N_o	Total number of road segments outside the service district
N_{Lt}	Number of Left turns
t_{Lturns}	Time penalty on left turns
N_{Rt}	Number of right turns
t_{Rturns}	Time penalty on right turns
N_{Ut}	Number of U-turns
t_{Uturns}	Time penalty on U-turns
N_{St}	Number of straight turns across intersections
t_{Sturns}	Time penalty on straight turns across intersections

Phase J: Create OD matrix & Solve

Phase A-I prepared all parameters and the objective function for the vehicle routing problem. In phase J, the vehicle routing problem is solved by the ArcGIS network analyst in a series of steps. The first step is that an origin-destination (OD) matrix is constructed from all the inserted TomTom midpoints together with the depot. ArcGIS network analyst uses Dijkstra’s algorithm to create the shortest pairs between all points, taking into account the network distances as specified by the network dataset. The second step involves the creation of an initial solution by inserting orders into one of the vehicles. The order is inserted to the most appropriate route (ESRI, 2017a). During the third step orders are replaced from position within a route and exchanged from one route to another. This exchanging of orders is based on the tabu search algorithm developed in-house by ESRI (ESRI, 2017a). The solving time for the three steps from the vehicle routing problem tabu list search differences per instance. In this case 903 nodes have been placed on to the network, two vehicles and some restrictive factors like time windows. Solving the vehicle routing problem on this instance takes between 1.5-9 hours on a desktop computer with an Intel i5 2500CPU @ 3.30GHz and 4.00 GB installed memory (RAM). The large time differences is caused by the number of nodes added to the vehicle routing problem and if additional conditions like districting is used.

When the tabu search algorithm achieved the local optimum, a total of three outputs are generated. Starting with the calculated route. This consist of one line and has some attribute data, like starting time, ending time and length. Secondly the list of orders, which contains information about the sequence of orders serviced and the time of servicing. Thirdly, the depot visits are listed, here the depot is visited two times; at the beginning and ending of the service. Although the vehicle routing problem is solved and the route directions are given, some last work has to be done. This will now be dealt with in the post-processing steps.

Phase K: Route traversing

Before one can report the routing and visualise the map, some additional outputs have to be created. This consists of turn, edges and junction information. To retrieve this information the create turn feature class tool is used. Together with the output created in Phase J: Create OD matrix & solve, all the necessary data is created for the route reporting. However, all data outputs concerning routing are created lumped together in their respective datasets. This means that, for example, the turns of all vehicles are delivered in one dataset. To create additional datasets which only contain the given data of a single vehicle, a split layer by attribute script is used. This created the needed datasets and exports these into a file geodatabase.

Phase L: Model reporting

Subsequently, the solution is made with the use of node routing, instead of arc routing. Placing a node on each arc makes sure that each arc gets serviced. However, when the model passes the node, the model output does generate information about the service between node to node. The interest here, however lies in the information about traversing arcs. The results need to be translated to arc routing and to be plotted on maps before one can decide upon the final routing. For the model report a template is created (figure **4.15**). Several components are extracted and calculate from the route output and route traversing and do correspond with the objective function (*formula 4.1*). These are highlighted in blue. The seconds are displayed in decimal time (1/100th of a minute).

The five components (i) Time from depot to first service road, (ii) Time from the last service road to depot, (iii) service time, (iv) deadhead time and (v) manoeuvre time do add up to the total travel time.

	Time route HR_045
Start time	00:00:00
First service road arrival time	00:11:59
Last service road departure time	01:45:09
End time at depot	02:00:14
Time from depot to first service road (min)	12.00
Time from the last service road to depot (min)	15.07
Service time (gritting)	58.75
Deadhead time	5.56
Manoeuvre time	28.85
Number of left turns	25
Left turns (min)	2.33
Number of U-turns	7
U-turn (min)	3.5
Number of right turns	125
Right-turn (min)	6.25
Number of straight across intersections	505
Straight across intersections (min)	16.83
Manoeuvre error margin	-0.23
Total travel time (min)	**120.23**
Total distance (kilometres)	**77.46**

Figure **4.15** Route report example

The manoeuvre time is broken down to left turns, right turns, U-turns and straight across intersections. The manoeuvre error margin is added because the vehicle routing travel time output did not correspond with the route traversing data. This was caused by that additional penalties triggered by the TomTom restricted turns input were not added to the objective function. These errors are subtracted because it seems that they are not calculated by the objective function. The model reporting seemed hard to automatically generate from the route calculation onwards. Therefore the route reports are manually created and calculated using the route output and route traversing datasets. In the discussion the reasons for failing to automate the model reporting process are discussed.

Phase M: Route Mapping

Next to the route reporting a routing map is produced. The route maps are designed manually as well. An example of the final product can be found in figure **4.16**. The visualisation of the route map is inspired by the current gritting maps of the municipality. For the routing arrows are added to the route line. With the use of a cartographic offset the single road lines are divided to left and right side of the road. Beginning and endpoints are added for when the gritting vehicle starts gritting the first road and the gritting of the last roads. Finally, all required arcs are added to the map, which helps displaying which arcs are not passed by this vehicle.

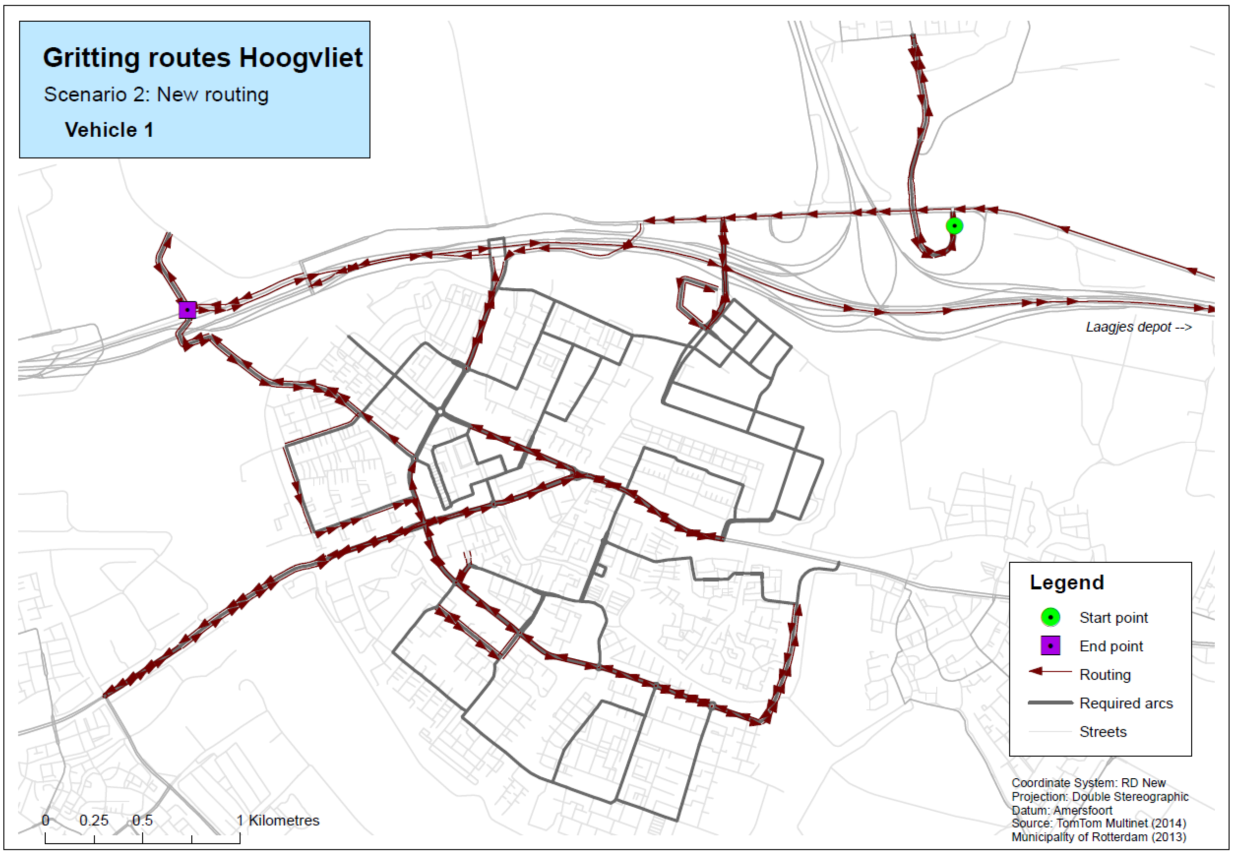

Figure **4.16** Route map example

4.7 Scenarios

In order to see what type of routing is interesting, four scenarios are developed. Each of the scenarios highlight a different aspect of the route creation; from creating more time efficient to more compact and sustainable routes. The scenarios are:

Scenario 1: Current routing	The current routing is loaded into the model. This is meant as a understanding of the current routing performance, as well as a benchmark on how the other scenarios and calculations turn out in perspective to the current routing.
Scenario **2**: New routing	The new routing does not impose any restrictions on any of the two vehicles or on the sequence of the gritting routes. The algorithm is set to search for the most time efficient routing.
Scenario **3**: Sectoring	With the help of administrative districts, the routes are categorised in sectors for creating more compact routes. Segments which fall outside the sector can still be included and are allocated to a nearby sector.
Scenario 4: Node reduction	The node reduction scenario reduces nodes between two gritting route junctions.

The routing model is initially developed to suite the new routing scenario. To calculate the current routing, node reduction, balancing and sectoring scenario some slight modifications have been made in the routing workflow.

Scenario 1: Current routing

To calculate the vehicle routing model it is necessary to feed the current routing into the proposed routing model. For this some slight modifications are done to the routing model workflow. Because the routing is already there, the vehicle needs to be guided over the TomTom network. This is done by using waypoints in the form of TomTom midpoints, and assign a sequence number. The option 'preserve sequence and relative order' is used by assigning the orders to the route. The route outcomes is evaluated if the route made the exact same route as the current routing. Some routing was different, but the miscalculations were small compared to the overall time. The differences were due to unjustifiable turns. It could be fixed if one could modify the network. As already mentioned, this is not possible.

Scenario 3: Sectoring

To the model the two administrative sectors are added. Not all nodes fall within the preassigned sectors. It is up to the algorithm to assign the remaining nodes onto one of the vehicles. The sectoring is also configured with soft boundaries. Not all nodes within a sector have to be assigned to that specific sector but can be placed at adjacent sectors as well.

Scenario 4: Node reduction

For the node reduction all the required arcs are dissolved into one line. This line is then split into separated polylines in case they cross, which created 254 arcs. Of these arcs 26 need to be gritted on both sides, resulting in 280 nodes. One disadvantage is that the network dataset is not modified to these new arcs. This is still using the 904 individual arcs. In order to minimize wrong routeing, all arcs which are not subject to gritting are made non-traversable. This excludes the possibility to use non-required neighbourhood roads. Excluded from these non-traversable arcs were motorways and regional roads. This made travelling to and from the depot possible.

4.8 Parameter settings overview

In the model many parameters are used. Many of these parameters are already discussed in setting up the model but are summarised here to provide an overview (table **4.4**).

Table **4.4** Parameter settings overview

Model parameter	*Details*	*Initial value*
TomTom Road segments (orders)	Name	ID
	Service Time	0.0
	TimewindowStart	00:00:00
	TimeWindowEnd	02:00:00
	Assignmentrule	Override
	CurbApproach	No U-turn* / Left** / Right**
Depot	Location	Giessenweg
Sector design (route zones)	RouteName	-
	IsHardZone	-
Fleet & staff assignment	Name	1 /2***
	StartDepotName	Giessenweg
	EndDepotName	Giessenweg
	EarliestStartTime	00:00:00
	MaxOrderCount	1000
	U-turn policy	Only allowed at intersections and dead ends
	Penalty on right turns****	3
	Penalty on left turns****	5
	Penalty on U-turns****	30
	Penalty on straight across intersections****	2
Strategy & Objectives	Time Attribute	Minutes (Minutes)
	Distance Attribute	[do not fill in]

if the road is passed once. **If the road is passed in both directions two orders are inserted. Insert Left for 1 order and right for 1 order. * two vehicles are used, named '1' and ''2'. **** Using the global turn evaluator*

Differences in parameter settings for the current routing scenario and sectoring scenario are given the following parameter input (table **4.5**-**4.6**).

Table **4.5** Current routing scenario

TomTom Road segments (orders)	Assignmentrule	Preserve order and relative sequence

Table **4.6** Sectoring scenario

Sector design (route zones)	RouteName	1 / 2
	IsHardZone	no

5. Results

This chapter is about elaborating the results that were obtained from running the various scenarios formulated in section **4.7**. Each scenario except the current routing scenario reflects a modification or decision which interferes with the vehicle routing (section **5.1**-**5.4**). The scenarios are created based on the need of the municipality of Rotterdam and technical route modifications. The route report is displayed in this section, whereby the route map displays both routes. At the end of this section the scenarios are presented in an overview and the models will be reiterated to check for model scenario accuracies.

5.1 Current routing

In the first scenario the current routing is evaluated. It is necessary to have knowledge over the current situation before examining other scenarios. The two routes which have been imported in the routing model are the main routes HR_044 and HR_045. The results have been added and the total travel time is summarized (table **5.1**). The total travel time consist of 197.52min, which is around 3 hours 17 minutes. The travel time is divided between two vehicles, one taking 2 hours and 1 minute and the other 1 hours and 17 minutes to drive from start to finish at the Giessenweg depot.

Table **5.1** Scenario 1: Current Routing

	Time route HR_044	Time route HR_045	Total
Start time	00:00:00	00:00:00	
First service road arrival time	00:11:18	00:11:59	
Last service road departure time	01:04:41	01:45:09	
End time at depot	01:17:18	02:00:14	
Time from depot to first service road (min)	11.31	12.00	23.31
Time from the last service road to depot (min)	12.60	15.07	27.67
Service time (gritting)	33.66	58.75	92.42
Deadhead time	8.26	5.56	13.82
Manoeuvre time	11.47	28.85	40.32
Number of left turns	33	25	58
Left turns (min)	2.75	2.33	5.08
Number of U-turns	1	7	8
U-turn (min)	0.5	3.5	4
Number of right turns	47	125	172
Right-turn (min)	2.35	6.25	8.6
Number of straight across intersections	176	505	681
Straight across intersections (min)	5.87	16.83	22.70
Manoeuvre error margin	-	-0.23	-0.23
Total travel time (min)	**77.30**	**120.23**	**197.52**
Total distance (kilometres)	**54.90**	**77.46**	**132.36**

A few things can be noticed for the current routing. At the total service time (gritting) a total gritting time of 92.42min is clocked (table **5.1**). This is more than the 86.68min that is expected from all the required arcs of serviced. This difference is explained by that the routes is categorised using the service arcs/deadhead arcs based on the data of the current routes of the Municipality of Rotterdam. Due to that the maps are constructed manually, arcs have been wrongly labelled as serviced, while they have been already serviced by another route. These wrong categorisations regularly happen at roundabouts. The total difference consists of 5.74min.

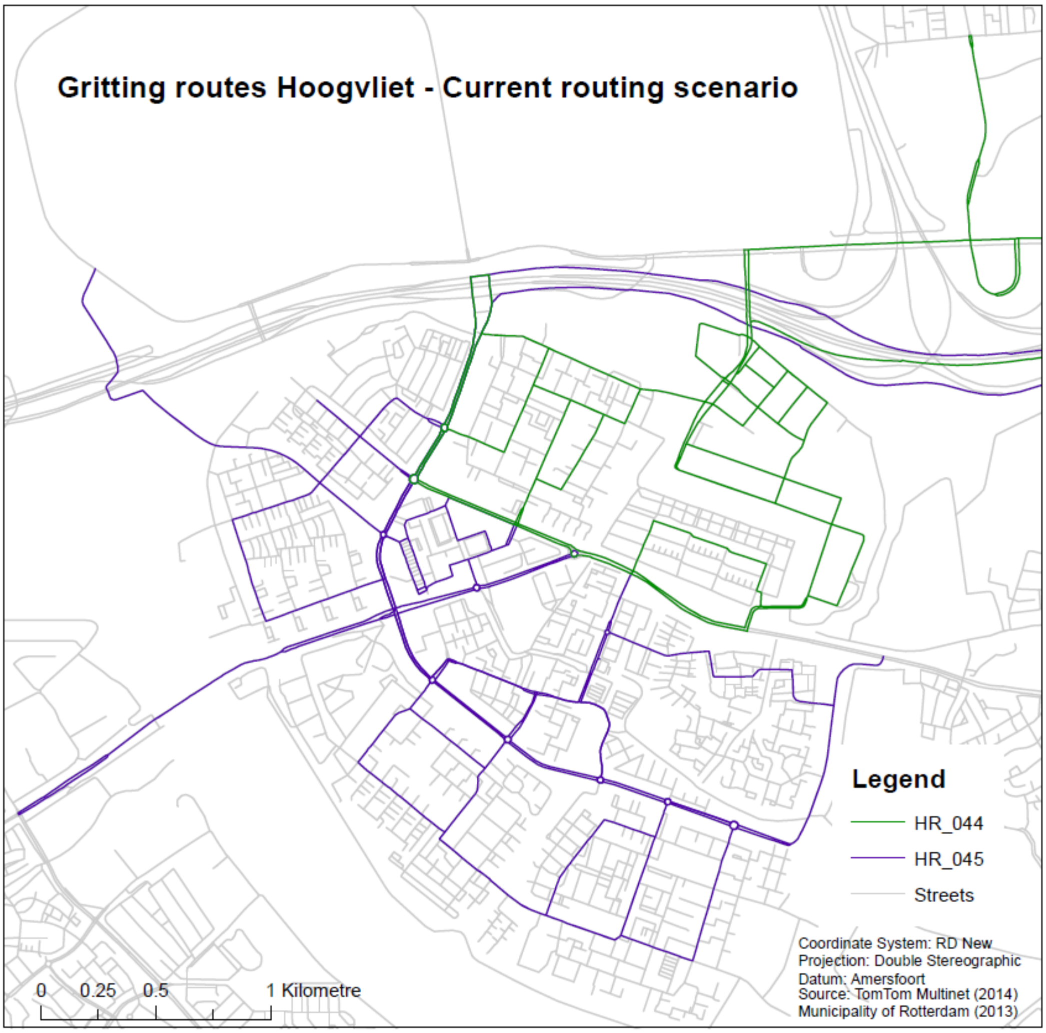

Figure **5.1** Current gritting routes of Hoogvliet

Also, the route could not be perfectly inserted into the routing model. A few exceptions are used to correctly deal with the problem at hand. This occurred for example at the Laning way, where the current routing wrongly crosses a one-way street. Therefore, the routing model routed this to the Laning road, deadheading the arc to enter the street in the other direction (figure **5.2**). In the other routing scenarios this will also be done. This problem is considered unlikely to happen, but not critical in further examination of the routes.

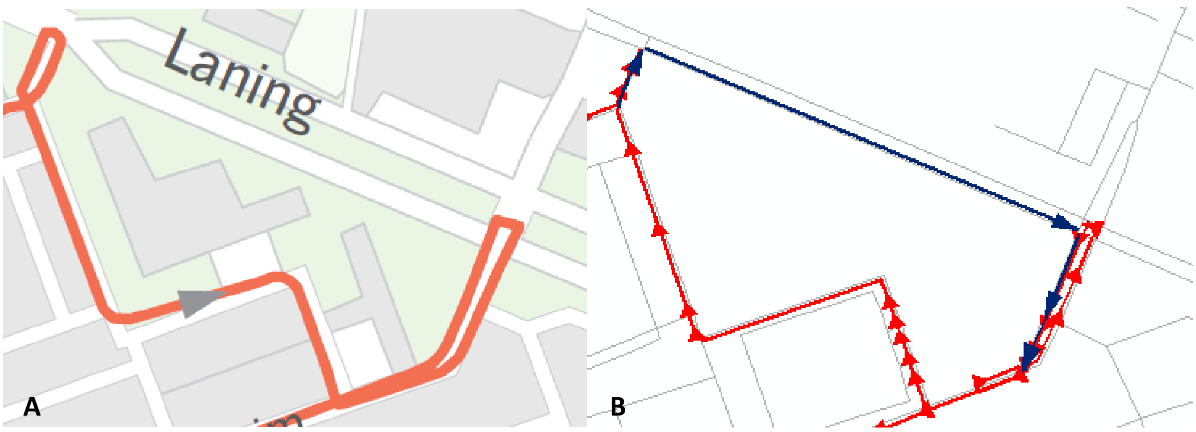

Figure **5.2** Fault in modelling current routing. (a) Route HR_045 makes an illegal one-way move at the Klenke road. (b) Detour on the Laning road, passing the Klenke road the other way around.

Overall the current routing is sufficiently implemented as the first scenario. The other three scenarios will be compared to this outcome, to see if more optimal routing can be created.

5.2 New routing

The new routing does not impose any restrictions on any of the two vehicles or on the sequence of the gritting routes. The algorithm is set to search for the most time efficient routing. The outcome is summarized in table **5.2**. The total travel time consist of 208.25min, a 5.4% increase to the current total gritting route time of 197.52min. Having the possibility to endlessly optimize for better routing, the scenario creates an outcome which performs worse than the current routing scenario.

Table **5.2** Scenario 2: New Routing

	Time route 1	Time route 2	Total	Comparison Current routing
Start time	00:00:00	00:00:00		
First service road arrival time	00:10:42	00:11:15		
Last service road departure time	01:59:21	01:04:15		
End time at depot	02:12:31	01:15:43		
Time from depot to first service road (min)	10.71	11.26	21.97	-5.7%
Time from the last service road to depot (min)	13.17	11.47	24.65	-10.9%
Service time (gritting)	55.99	30.69	86.68	-6.2%
Deadhead time	17.07	10.43	27.50	99.1%
Manoeuvre time	35.58	11.87	47.45	17.7%
Number of left turns	68	23	91	
Left turns (min)	5.67	1.92	7.58	49.2%
Number of U-turns	8	6	14	
U-turn (min)	4	3	7	75.0%
Number of right turns	135	58	193	
Right-turn (min)	6.75	2.9	9.65	12.2%
Number of straight across intersections	585	145	730	
Straight across intersections (min)	19.50	4.83	24.33	7.2%
Manoeuvre error margin	-0.33	-0.78	-1.12	
Total travel time (min)	**132.52**	**75.72**	**208.25**	**5.4%**
Total distance (kilometres)	**74.55**	**62.17**	**136.72**	**3.3%**

For the procedure that is followed one may want to look at the routing table. The last arc gritted at route one is 01:59:21. This means that route one did not have enough capacity to take on additional nodes. In the swapping process it could for some reason not be taken into account. This lead to the routing in total being a little awkward. Especially the second route touched upon some required arcs, but is driving through the whole of Hoogvliet, only servicing a relative small subsection of the arcs required (figure **5.4**, next page). For an indication on how the routing algorithm operates a closer look is taken. Two times the route exits the motorway to only grit one route and goes back to the motorway. It takes time to enter the motorway ramp, grit a few arcs and then go back to the same motorway via another ramp to continue the journey. This routing procedure can be considered suboptimal.

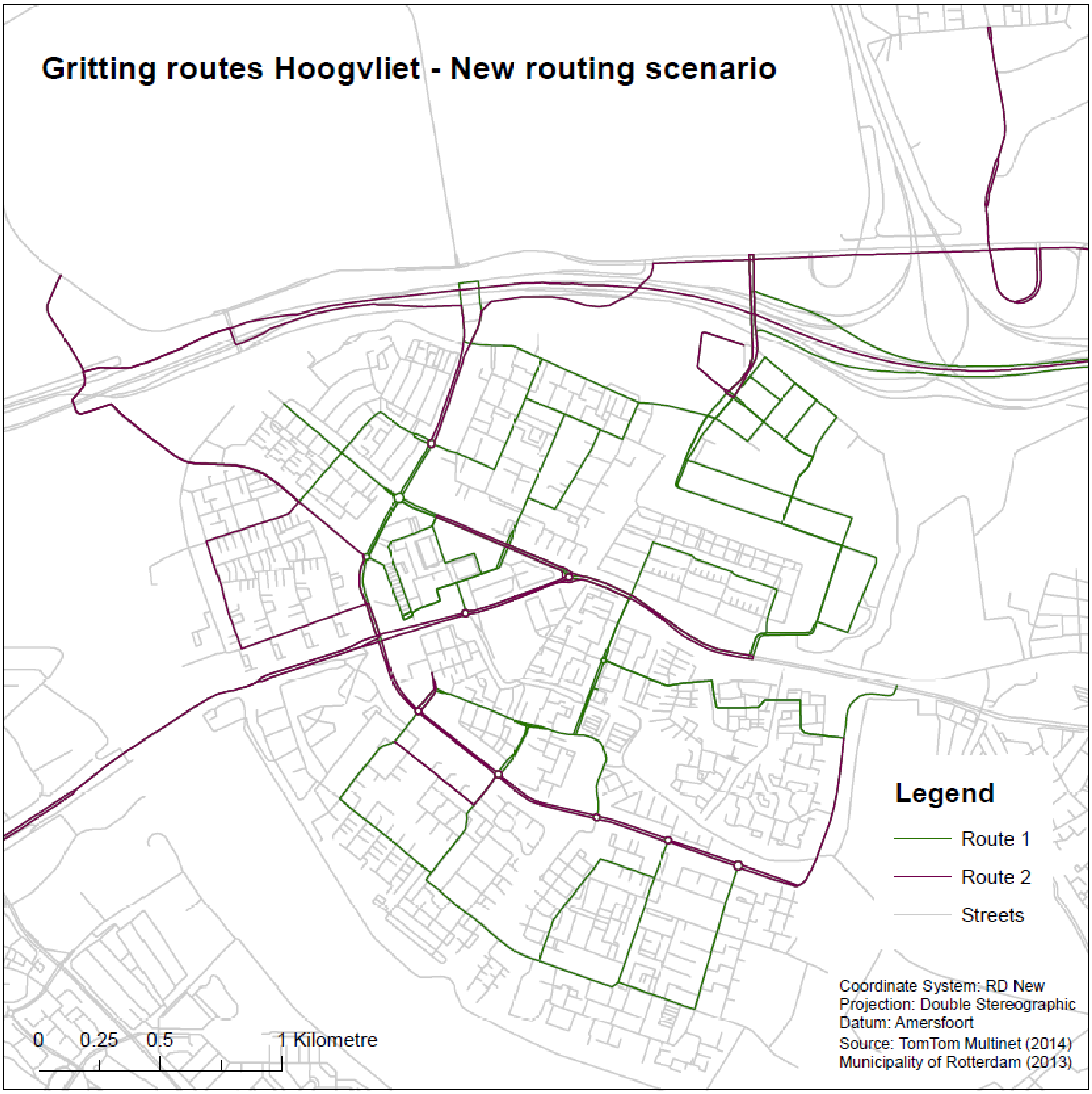

Figure **5.3** Gritting routes Hoogvliet in the new routing scenario

Figure **5.4** zoom in on the A15 motorway exists. (a) Route 1 services both motorway exits, but (b) route 2 also services these arcs. Motorway exits indicated by the black arrows.

Furthermore, taking a close look to the routing. Some nodes have been strangely serviced in order (figure **5.5**). This is a sign that the 2-opt moving does not work perfectly, or that the tabu search has reached a suboptimum without considering these moves. Having these flaws does have negative influence on the routing. It is also impossible to modify the algorithm in order to change these obstacles. What will be done however is in each scenario try to eliminate some of the downsides of this scenario and aiming for routing which scores significantly lower in the total travel time. The next scenario, balancing, will try to account for routing which is more balanced and compact. This will now be explored.

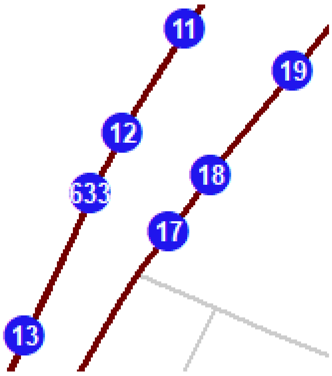

Figure **5.5** Not completed 2-opt move. An arc sequence 11-12-13, with node 633 being serviced in between.

From a manual route making point of view one can point to many possible route flaws. Two things may be done to resolve this. One being that points can actually swap parts of the route, many arcs need to switch simultaneously. Also, the points are not pre-clustered. This makes the routing widespread. The next two scenarios are designed to anticipate to these design flaws.

5.3 Sectoring

With the help of administrative districts, the routes are categorised in sectors for creating more compact routes. Segments which fall outside the sector can still be included and are allocated to a nearby sector. Two sectors have been created, each for one route (figure **5.6**, next page). The total travel time of the sectoring scenario is 214.55 (table **5.3**), which costs 8.6% more travel time than the current routing. It is also higher than the new routing scenario, which has 208.25min (table **5.2**).

Table **5.3** Scenario 3: Sectoring

	Time route 1	Time route 2	Total	Comparison Current routing
Start time	00:00:00	00:00:00		
First service road arrival time	00:10:42	00:11:15		
Last service road departure time	01:51:22	01:19:24		
End time at depot	02:02:59	01:31:33		
Time from depot to first service road (min)	10.71	11.26	21.97	-5.7%
Time from the last service road to depot (min)	11.61	12.14	23.75	-14.2%
Service time (gritting)	54.45	32.24	86.68	-6.2%
Deadhead time	18.11	15.57	33.68	143.8%
Manoeuvre time	28.12	20.35	48.47	20.2%
Number of left turns	53	37	90	
Left turns (min)	4.42	3.08	7.50	47.5%
Number of U-turns	11	6	17	
U-turn (min)	5.5	3	8.5	112.5%
Number of right turns	112	78	190	
Right-turn (min)	3.9	5.6	9.5	10.5%
Number of straight across intersections	385	329	714	
Straight across intersections (min)	12.83	10.97	23.80	4.8%
Manoeuvre error margin	-0.23	-0.60	-0.83	
Total travel time (min)	**122.99**	**91.56**	**214.55**	**8.6%**
Total distance (kilometres)	**73.26**	**65.97**	**139.22**	**5.2%**

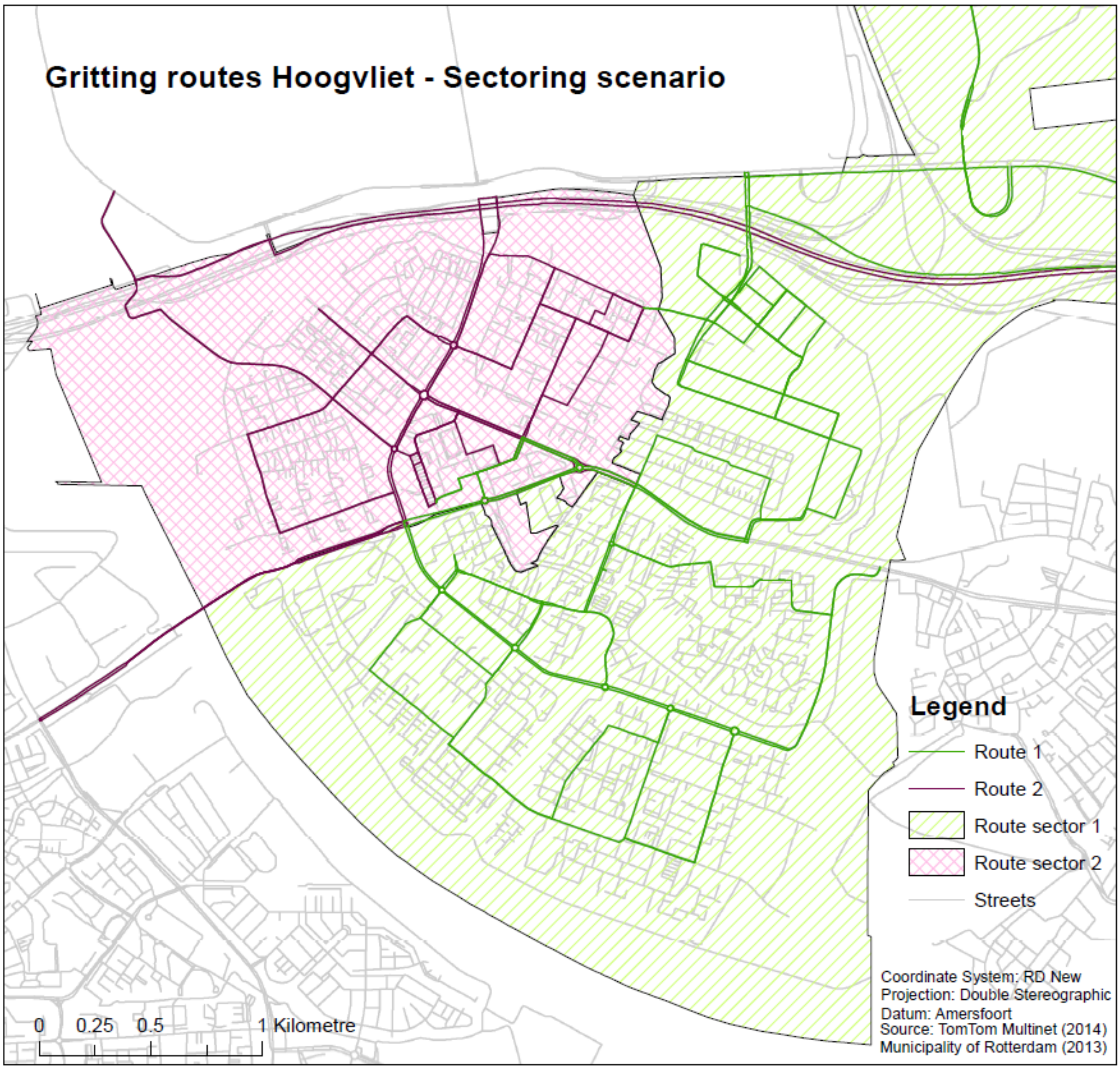

Figure **5.6** Gritting routes Hoogvliet in the sectoring scenario.

The sectoring scenario performs quite poorly. The deadhead time is up by 243.8% in comparison to the current routing scenario (table **5.3**, previous page). It also makes a lot of additional U-turns, 17 in total against 8 for the current routes. U-turns are considered to be undesirable. Even with an assigned 30 second penalty for U-turns this scenario makes in total seventeen U-turns. Also the undesirable left turns are 47.5% more than the current routing scenario. Overall, it can be concluded that the sectoring scenario, as being proposed here, is considered sub-optimal at best. The combination of administrative districts did not propose sufficient routing.

5.4 Node reduction

The node reduction scenario reduces nodes between two gritting route junctions. The results and routes are summarized (table **5.4** & figure **5.7**, next page). The total gritting time consist of 186.34, which is 5.7% lower than the current gritting scenario. The decrease in total gritting time is significant. The total manoeuvre time also decreased (table **5.4**).

Table **5.4** Scenario 4: Node Reduction

	Time route 1	Time route 2	Total	Comparison Current routing
Start time	00:00:00	00:00:00		
First service road arrival time	00:10:34	00:11:08		
Last service road departure time	01:56:21	00:47:20		
End time at depot	02:07:50	00:58:30		
Time from depot to first service road (min)	10.57	11.14	21.71	-6.8%
Time from the last service road to depot (min)	11.47	11.16	22.64	-18.2%
Service time (gritting) Deadhead time	75.56	27.88	103.45	-2.6%
Manoeuvre time	30.23	8.32	38.55	-4.4%
Number of left turns	57	21	78	
Left turns (min)	4.75	1.75	6.5	27.9%
Number of U-turns	8	3	11	
U-turn (min)	4	1.5	5.5	37.5%
Number of right turns	129	28	157	
Right-turn (min)	6.45	1.4	7.85	-8.7%
Number of straight across intersections	456	130	586	
Straight across intersections (min)	15.20	4.33	19.53	-14.0%
Manoeuvre error margin	-0.17	-0.67	-0.83	-6.8%
Total travel time (min)	**127.84**	**58.50**	**186.34**	**-5.7%**
Total distance (kilometres)	**76.78**	**51.45**	**128.23**	**-3.1%**

The disadvantage of the node reduction scenario is that not all required arcs are serviced. Nine sections in total have been neglected in the routing process (figure **5.7**). The total loss of these sections is calculated to be 6.5 minutes (table **5.5**). Adding these missed arcs the total travel time is recalculated to be 192.85, compared to 197.52 of the current routing scenario. This does not include manoeuvre time and additional deadhead time to reach the missing arcs. This reduces the total travel time to minutes or less and it can even be that the node reduction scenario performs worse than the current gritting scenario.

Next, the route again has an increase in left turns and U-turns. Both turns are considered suboptimal for usage, because of the special manoeuvres it takes. Especially in winter times, when snow and ice can limit the drivers vision and making manoeuvre increases risk for traffic accidents. With manoeuvres to be added to this route, the amount of turns and thus left and U-turns will only increase. Also, the route is not compact. The second vehicle crosses almost every Hoogvliet neighbourhood.

Table **5.5** Gritting times of missed arcs due to node reduction

	Per side (min)	Total (min)
One sides	1.65	1.65
Both sides	2.43	4.86
Total missed arcs		**6.51** minutes

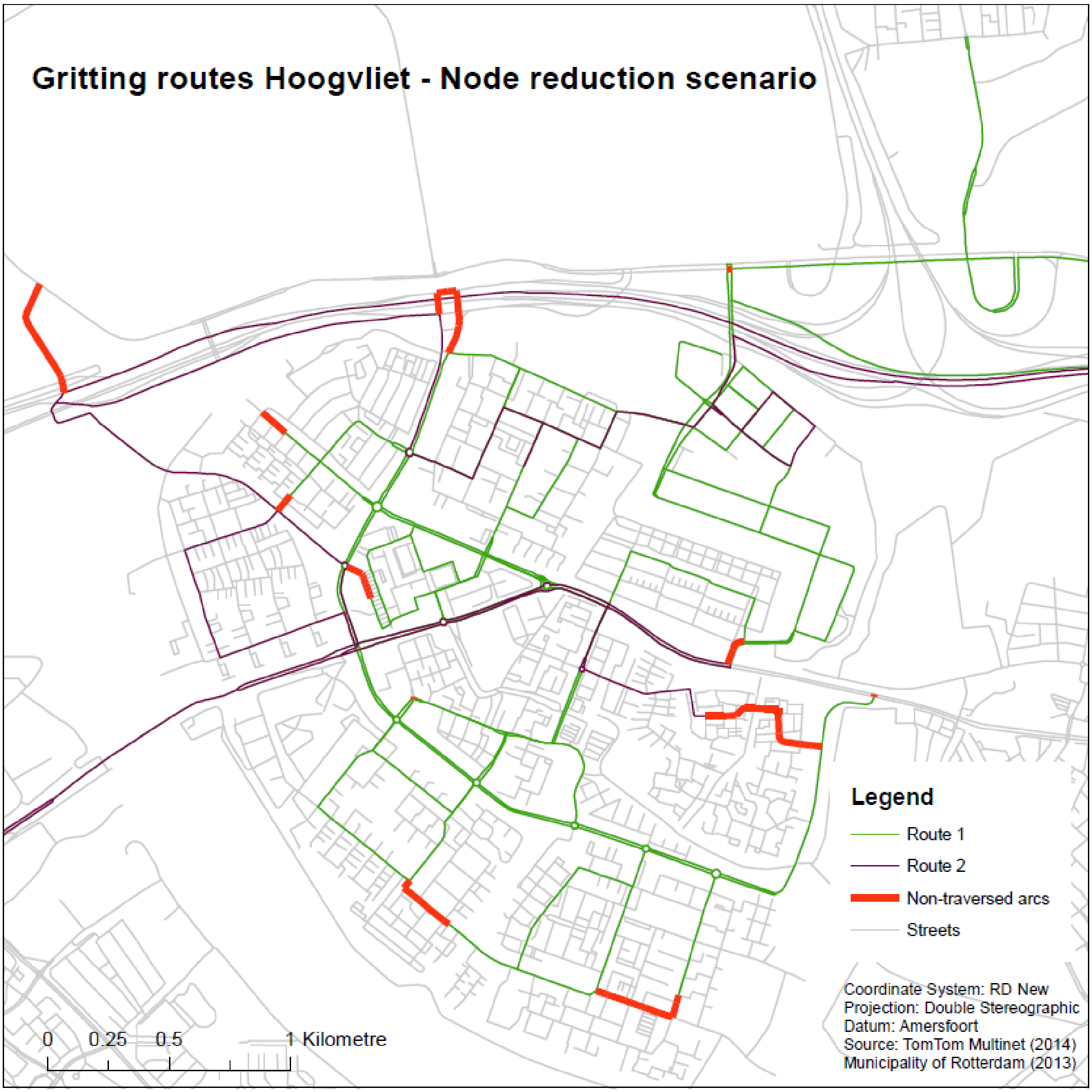

Figure **5.7** Gritting routes Hoogvliet in the node reduction scenario

5.5 Overview routing

The four scenarios were designed to analyse the routing algorithm on the gritting routes of Hoogvliet. The first scenario enabled us to capture data from the current routing. The other three scenarios were designed to test and modify the routing algorithm to outperform the manual made routes. The results are summarized (table **5.6**). A single model run of all four scenarios gave a good indication on how the algorithm performed and what the major drawbacks are. These drawbacks are:

i. Not all aspects of the current routing could be incorporated due to illegal vehicle manoeuvres.
ii. The first vehicle seems to always fills vehicle one first. This leads to route imbalances in vehicle workload.
iii. The swapping between vehicles seems to not work optimally. To counter this the node reduction scenario is calculated, but in this scenario not all required arcs are serviced.
iv. Vehicles make additional turns compared to the current routing. Especially non-desirable turns as left turns and U-turns did increase most drastically.
v. The node reduction scenario only outperformed the current routing. However, some arcs remained serviced. If these arcs are added to the total driving time, the difference to the current routing scenario is less than five minutes. This is excluding additional manoeuvres and deadhead.

To interpret the results a critical reflection is given. This will go more in depth about the algorithmic performance and other issues regarding route modelling. This is discussed in the next chapter.

Table **5.6** Overview routing scenarios

	scenario 1: current routing	**scenario 2: new routing**		**scenario 3: districting**		**scenario 4: node reduction***	
	Travel time	*Travel time*	*difference (%)*	*Travel time*	*difference (%)*	*Travel time*	*difference (%)*
Time from depot to first service road (min)	23.31	21.97	-5.7%	21.97	-5.7%	21.71	-6.8%
Time from the last service road to depot (min)	27.67	24.65	-10.9%	23.75	-14.2%	22.64	-18.2%
Service time (gritting)	92.42	86.68	-6.2%	86.68	-6.2%	103.45	-2.6%
Deadhead time	13.82	27.50	99.1%	33.68	143.8%		
Manoeuvre time	40.32	47.45	17.7%	48.47	20.2%	38.55	-4.4%
Number of left turns	58	91		90		78	
Left turns (min)	5.08	7.58	49.2%	7.50	47.5%	6.5	27.9%
Number of U-turns	8	14		17		11	
U-turn (min)	4	7	75.0%	8.5	112.5%	5.5	37.5%
Number of right turns	172	193		190		157	
Right-turn (min)	8.6	9.65	12.2%	9.5	10.5%	7.85	-8.7%
Number of straight across intersections	681	730		714		586	
Straight across intersections (min)	22.70	24.33	7.2%	23.80	4.8%	19.53	-14.0%
Manoeuvre error margin	-0.23	-1.12		-0.83		-0.83	
Total travel time (min)	**197.52**	**208.25**	**5.4%**	**214.55**	**8.6%**	**186.34**	**-5.7%**
Total distance (kilometres)	**132.36**	**136.72**	**3.3%**	**139.22**	**5.2%**	**128.23**	**-3.1%**

* Not all required arcs are serviced in this scenario.

6. Discussion & future research

The adaptation of a gritting routing model within a GIS is considered highly relevant, but still holds many limitations. These have been encountered and presented during this research. The following sections are devoted to discussing key findings and, where possible, to give directions towards further research areas and topics.

6.1 Algorithmic optimization applicability & GIS Routing software

At the centre of the routing model workflow is the used routing algorithms to solve the vehicle routing problem. Dealing with a rather large arc routing problem, it was not feasible to use exact algorithms in order to determine optimal routing scenarios. Instead, a metaheuristic tabu search algorithm is used which could provide near-optimal solutions for a large-sized problem, which included more complex constraints such as time-windows and turn restrictions. A literature review highlighted that almost no benchmarks studies exist to compare between own invented algorithmic solutions and manual routes in comparison to algorithms used by commercial GIS software vendors. This resulted into the analyses to insert two of the current manually created gritting routes of Hoogvliet in the routing model and next to compare this with vehicle routing algorithm of ArcGIS network analyst with the same routing restrictions.

Results indicated that nor the new routing scenario, nor the districting scenario came close to the manually created routing in terms of total vehicle travel time. Even though in the current routing scenario more time is spent on deadheading than implicated and deadheading time increased by a factor two. In the node reduction scenario, this inefficient swapping of arcs was removed by minimizing nodes in order to traverse. Partially this solved the problem of those generating routes which contained too much deadhead, but as well generated the additional problem of not servicing a percentage of the arcs. It is reasonable to assume that there are multiple explanations for this outcome.

On the technical side the routing algorithm is a black-box. The software supplier in charge often does not clearly state their solution methods, and these cannot be changed (Mapa & Lima, 2014: p. 845; Curtin et al., 2014). This also goes for the deployed GIS routing algorithm; it was known on forehand that the algorithm is built for vehicle routing problems but not for arc routing problems. The translation of arc routing into vehicle routing, has as a result that it is unknown if the algorithm handles this translation adequately. The algorithm is normally used to solve package delivery problems, instead of orders being densely placed within the network. This could, in the end, lead to inefficient algorithmic deployment.

Ideally, one would like to modify the algorithm to see if this leads to better routing. There are many ways to accomplish this. Six points have been identified to tweak the tabu search algorithm to achieve better results, which are currently not possible and thus left unexplored. Insofar it is possible context is added which point in the direction found in the routing results.

First, it is unclear how the initial solution is formulated. How exactly are the arcs (represented as nodes) assigned into the initial routing of vehicles and how does this effect routing outcome. Having the possibility to change this, might create completely new starting solutions and thus different points of departure of this optimization process. It is noticed during the creation of the route that the first one of two routes is always full of orders. This might be the result of that firstly the insertion algorithm fully fills the first route and only thereafter assigns remaining orders onto the second one. This balance remains throughout the swapping procedure, and it is rather unknown if this is efficient or that it is due to order insertion instructions.

Secondly, GIS does not give any insight into the solutions from the tabu list. This list keeps the history of recently considered candidate routing solutions, until these are refused (f.i. sufficiently far in the past) (Luke, 2015). The tabu list may indicate were exactly the algorithm is trapped in local optimum. So if a candidate solution performs worse than the current solution, these are still accepted and the algorithm is not permitted to hold on the current solution. Insight in the tabu list can be an input to define strategies, in order to optimize the usage of a different realm of the search space. As a result in the algorithm might come up with a better routing which minimizes overall driving time.

Third, the length of the tabu list used (*thetha*) is unknown. It is however known that different values of thetha do indeed produce different routing outcomes (Krichen et al., 2014). Having a short tabu list leads to the algorithm get stuck in a local optimum, whereby a longer tabu list leads to longer processing time but does not ensures better routing outcomes.

Fourth, the randomness of swaps like 2-opt, 2,5 opt and/or swaps between routing is unknown. Assigning different stochasticity on swapping procedures could utilize the search space in a different way. It is noticed that routes are ordinally ranked (vehicle 1, vehicle 2), with as a consequence that vehicle 1 receives more nodes to service. Not only could this procedure be built-in into the insertion of orders, but also into the stochasticity of swapping nodes.

Fifth; invisibility of algorithmic calculations makes that one cannot check if the parameters which are set at the user input, are processed correctly. The user has no allowance to see if the algorithm uses time-windows and if it turns constraints properly in the route creation. In deploying routing technology, a difference became visible in the reported overall minutes between route information and underlying edge table. This difference is created due to additional time penalties in the turn restriction information of TomTom. There was no possibility to check which was the time used of the objective function to develop a routing solution. Dive into the algorithm is the best way to find this out.

Sixth, the speed of the algorithm and the iterations per minute are unknown. No information is given if the algorithm is working efficiently. Information about this process could help with a couple of services. The algorithm for instance has a quite long processing time for a rather simple route. The new routing scenario takes 4.5 hours to calculate, while the districting scenario takes around 9 hours. There is no limitation of the searching time of the algorithm, nor does the algorithm provide information about the best solution found. It is also found that the solving time for the algorithm increases exponentially when adding additional nodes (Curtin et al., 2014: p.294). This makes it hard to scale the algorithm for taking on more routes. Next, ArcMap only uses 4gb of RAM for processing purposes, resulting in a slowing down of the algorithmic speed significantly.

To solve the issues a modifiable routing algorithm should be developed, constructed to deal efficiently with arc routing, within a GIS environment. An exploration of software possibilities led to the conclusion that these initiatives are currently non-existent inside GIS software. However, some integration between GIS and routing algorithms have been successfully reported in literature. Kramberger et al. (2012) successfully reported an application in ArcGIS for a Chinese postman problem with priority routing. Krichen et al. (2014) uses an integration between CPLEX and QGIS to solve a vehicle routing problem and Hajibabai (2014) made a snow route optimizer plugin for ArcMap. None of these studies did share their source code and/or program, leaving the GIS community with a lack of usable optimization programs for GIS routing. A research direction could be the development of a tool for arc routing (in GIS), including access to the public, and creating the opportunity for the user to adjust the route optimization algorithm manually for rather technical parameters.

A second strand of research could be devoted to create benchmarks for GIS routing problems. The only study which came near for the travelling salesman problem was published by Curtin et al. (2014). It would be beneficial to produce similar studies for GIS vehicle routing or arc routing solutions. Lum (2018) recently released a tool for automatic creation of routing instances based on real network topology of OSM data, which could be used to create instances for comparison. Until now it is not conceivable to judge GIS routing algorithms on their performance, which makes it nearly impossible to choose a GIS program.

6.2 Graph simplification & manipulation

To calculate routes, a network dataset of TomTom Multinet is used in order to have a graph-based abstraction of the real-world road network. This network is loaded in ArcMap and used successfully to calculate routing. In applying the routing model to the Hoogvliet only suboptimal results have been achieved. Although not explicitly researched, routing outcomes suggest that the high number of traversed arcs is the cause of this problem. When reviewing the literature one finds evidence that the complexity of routing problems exponentially increases with the number of arcs or nodes added. Limiting the number of traversed arcs seems promising in reducing the complexity of the problem. To analyse this assumption a scenario is added whereby the nodes were reduced as much as possible. The passing arcs were dissolved and reconfigured according to their newly created nodes.

Results of the graph simplifications clearly show that it reduces the total travel time significantly of vehicles by a substantial number. While the new route and districting scenario had an increase in total travel time, the node reduction scenario was the only one with less total travel time, when compared to the current routes. The method, however, has some drawbacks. The most important one is that routes do not automatically pass all required arcs. In the simplification process some arcs have been oversimplified, resulting in unreliable routes, which have to be manually adjusted and checked before considered valid. While some adjustments in the ability to pass arcs and increased penalty to U-turn vehicles is added, these instances still occur. Especially when the vehicle enters or exits a motorway inconceivable arc routing plays a role.

To account for more realistic routing, measures have been taken which can negatively affect the routing. For instance, routes other than highways and local access roads are removed from the analysis, in order to ensure correct routing onto the nodes. Although this really helps, it implies that the network is limited in options and increases travel time of global optima, as well as result in arcs which cannot be fulfilled. For example, a one-way street where a U-turn is not allowed and the corresponding adjacent streets is marked as unpassable. Manually adding this to the route, together with adding arcs and turn movement needs to adjust the objective function. This is inconvenient, prone to errors in both the calculation of time and possibly violating turn constraints.

Next to simplifying the graph to end up with more optimal routing results other graph manipulation techniques would be needed. The multiple passes problem, for instance, forces nodes to be used as ways to fill in arcs; one cannot place multiple nodes on a single arc. If the vehicle drives by, all the nodes will be filled. One way of resolving this issue is to create multiple arcs to the same junction nodes. Then, nodes can be placed on both arcs, representing the same street. Another issue is the creation of new roads, which is impossible at the moment. One would like to add roads at e.g. market places and/or squares. Here the vehicle can grit the market square at one end and drive to the street on the other side of the square. Unfortunately this option is not available at the moment.

To the extent of discussing implications of results, and not being able to adopt this in the vehicle routing problem, is considered one of the biggest drawbacks. This scenario clearly shows a massive reduction in vehicle routing time. If it was possible to merge these arcs, reconfigure the network and inserting U-turns onto intersections. This would have been a massive improvement. Further research on finding ways to achieve this are warranted. Or built a completely new network, but somehow adding the TomTom data of the remaining parts back into the newly composed network.

6.3 Districting

For the districting of Hoogvliet ten neighbourhood districts are used and divided into two sectors which respectively have been added to the vehicle routing problem. Results show that more compact and balanced routes are being produced, despite the fact that districting increases the total vehicle driving minutes. The districting protocol used allows us to create soft boundaries: if nodes are serviced by an adjacent sector this yields substantial benefits in driving time reduction. Next to an increase in total driving time a few points can be discussed by implementing the administrative districting procedure.

Seeing the routing problem as a test for a broader application to the municipality of Rotterdam, some drawbacks are foreseen. While districting can help to deduce the vehicle routing problem complexity, districting also increases the solving time with a factor two. As it was impossible to solve the vehicle routing problem for the whole municipality of Rotterdam, districting would reproduce worse analyses. One would benefit that total solving time decreases rather than increases, especially when pre-set administrative boundaries are used in the route modelling algorithm. The same disadvantage applied to the insertion of route nodes. The route nodes are preferable placed to vehicles based on ordinal ranking. It seems that vehicle 1 is more likely to add orders to vehicle 2 then the reverse option.

The assignment of districts was performed rather arbitrary, based on administrative boundaries. Those were subjectively chosen by the route designer to account for good routing. While there are solutions being proposed to find location allocation for arc routing problems, these problems are also NP-hard and not well researched in literature (Chen, 2017). No implementation of arc routing districting based on network characteristics was found for GIS systems. Providing an implementation for arc routing districting based on network characteristics in GIS would be an interesting topic for further research.

6.4 Asset management data & digitisation

The routing model workflow allowed the description of acquiring, cleaning and manipulating asset management network data. This aim was attained by transforming digitized lines in a GIS to an asset management dataset compatible to be added to a street network for routing purposes. Elaboration of these steps is described during the first four steps of the routing workflow methodology. In the pursuit of digitizing and transforming road asset management data several remarks can be made about data acquisition and processing.

At the digitisation of the current gritting routes to TOP10NL road parts and later the transformation to the TomTom arcs many errors occur which need to be manually resolved After selecting categories within the dataset a subsection of wrongly selected parts still occurs, leading to manual resolvement, which in its turn may lead to human resolvement errors. Transforming the TOP10NL road parts to TomTom road segments inherits the same issues. Digitisation errors, again call for manual adjustments of relationships between asset classes.

It can be augmented that storing of route attribute data into TOP10NL is aggregated too spatially. Data are not viewed on lane level, but rather as an aggregation of lanes. In transforming to TomTom midparts the TOP10NL crossroads are excluded from digitisation. These have not been digitised, including that information on crossroads is excluded in the analyses.

Asset management data needs practical embedding within the organisation. The solution of asset management requires updating, and certainly not only rerouting, which requires people to manage those data. Due to data digitisation processes, which has many digitisation steps and is prone to errors, it might not be suitable to implement this within the organisation. A more simplistic approach could rather be implemented. This loss of perceived benefits of building an own data infrastructure will trade-off against user simplicity.

6.5 Route reporting & visualisation

The use of vehicle routing gave the additional problem that the output generated was concerned by services nodes rather than arcs. Post-processing was required to recalculate route statistics and create route visualisation. While both route reporting and visualisation have been generated, some points are summed up which require attention.

The original aim was to automatize the post-processing of route reporting by means of an ArcGIS ModelBuilder. As building of this model was stuck on some points, the aim had to be discarded. These problematic points being (i) the TomTom mismatched between total travel time reported in the total routing and generated traversed source features. This made joining of the two datasets very difficult Next, the (ii) generated output was delivered for all vehicles combined. It was not possible to iterate *n* vehicles for automated route reporting. Instead, Python scripts and manual steps were required to split the vehicles and processed them for each separate vehicle. Also, (iii) not all the wished data could be appropriately selected within the model. Difficult queries with travel times only found within the routing output where required to use as an input by the user. Then, the model (iv) the model executed badly and relations between processing steps were needed to be manually drafted each time the model ran. Lastly, (v) the overall model became too complex too many processing steps and joins were formulated into the model. Also, running the model took five minutes to process a single route report. This is not ideal for generating on-the-fly route statistics.

These inconveniences led to a manual creation of route reports, which has some downfalls, in which there was room for manual digitisation errors and the route reporting could not been automatically written down. Some information could be derived from route output data provided by ArcMap, of which the most important one was the total travel time; this could easily be derived from the route statistics. To get more insight in routing and to get a better grasp on the routing, more statistics are required and controlled by the route maker. As it is easy to use but does not create most optimal routing performances. Important statistics as deadheading could not be derived, so not which roads where deadheaded and which were not; basic information when planning gritting routes.

For route visualisation drawbacks were noticed as well. Like the automatization of route reports the automatization of map plotting is something not easily achieved in ArcGIS. Possibly it can be done by programming, there was no time left to undertake this issue. But for the manual plotting, some remarks could be made about the routing maps. Those maps are not very clear and although routes are plotted on both left and right side of roads, one cannot conclude how many times these routes pass this particular side of the road. Also the route connection on junctions is not clear. Ideally these maps should be created manually by cartographers. It is also impossible to see which parts of the road are considered deadhead and which ones are not. When more than one route is plotted on the map and they show some overlap, one has to choose one visible route, implying comparison of an integral routing plan will be difficult. A solution might be the use ArcGIS schematics and built rules or tools to automatically plot routes in such a way that these do not show any overlap.

Although this point is worth noticing for route evaluation, itis less interesting for drivers which want to use route navigation and GPS technology in their car. It depends on the view of the organisation if paper maps are needed for backup, or that technology will slowly phase out or: erase paper route maps in a winter service organisation.

6.6 Calculating network travel times

TomTom Multinet data is used for the availability of reliable travel times, which is a key feature that open data sources such as OSM do not provide in a reliable way. Although the use of network travel times is successfully applied in route modelling, some remarks can be made regarding the use of travel times in route calculation.

Actually, it is unclear how the TomTom travel times are calculated. In the documents which were provided when achieving the network dataset no explanation on the calculation part was provided. This is in sharp contrast to the detailed way in which other features, such as network topology, are described in their user manual. The user has no other option than to trust the expertise of TomTom on information about travel times.

Travel times themselves are also unreliable for the case of gritting. The speed of the TomTom Multinet dataset is used, but this is normally driven(used) by cars instead of gritting vehicles. A trial run on a winter service vehicle in Rotterdam revealed that regular maximum car speeds were reached driven by the drivers. This does not include the acceleration of the vehicle; this might affect the calculated travel time negatively. Some scholars therefore calculate different travel speeds for arcs which have already been gritted in comparison to arcs which need to be gritted (Holmberg, 2010: p.982). Differences also do exist in the use of assigning time to turn penalties. The turn penalties were already assigned by TomTom Multinet. However, this category was simplified, so not taking into account were differences in turning movement in combination with road hierarchies.

To account for these changes two solutions are possible, both not yet investigated. These are is the performance of sensitivity analyses on the effect on parameters like travel time and turn movement time. Tweaking these parameters does provide insight in how these values create routes. Interesting results especially lie in penalizing U-turns and right turns, since these manoeuvres are not preferred. Another solution is to calibrate the model with the input of GPS data from actual gritting vehicles. This can shed light on the differences in travel time between the TomTom Multinet data and the situation outside.

Travel times used are based on static information of giving only one travel time per arc. This is sufficient for calculating all routes but lacks realism in dynamic scenarios like traffic jams or poor weather conditions. Especially in these situations historical traffic data and/or adding spatiotemporal traffic data may help in creating more robust scenarios and thus routing. This allows the user to appropriately assign risk labels to routing being subject for large travel time differences. One may also notice that real-time traffic data sources are not included. Although placed outside the research scope in chapter one, this may adopt real-time information into other applications of the municipal winter service organisation.

A last remark can be made about the external and internal revision rate of network data, which originate from 2014. To provide route makers with the most updated network information one must obtain an updated network dataset version and thereafter built a new version. The user must put his trust in the correctness of network topology and lane information.

6.7 Routing characteristics

At the identification of routing characteristics it became apparent that there are many factors to include into the routing model. To deliver more detailed work on the essentials of this model, some routing characterises have been excluded from research. Ideally, they would be included in the final route model workflow. Three main characteristics will be briefly discussed: salt usage, lane prioritization and the adding of bike lanes.

The most conspicuous of the missing routing characteristics was not taking salt usage into account. The motivation was twofold: the task had been assigned within the municipality to another colleague and in conversations with the winter service section the level of salt use does not seem to be of critical importance. The vehicles are already time bounded and did not need to refill within this time window. For the analyses, however, this implies that the exclusion of factors simplified the model. But in the next phases of the WINTER project the calculation of salt usage is formulated as a goal itself. The current asset management data approach of TOP10NL data can give a rough estimation of salt usage, but might fail in precisely measuring salt usage, something to keep in mind for later stages of the WINTER project.

Many routing models do take route prioritisation into account when formulating routes. Within the municipality of Rotterdam the most critical infrastructure was already placed within an access route category. The access routes contained all roads which included many of the points which needed fast gritting, e.g. bridges and other critical infrastructure and frost spots. In the calculation on roads of secondary importance it is advisable to insert roads prioritization. One examples is the gritting of main routes first in certain sectors before moving into residential areas. The vehicle problem solver of ArcGIS does allow route prioritization. Using these options affect the routing outcome and it negatively affects the calculation time of routes, which is not researched and thus unknown.

Last, the dataset does not contain bike lanes, so it is completely unknown if routing work adequate on bike lanes. And on top, these bike lanes are used by different vehicles. Again, characteristics are unknown of routing these specific vehicles. The network dataset did not contain bike roads either, and it is therefore unknown if TomTom can deliver these data, not its quality and if the routing works properly using the same route modelling workflow which is created for route modelling gritting vehicles.

6.8 Route updating procedure

The routing model workflow creates static routing by using geographical information management software. While routing can be calculated and implemented the network design of Rotterdam is temporal and it changes continually. Currently all routes are revised annually by cartographers. Adopting a routing model would suggest a different update procedure and its model should be rerun to detect if the renewed road network could be used in the same manner, or that time saving measures can be implemented. However, adopting route modelling and rerunning takes personnel specialized in network modelling, and on top GIS network analyses knowledge is not a standard skill. Ideally, specialists need to join the organisation for many years in order to keep knowledge within the organisation. Not understanding route modelling could cause human errors in the route modelling process, which in its turn can lead to significant delays.

As pointed out earlier, the internal and external revision rate of network data is important for the update frequency. Route network datasets can become out-of-date; software renewal leads to new versions. Updating routing is not only needed in the current dataset, but routes need to be digitised as well in the new one. All these operations are very time costly and GIS network analytics skills are required. This together is far more difficult than the current practice of updating routes by drawing lines.

7. Conclusion & Recommendations

7.1 Conclusion

A conclusion summarizes the total content of this thesis. An answer will be given to the five sub research questions and subsequently the main research question will be answered.

1: How is the current gritting of roads organised?

The current gritting roads responsibilities are assigned to the winter service organisation (chapter **2**). These take care of all operations for network design, transportation management, staff management and inventory control. The winter service organisation must compel to the road law to provide safe travel for all road users. The most important requirement is a two-hour time window for municipal roads in poor weather conditions but is retained in all routing situations. Salt capacity on vehicles is however not seen as a constraining factor.

The municipal gritting routes for motorways are divided into two categories: access routes and other main motorway routes. Access routes consist of critical infrastructure and frosty spots. To identify gritting routes multiple criteria are used, amongst them main motorway roads, access roads, bus lanes, P&R locations, shopping areas and calamity routes for hospitals, ambulance and police personnel, and fire stations (chapter **2.4**). Two routes gritted scenarios exist: only grit access routes or grit every route. Which routing scenario is executed depends on the weather forecast. All routes are created and adjustments are manually drafted by in-house cartographers.

2: Which characteristics are considered relevant for modelling gritting routes?

Six characteristics have been distinguished which are considered relevant: transportation network, road segments, sectors, vehicle & depots, routes & drivers and route objectives (chapter **3.2**). These characteristics suit the problem description, whereby four elements are described which are needed for this routing problem:(i) the use of heterogeneous vehicles, (ii) multiple depots locations, (iii) graph representation of a transportation network with one-way and two-way streets to be serviced and (iv) not every road segment may need to be serviced. Together with the characteristic of the (v) two hour-time window in the previous chapter these make up the most important requirements.

The other important characteristic is the modelling approach choice; the one chosen is the vehicle routing problem with a time-window (chapter **3.3**). The vehicle routing problem includes algorithms which are well studied and integrated within most commercial GIS software (chapter **3.4**-**3.5**). Routing model characteristics have been summarized and their relationships have been defined in the conceptual model (chapter **3.6**).

Sub question 3: How can these characteristics be incorporated into a routing model?

The characteristics of the conceptual model have been translated into a GIS routing model workflow (chapter **4.4**). Thirteen phases have been distinguished, ranging from the creation of the network dataset to visualise the staff routing output. The routing model begins with a process for acquiring, cleaning and manipulation asset management network data, defined in data input and pre-processing stage of the GIS routing model workflow. At the core the routes are formulated using the vehicle routing solver of ArcGIS network analyst, which uses a meta-heuristic tabu search based algorithm. The routing output is then generated and tweaked to represent arc traversals of gritting vehicles. In the routing model workflow, a possibility is added that some of the data input and parameters can be changed throughout the process.

Sub question 4: How does the routing model perform regarding the decrease of driving time?
To evaluate the performance two current gritting routes of Hoogvliet have been added to the routing model. Results have been compared and three scenarios are suggested: a new routing scenario, a districting and node reduction scenario. The new routing and districting scenario had an increase in total vehicle travel time of 5.4 % and 8.6%. The node reduction scenario did outperform the current gritting routes by 5.3% but did leave some arcs ungritted and unconnected inside the routing (chapter **5.5**).

The model did a run with 904 service nodes in the new scenario and districting scenario. In the node reduction scenario, a total of 280 nodes are serviced. The solving time for the scenarios is between 1.5 and 9 hours.

Sub question 5: To what extent can the GIS routing model be implemented within the organisation?
Although the routing model can be used to decrease driving time, it was tested at only two gritting roads in Hoogvliet. For implementation the routing calculations have to scale to 30 main gritting routes. To implement some issues remain on both technical and organisational issues (chapter **6.1**). The algorithm is not specially designed for large arc routing problems and has poor performance both in speed & accuracy. Districting is necessary to account for these issues. Furthermore, the network dataset cannot be simplified to reduce model solving complexity. From an organisation perspective, routing is labour intensive and quite specific. If one wants to proceed in recalculate the routing just once, one may want to consider these points before adopting a GIS routing model within the organisation.

The five sub questions have been answered. Now the main questions will be answered:

Main research question: To what extent can the adaptation of a routing model decrease the driving time of gritting vehicles in the municipality of Rotterdam?

This thesis was concerned with creating a route modelling workflow to calculate the total travel time of gritting vehicles. It is shown for two routes at Hoogvliet that the routing model, using a tabu search algorithm of ArcGIS, can decease total travel time for 5.3% percent in the node reduction scenario. However, the model did leave some arcs ungritted and unconnected in the routing. Manual reconfiguration of routing is required to create sufficient routing, which also increases the total travel time.

In the routing process some characteristics could not be properly modelled. The road network could not be modified. This meant that the graph could not be simplified correctly, which gave algorithmic problems and unfinished routing. A not modifiable graph also meant that the network could not be expanded with additional roads and that multiple passing of one road was not possible to model. Furthermore the algorithmic performance was is considered both poor on speed and accuracy. Lastly, the routing is labour intensive and quite specific.

Overall the chosen approach is considered not sufficient for adopting in a large municipality. The factor of improvement is considered low for adopting the proposed route creation modelling workflow. Furthermore, issues regarding the graph simplification, algorithmic performance and organisation implementation should be resolved before adapting a winter service vehicle routing model.

7.2 Recommendations for the municipality of Rotterdam

To accompany the municipality of Rotterdam in the process of automatizing the ICT of gritting operations four recommendations are formulated.

i) **Obtain or outsource the GIS software infrastructure to adequately solve the formulated winter service (arc) routing problem**
Solving large winter gritting arc routing problems is too difficult using the ArcGIS tabu search algorithm for vehicle routing problems. A different GIS software architecture is required which is considered a niche market in routing software. Most winter service routing problem formulations focus on salt capacity limits for vehicles, while in the case of Rotterdam time window violations is the main limitation for modelling. In the software exploration (chapter **4.3**) a company called RouteSmart offers specialized arc routing software as a plugin for ArcGIS and offer help with route formulation. It might be beneficial to explore this as an option and/or to seek to team up with external parties specialized in arc routing.

ii) **A combination of routing software and hands-on knowledge is always needed**
Routing software cannot automate everything. It is always a synergy between the route software and route makers. Also, due the complex nature of the optimization suboptimal routing is created. Rerunning the model several times may result in better routing. Also changing parameters like constraints, districts and speed limits may generate different routes. Route creation is an iterative process which require devoted attention by users.

iii) **Create a storage for winter service asset management data**
Th current gritting routes are stored as digitized lines within a database. There is no spatial data infrastructure set up for gritting operations. It would be recommended to create a basic information storage infrastructure for gritting data. Preferably in corporation with the road authority. The setting up of this infrastructure is dependent on the chosen software architecture. This thesis uses TomTom data for linking asset management data, but routing software vendors use different commercial network datasets. First define the GIS software before one set up the winter service asset management data storage.

iv) **Embed the new route updating within the organisation**
The route update is done by manually drawing routes. With a new system the updating process will likely change to digital updating in different software and later on navigation systems. Do not underestimate the time it cost to develop new routing for these vehicles and modifications it takes to develop good routing in the first years of operation. This point also includes holding the network data to a constant quality standard and check for network updates.

8. Literature

Anbuudayasankar, S. P., Ganesh, K. & S. Mohapatra (2014), Models for Practical Routing Problems in Logistics: Design and Practices. Switzerland: Springer International Publishing.

Assad, A.A & B.L. Golden (1995), Arc routing methods and applications. In M.O. Ball, T.L. Magnanti, C.L. Monma & G.L. Nemhauser, Handbooks in operations research and management science 8: network routing. Amsterdam: North-Holland, pp. 375-484.

Benjamin, A.M. (2011), Metaheuristics for the waste collection vehicle routing problem with time windows. PhD thesis, Brunel University, Uxbridge, UK.

Bingham, B.V. (2008), Route Planning: Winter Applications. Master thesis, University of Redlands.

Bodin, L., & B. Golden (1981), Classification in vehicle routing and scheduling. Networks 11, pp. 97-108.

Caceres-Cruz, J., Arias, P., Guimarans, D., Riera, D. & S. A. Juan (2014), Rich vehicle routing problem: Survey. ACM Computing Surveys 47:2, pp. 1-32.

Campbell, J.F. & A. Langevin (2000), Roadway snow and ice control. In: M. Dror (Ed.), *Arc routing: theory, solutions and applications*. Boston, MA: Kluwer, pp. 389-418.

Corberán, A. & C. Prins (2010), Recent results on arc routing problems: an annotated bibliography. Networks 56, pp. 50-69.

Cordeau, J.-R, M. Gendreau, G. Laporte, J.-Y. Potvin & F. Semet (2002), A guide to vehicle routing heuristics. Journal of the Operational Research Society 53:5, pp. 512-522.

Curtin, K.M., Voicu, G., Rice, M.T. & A. Stefanidis (2014), A comparative analysis of traveling salesman solutions from geographic information systems. Transactions in GIS 18:2, pp. 286-301.

Dowds, J., Novak, D.C. & D. Scott (2016), Identifying Best Practices for Snowplow Route Optimization. Minnesota: Minnesota Department of Transportation.

Dussault, B., Golden, B., Groër, C. & E. Wasil (2013), Plowing with precedence: A variant of the windy postman problem. Computers & Operations Research 40:4, pp. 1047-1059.

Edmonds, J. & E.L. Johnson (1973), Matching, Euler Tours and the Chinese postman. Mathematical Programming 5: 1, pp 88-124.

ESRI (2018), ArcGIS Network Analyst [online], https://www.esri.com/software/arcgis/extensions/networkanalyst [cited 23-04-2018]

ESRI (2017a), Algorithms used by the ArcGIS Network Analyst extension [online] http://desktop.arcgis.com/en/arcmap/latest/extensions/network-analyst/algorithms-used-by-network-analyst.htm [cited 02-08-2017]

ESRI (2017b), ArcGIS Network Analyst Network Elements [online] http://desktop.arcgis.com/en/arcmap/latest/extensions/network-analyst/network-elements.htm [cited 04-06-2017]

Essink, B. (2014), Scenario analysis of a ice and snow control program on the tactical level. Master thesis: university of Twente.

Eksioglu, B., Vural, A.V. & A. Reisman (2009), The vehicle routing problem: A taxonomic review. Computers & Industrial Engineering 57: 4, pp. 1472-1483.

Fischer, M. (2004), GIS and network analysis. In: Hensher, D., Button, K., Haynes, K., Stopher, P. (Eds.), Handbook of Transportation Geography and Spatial Systems. Amsterdam: Elsevier Press, pp. 391-408.

Frederickson, G. N., Hecht, M. S. & C. E. Kim (1978), Approximation Algorithms for some Routing Problems. SIAM Journal of Computing 7, pp. 178-193.

Gáspár, L. & Z. Bencze (2016), Salting Route Optimization in Hungary. Transportation Research Procedia 14, pp. 2421-2430.

Garey, M. R. & D.S. Johnson (1979), Computers and Intractability - A guide to NP-completeness. San Francisco (CA, USA): W. H. Freeman and Company.

Gendreau, M., Laporte, G. & J-Y Potvin (2002), Metaheuristics for the capacitated vehicle routing problem. In: Toth, P., Vigo, D. (Eds.), The vehicle routing problem. Philadelphia, PA: SIAM, pp 129-149.

Gendreau, M. & J-Y Potvin (2005), Meta-heuristics in Combinatorial Optimization. Annals of Operations Research 140:1, pp. 189-213.

Gerlagh, L.B. (1998), Efficiente Routering van Strooiwagens ten behoeve van gladheidsbestrijding. Delft: Delft University press, WBBM report series 38.

Groves, G. & J. Van Vuuren (2005), Efficient heuristics for the Rural Postman Problem. ORiON 21:1, pp. 33-51

Gutiérrez, E.V. & C. J. Vidal (2013), Home health care logistics management: Framework and research perspectives. International Journal Industrial Engineering Management 4:3, pp. 173-182.

Hajibabai, L. (2014). Scheduling and routing of service trucks and planning of resource replenishment locations for winter roadway maintenance. PhD Dissertation, University of Illinois.

Hajibabai, L. & Y. Ouyang (2016), Resource replenishment location planning for service trucks under network congestion and routing constraints. Transportation Research Record Journal of the Transportation Research Board 2567, pp. 10-17.

Han, H. & E. Ponce Cueto (2015), Waste collection vehicle routing problem: literature review. Traffic Engineering Review 27:4, pp. 345-358.

Hertz, A. (2005), Recent trends in arc routing. In: Hartman, I., Golumbic, M. (Eds.), Graph Theory, Combinatorics and Algorithmics: Interdisciplinary Applications. Boston: Kluwer, pp. 215-236.

Heywood. I., S. Cornelius & S. Carver (2011), An introduction to geographical information systems. Harlow/England: Pearson Education Limited. Fourth Edition

HGH (2018), Historisch Genootschap Hoogvliet – Hoogvliet 1934-1973 [online], http://www.historischhoogvliet.nl/hoogvliet-1934-1973.html [cited 31-05-2018]

Holmberg, K. (2010), Heuristics for the rural postman problem. Computers & Operations Research 37, pp. 981-990.

Jang, W., Noble, J.S. & T. Hutsel (2010), An integrated model to solve the winter asset and road maintenance problem. IIE Transactions 42:9, pp. 675-689.

Júnior, P. (2008), Integration of geographic information systems, meta-heuristics and multi-criteria analysis for territories alignment. Thesis Faculdade de Engenharia da Universidade do Porto.

Keenan, P. (2001), Spatial decision support systems for large arc routing problems. PhD thesis: University College Dublin.

Keenan, P. (2008), Modelling vehicle routing in GIS. Operation Research International Journal 8, pp. 201-218.

Kim, S. & S. Bae (2016), Optimal solution to the vehicle routing problem by adopting a meta-heuristic algorithm. Transportation Planning and Technology 39:6, pp. 574-585.

Kramberger, T., Zerovnik, J., Strubelj,. G. & K. Prah (2013), GIS technology as an environment for testing an advanced mathematical model for optimization of road maintenance. Central European Journal of Operations Research 21:1, pp 59-73.

Krichen, S., Faiz, S., Tlili, T. & K. Tej (2014), Tabu-based GIS for solving the vehicle routing problem. Expert Systems with Applications 41, pp. 6483-6493.

Kuby, M., Tierney, S., Roberts, T. & C. Upchurch (2005), A Comparison of Geographic Information Systems, Complex Networks, and Other Models for Analyzing Transportation Network Topologies. Hampton: NASA Langley Research Center.

Laporte, G. (1992), The vehicle routing problem: An overview of exact and approximate algorithms. European Journal of Operational Research 59:3, pp. 345-358.

Laporte, G. (2009), Fifty Years of Vehicle Routing. Transportation Science 43:4, pp. 408-416.

Levinson, D. & A. El-Geneidy (2007), Network Circuity and the Location of Home and Work. Harrowgate, England.

Letchford, A.N. & R.W. Eglese (1998), The rural postman problem with deadline classes. European Journal of Operational Research 105:3, pp. 390-400.

Loidl, M., Wallentin, G., Cyganski, R., Graser, A., Scholz, J., & E. Haslauer (2016), GIS and Transport Modeling-Strengthening the Spatial Perspective. ISPRS International Journal of Geo-Information 84:5, pp.1-23.

Luke, S. (2015), Essential of Metaheuristics, a set of undergraduate lecture notes. Second edition, October 2015.

Lum, O. (2017), Solving, generating, and modeling arc routing problems. PhD Thesis, University of Maryland.

Lum, O., Golden, B. & E. Wasil (2018), An Open-Source Desktop Application for Generating Arc-Routing Benchmark Instances. INFORMS Journal on Computing 30:2, pp. 361-370.

Mapa, S. & R. Lima (2014), Combining Geographic Information Systems for Transportation and Mixed Integer Linear Programming in Facility Location-Allocation Problems. Journal of Software Engineering and Applications 7, pp. 844-858.

Mourão, M. C. & L.S. Pinto (2017), An Updated Annotated Bibliography on Arc Routing. Networks 70:3, pp. 144-194.

Michiels, W., Aarts, E.& J. Korst (2007), Theoretical aspects of local search. Springer Science & Business Media.

Mitroff, I. I., Betz, F., Pondy, L.R. & F. Sagasti (1974), On Managing Science in the Systems Age: Two Schemas for the Study of Science as a Whole Systems Phenomenon. Interfaces 4:3, pp. 46-58.

Municipality of Rotterdam (2018), Buurtmonitor [online] https://rotterdam.buurtmonitor.nl/jive?cat_open=Beleidsthema%27s/Demografie [cited 23-04-2018]

Municipality of Rotterdam (2015), Beleidsplan Gladheidsbestrijding 2015-2020.

Municipality of Rotterdam (2014), Gladheidbestrijding op z'n Rotterdams. Presentatie landelijk congres gladheidsbesrijding oktober 2014.

Municipality of Rotterdam (2013), Uitvoeringsplan Gladheidsbestrijding.

Muyldermans, L., Cattrysse, D., Van Oudheusden, D. & T. Lotan (2002), Districting for salt spreading operations. European Journal of Operational Research 139:3, pp. 521-532.

Nixon (2009), National advances in winter maintenance. Paper presented at the 8th annual road salt symposium.

Noble, J.S., Jang, W., Klein, C.M. & C. Nemmers (2006), An integrated system approach to the development of winter maintenance/management systems. Final Report MTC Project 2005-03, Midwest Transportation Consortium, Iowa State University.

O'Connor, D.L. (2013), Solid Waste Collection Vehicle Route Optimization for the City of Redlands, California. Master thesis, University of Redlands.

O'Keefe, K., & X. Shi (2006), Anti-icing and Pre-wetting: Improved Methods for Winter Highway Maintenance in North America. Proceedings of the Transportation Research Board Annual Meeting, January 22-26, 2006, Washington, D.C.

PDOK (2017), TOP10NL [online] https://www.pdok.nl/nl/producten/pdok-downloads/basisregistratie-topografie/topnl/topnl-actueel/top10nl [cited 02-08-2017]

Perrier, N., Campbell, J.F., Gendreau, M. & A. Langevin (2010), routing models and algorithms for winter road spreading operations. CIRRELT-2010-53.

Perrier, N., Langevin, A. & J.F. Campbell (2007), A survey of models and algorithms for winter road maintenance, Part III: vehicle routing and depot location for spreading. Computers & Operations Research 34, pp. 211-257.

PG Routing (2018), PG Routing project [online] http://pgrouting.org/ [cited 23-04-2018]

Toth, P. & D. Vigo (eds) (2002), The vehicle routing problem, vol 9. SIAM, Monographs on Discrete Mathematics and Applications, Philadelphia.

Thill, J. (2000), Geographic information systems for transportation in perspective. Transportation Research Part C: Emerging Technologies 8, pp. 3-12.

Quirion-Blais, O., Langevin., A., Lehuéde, F., Peton., O. & M. Trépanier (2016), Solving the Large-Scale Min-Max K-rural Postman Problem for Snow Plowing. CIRRELT-2016-56.

Tagmouti, M., Gendreau, M. & J-Y. Potvin (2011), A dynamic capacitated arc routing problem with time-dependent service costs. Transportation Research Part C: Emerging Technologies 19:1, pp.20-28.

Talbi, E.G. (2009), Metaheuristics: From Design to Implementation. John Wiley & Sons, Inc.

TransCAD (2018), TransCAD Transportation Planning Software [online], https://www.caliper.com/tcovu.htm [cited 23-04-2018]

Xie, B., Li, Y. & J. Jin (2013), Vehicle Routing Optimization for Deicing Salt Spreading in Winter Highway Maintenance. Procedia – Social and Behavioural Sciences 96, pp. 945-953.

Appendices

Appendix A: Gritting Routes HR_044 and HR_045


Vondelingenweg
Botlekweg
Botlektunnel
Oude Maasweg
Digna Johannaweg
Mosselstr.
Oude Wal
Aveling
Parelvisserssstr.
Troubadourlaan
Fideliolaan
Toscalaan
Oudelandseweg
Hoefsmidstr.
Gaderingviaduct
Nieuwe Langeweg
Klompenmakerstraat
Mandenmakerstraat
Laning
Max Havelaarweg
Herikweg
Tijmweg
Groene Kruisweg
Spijkenisserbrug
Nieuwe Wetering
Hoogvlietsekerksingel
Koddeweg
Kaperslhoekseweg
Endenhout
Overwolde
Baarsweg
Steurweg
Horsweg
Kruisnetlaan
Boveneind
Speerreep
Aalreep
Janswaal
Dorpsweg
Schenkelweg
Rozenlaan
Stationsstr.
Voedingskanaal
Haven

HR-045

Appendix B: TomTom Multinet UML Relationship model

This attachment has been removed from the public version of the report. The documents are available upon request only. Please contact R.J.W.dekleijn@student.utwente.nl

Appendix C: Routing workflow processing steps ArcMap

For the routing workflow ArcMap is used. This appendix described the processing steps of each of the phases of the routing workflow which is described at p. 42. The phases are listed in in table **Ac.1**

Table **Ac.1** Phases of the routing workflow

i	Create network dataset	Adding TomTom network in ArcGIS format
A	Digitisation	The translation from digitised lines into TOP10NL road parts
C	Transformation	Transforming the TOP10NL road parts to (TomTom) road segments
D	Arc to node routing	Creating nodes from arcs

Colour scheme used in this workflow process:

Underlined	Instructions for manual processing steps
In Italic Green	SQL expressions
Blue Underlined	Download link for online toolboxes
	Clickable action

Phase i: TomTom network Rotterdam

This section describes the correct transformation of the TomTom network dataset into a compatible ESRI ArcMap format. This preliminary step has to be done manually before creating the routing model.

The delivered TomTom network dataset is already set to the RD_New coordinate system (directory: …Netwerkdata_TomTom/RDNew). If a new version is acquired and used, make sure to adjust the coordinate system to RD_New.

Download the Street data processing toolbox

1. Download the Street data processing toolbox from https://github.com/Esri/street-data-processing-tools/releases
2. Install the appropriate version according to the guidelines (for ArcMap 10.3.1, download the Street Data Processing Tools v10.3.1.2).
3. Open the .zip file and copy the toolbox to a file directory and follow the instructions as described on GitHub.

Transforming the TomTom network dataset in a compatible ESRI ArcMap format

4. Open ArcMap and go to Geoprocessing -> ArcToolbox
5. Right click the ArcToolbox and click on Add Toolbox. Add the Street data processing toolbox which you unzipped.
6. Open data Street data Processing Tools -> TomTom -> Process MultiNet Street data which should be added to the ArcToolbox.
7. Add the NW, MN, MP, SI, SP and RS table from the …Netwerkdata_TomTom/RDNew directory. Check the 'Create Network Attributs in Metric (optional)' button.
8. Click on Ok. The network dataset is created.

Clipping the network to Rotterdam

The network will be clipped to the municipality of Rotterdam, to reduce loading time.

9. Open the 'Distributed Geodatabase' toolbar.
10. Click the ''Extract Data' button.
11. Check the box 'Show advanced options for overriding data extraction defaults'
12. For the spatial extent of the municipality of Rotterdam, use the following extent:
    Display extent:
    Left: 52580
    Right: 105100
    Top: 450777
    Bottom: 425873
    Include all the items for the extraction.
13. Click next, and check the box for 'require no further action'.
14. Save the created network dataset.

Building the network dataset

15. Go to the Arc Toolbox -> Network Analyst Tools -> Network Dataset -> Build Network
16. Choose the 'Routing_ND' as input for the network dataset and click OK.

Output 0: The TomTom is now loaded in ArcMap for the municipality of Rotterdam in an ESRI network dataset format.

Phase A: Digitization

In this section the digitized lines are transformed to the correct TOP10NL road parts. Steps 1-6 are automated in ArcMap using the model builder. Step 7-12 are manually steps.

Joining line attributes to TOP10NL road parts

1. In ArcMap, click ‘File -> Add Data -> Add data’ and add the Roadpart_polygon and GrittingRoutes_HR to the map.
2. At Selection, click on ‘Select By Location.’ Use the ‘select features from’ selection method. Select ‘Roadpart_polygon’ as the target layer and ‘GrittingRoutes_HR’ as the target layer.
3. Click Ok. The attribute table of the GrittingRoutes_HR is now joined to the Roadpart_polygon dataset based on location.

Automatic road part selection based on relevant attributes

Not all road parts selected by the use of location are relevant. To account for this a selection is made based on attribute characteristics, such as traffic use and road type.

4. Open the Select (Analyses) Tool. Use the output of step 3 as input, and use the SQL Expression *routenummer = 'HR044' OR routenummer = 'HR045'.*
5. Open the Select (Analyses) Tool. Use the output of step 4 as input, and use the SQL Expression: *HOOFDVERKEERSGEBRUIK_CSV = 'busverkeer' OR HOOFDVERKEERSGEBRUIK_CSV = 'busverkeer|fietsers, bromfietsers' OR HOOFDVERKEERSGEBRUIK_CSV = 'gemengd verkeer' OR HOOFDVERKEERSGEBRUIK_CSV = 'gemengd verkeer|busverkeer' OR HOOFDVERKEERSGEBRUIK_CSV = 'gemengd verkeer|fietsers, bromfietsers' OR HOOFDVERKEERSGEBRUIK_CSV = 'gemengd verkeer|voetgangers' OR HOOFDVERKEERSGEBRUIK_CSV = 'snelverkeer|gemengd verkeer'*
6. Open the Select (Analyses) Tool. Use the output of step 5 as input, and use the SQL Expression: *TYPEWEG_1 = 'hoofdweg' OR TYPEWEG_1 = 'lokale weg' OR TYPEWEG_1 = 'overig' OR TYPEWEG_1 = 'regionale weg' OR TYPEWEG_1 = 'straat'.*

Manual road part selection

Based on both spatial and functional selection still some road parts are wrongly digitized or not selected. This check has to be done manually.

7. At selection, click on ‘Select By Attributes’. Use the ‘Strooiroutes_HR” layer and use method: create a new selection with the SQL Expression: *routenummer = 'HR044' OR routenummer = 'HR045'*
8. Compare the digitized lines (step 7) with the TOP10NL road parts (step 6).
   If the gritting routes are correctly digitized to road parts, save the output (step 12)
   If there are road parts which are should not be in the road parts selection (step 9 & 12)
   If road parts still need to be included in the road parts selection (Step 10-12)
9. Use the ‘select features’  button and select the irrelevant road parts. After selection, right click the layer Road part layer and ‘open attribute table’. At the table, switch the selection  . Close the attribute table and right click the road part layer and Select ‘selection -> Create layer from selected features.
10. Use the road part input data (step 1) to select the missing road parts with the ‘select features’  button. If all missing road parts are selected, right click on the layer and use ‘Selection -> Create layer from selected features’.
11. Go to Geoprocessing -> Merge. Use the Road parts (from either step 8 or 9) with the additional road parts which are selected in step 10. Select OK.
12. Save the layer output using ‘Data -> Export data’.

Output A: A dataset containing all relevant TOP0NL road parts with a joined attribute table from the original gritting routes.

Phase C: Transformation

The next step consists of selecting the correct TomTom street segments and convert these street segments into mid points. This will enable the use of network analyses. Part 1. Steps 1-3 are automated in ArcMap using the model builder. Step 4-13 will have to be done manually.

Select TomTom street segments

1. In ArcMap, click 'File -> Add Data -> Add data' and add the TOP10NL Road parts dataset as of the output of Section A: Digitization. Furthermore, add the network dataset as created in Appendix 0: TomTom network Rotterdam.
2. Go to 'Selection -> Select by location'. Use the 'select features from' selection method with the 'Streets' as Target Layer and the TOP10NL Road parts dataset as source layer.
3. Right click on the Streets layer and Select 'selection -> Create layer from selected features. Export the data from the newly created layer by right click the layer and go to 'data -> Export data. Click 'yes' for 'Do you want to add the exported data to the map as a layer?'. This allows the user for not editing the network dataset, but instead using it as an alternative dataset.

Manual TomTom line segment selection

The TOP10NL Roadparts should match the TomTom line segments. However, due to the spatial selection some parts are either wrongly selected or not selected at all. To adjust for these digitization errors additional manual steps are required.

<u>If there are TomTom street segments which are should not be in the selection (step 4 & 7)</u>

<u>If TomTom line segments need to be included in the selection (Step 5-7)</u>

4. Use the 'select features' button and select the irrelevant road parts. After selection, right click the layer Road part layer and 'open attribute table'. At the table, switch the selection . Close the attribute table and right click the road part layer and Select 'selection -> Create layer from selected features.
5. Use the TomTom network dataset as input data (step 1) to select the missing road parts with the 'select features' button. If all missing road parts are selected, right click on the layer and use 'Selection -> Create layer from selected features'.
6. Go to Geoprocessing -> Merge. Use the Road parts (step 4) with the additional road parts which are selected in step 5. Select OK.
7. Save the layer output using 'Data -> Export data'.

Create TomTom line segment midpoints

8. Download the ET GeoWizard 11.4 tool for ArcGIS 10.3 at http://www.ian-ko.com/Downloads.html
9. Open the .zip file and follow the setup instructions from the installation. You might have to restart ArcMap in order to use the functionalities.
10. Go to Customize -> Toolbars -> ET Geowizards. An additional window will open

11. Click on the logo and go to Convert -> Polyline to point. Click on 'Go'. Select the polyline layer which you created (step 7) and specify the output feature class.
12. Click on next and specify the 'Middle Points' conversion option. Uncheck all the boxes and hit 'Finish'.
13. Right click on the newly created middle point layer and save the output using 'Data -> Export Data'.

Output C: In this section two output layers are created: (i) the TomTom Line segments and (ii) the TomTom Line segments midpoints.

Phase D: Arc to node routing and attribute transfer (part 1)
Part one consists of matching the TOP10NL road parts to the correct TomTom midpoints. Step 1-10 and 14-16 have been created in ArcMap Model builder. Steps 11-13 and 17-19 will have to be done manually.

Select TOP10NL road links & convert to points

1. In ArcMap, click 'File -> Add Data -> Add data' and add the TOP10NL Road parts dataset as of the output of Section A: Digitization. Furthermore, add the TomTom point dataset as created in Appendix C:Arc to Node routing.
2. Go to 'Selection -> Select by attributes'. Use the 'TOP10NL Road parts dataset as layer and choose 'Create a new selection' method. For this use the SQL expression: *typeInfrastructuur = 'verbinding'*. Click 'Ok'.
3. Convert these road inks to points with the Feature To Point (Data Management) tool. This will make one point from the polygon objects.
4. Add XY coordinates to these point objects with the Add XY Coordinates (Data Management) tool. These coordinates are needed in a later stage.
5. Use the near (Analyses) tool to identify the nearest TomTom points to the TOP10NL road part points. Use the 'TomTom mid points' as input features and the 'Top10NL road part (as created in step 2) as near feature. This step will create an attribute called 'NEAR_FID', which indicates the nearest TomTom mid point to the TOP10NL road parts.

Create connection links between TOP10NL road links and TomTom midpoints

6. Open the Join Field (Data Management) tool. Use the TomTom mid points (step 5) as input table. The input join field is the 'NEAR_FID'. Use the TOP10NL road part points (step 4) as join table. Use the OBJECTID as Output join field.
7. For now the joining of these tables give a lot of additional attributes which are not of interest yet. Use the Delete Field (Data Management) tool to remove these. Delete all attributes except for: ET_X , ET_Y (the coordinates of the TomTom midpoints), NEAR_FID (indication nearest TomTom midpoint) and POINT_X and Point_Y (coordinates top10nl road part point).
8. Right click the layer TomTom mid points and 'open attribute table'. At the table, click table options and choose 'Add Field…'. Name the field 'IDroadpartchange' and keep the data type a short integer. Click 'Ok'.
9. Select the newly made IDroadpartchange row, right click and hit 'Field Calculator'. For the expression, use: [NEAR_FID]. This will make a copy of the NEAR_FID to the IDroadpartchange field. This field will be used later.
10. Use the 'XY To line' tool. Use ET_X and ET_Y as start fields and Point_X and Point_Y as End fields. These lines graphically indicate the relation between the tomtom lines and road part polygons, in a simplified point-line-point view.

Manual near check (1)

The output created gives a visual overview of which TOP10NL road parts are connected to which TomTom lines. This connection has to be check manually. <u>In case if there are wrong connections made:</u>

11. Go to Customize -> Toolbars -> Editor. Right Click on Editor in the Editor menu and hit 'Start Editing'. Choose the 'TomTom midpoints' layer for editing.
12. Right click the layer TomTom mid points and 'open attribute table'. At the table, go to the IDroadpartchange field. In this field, change any of the wrongly assumed connections by changing the ID to the correct connection.
13. If all the connections have been updated, go to the editor menu and save the edits. After saving, stop the edit session.

Manual near check (2)
In the previous step 13 the connections have been updated. In this manual near check it is looked if the connections are updated correctly.

14. Open the Join Field (Data Management) tool. Use the TomTom mid points (step 13) as input table. The input join field is the 'IDroadpartchange'. Use the TOP10NL road part points (step 4) as join table. Use the OBJECTID as Output join field.
15. Again, this join gives additional attributes which are not of interest in this stage of the process. For this the Delete Field (Data Mangement) is used to remove these. Only keep the attributes ET_X, ET_Y (the coordinates of the TomTom midpoints), NEAR_FID and Idroadpartchange (indication nearest TomTom midpoint) and POINT_X_1 and Point_Y_1 (coordinates top10nl road part point). Make sure to delete the POINT_X and POINT_Y coordinates. These belong to the previous manual near check.
16. Use the 'XY To line' tool. Use ET_X and ET_Y as start fields and Point_X_1 and Point_Y_1 as End fields. These lines graphically indicate the relation between the TomTom lines and road part polygons, in a simplified point-line-point view.
17. Check if the updated points and lines are correct. <u>If this is still not the case, repeat steps 11-13</u>. In case there are still many connections made wrong, a second manual near check can be executed as described in steps 14-16.

Transferring attributes TOP10NL to TomTom midpoints
The next steps encompass the attribute transfer from the TOP10NL road parts to the TomTom midpoints. For this the TOP10NL ID is used as the ID as the connector.

18. Open the Join Field (Data Management) Tool. Use the TomTom mid points (step 14) as input table. The input join field is the 'IDroadpartchange'. Use the TOP10NL road part points (step 4) as join table. Use the OBJECTID as Output join field.
19. If the join is successfully, the attribute data which was needed to ensure the correct join can be removed. These attributes are: ET_X, ET_Y, NEAR_FID, Point_X(_1) and Point_Y(_1). Keep the attribute of IDroadpartchange. If the user do not wish to remove these attributes, they might be hided in the attribute table as well using 'Turn field off ' option.

Output D (part 1): All the TomTom lines via a TomTom midpoint have been assigned to the correct TOP10NL road part. Furthermore the attribute data of the TOP10NL has been transferred. Any additional data which the user wants to add later can be easily joined with the use of the TOP10NL ID. Additionally, in model builder some additional layout is added with the use of the 'make feature layer' and 'apply symbology from layer' tools and .lyr layout inputs.

Phase D: Arc to node routing and attribute transfer (part 2)
In appendix D (part 1) all the TOP10NL road parts have been assigned to the correct TomTom midpoints. In part 2 the remaining a TOP10NL road part, which have not been assigned to a TomTom mid point yet, will be joined.

1. In ArcMap, click 'File -> Add Data -> Add data' and add the TomTom midpoint dataset as the output of Appendix D1: Attribute transfer (part 1). Also add the road part dataset without the junctions in points as selected in Appendix D1: Attribute transfer (part 1), step 3.
2. Open the Join Field (Data Management) tool. Use the TomTom mid points as input table. The input join field is the 'IDlokaal'. Use the output of Appendix D1: Attribute transfer (part 1) as join table. Use the IDlokaal as Output join field.
3. At selection, click on 'Select By Attributes'. Use the 'TomTom mid point" layer and use method: create a new selection with the SQL Expression: IDroadpartchange > 0.
4. Use the Erase (Analyses) tool. Take the road part dataset without junctions as input dataset and the TomTom mid point selection (step 3) as erase feature.
5. Take the output of step 4 and add XY coordinates (Data Management).

Create connection links between the remaining TOP10NL road links and TomTom midpoints

6. Click 'File-> Add data -> Add data' and add the TomTom midpoints as created in Output C.
7. Use the near (Analyses) tool to identify the nearest TomTom points to the TOP10NL road part points. Use the 'TomTom mid points' from output C as input features and the 'Top10NL road part point features (as created in step 5) as near feature. This step will create an attribute called 'NEAR_FID', which indicates the nearest TomTom mid point to the TOP10NL road parts points.
8. Right click the layer TomTom mid points and 'open attribute table'. At the table, click table options and choose 'Add Field…'. Name the field 'IDtomtomchange' and keep the data type a short integer. Click 'Ok'.
9. Select the newly made IDtomtomchange row, right click and hit 'Field Calculator'. For the expression, use: [NEAR_FID]. This will make a copy of the NEAR_FID to the IDtomtomchange field. This field will be used later.
10. Use the 'XY To line' tool. Use Point_X and Point_Y as start fields and Near_X and Near_Y as End fields. These lines graphically indicate the relation between the remaining TomTom points and road part polygons, in a simplified point-line-point view.

Manual near check (3)
The output created gives a visual overview of which the remaining TOP10NL road parts are connected to which TomTom lines. This connection has to be check manually. <u>In case if there are wrong connections made:</u>

11. Go to Customize -> Toolbars -> Editor. Right Click on Editor in the Editor menu and hit 'Start Editing'. Choose the 'TOP10NL road part point' layer (step 8) for editing.
12. Right click the layer TomTom mid points and 'open attribute table'. At the table, go to the IDtomtomchange field. In this field, change any of the wrongly assumed connections by changing the ID to the correct connection.
13. If all the connections have been updated, go to the editor menu and save the edits. After saving, stop the edit session.

Manual near check (4)
In the previous step 13 the connections have been updated. In this manual near check it is looked if the connections are updated correctly.

14. Open the Join Field (Data Management) tool. Use the TOP10NL road part points (step 14) as input table. The input join field is the ‘IDtomtomtchange’. Use the TomTom mid points (step 13) as join table. Use the OBJECTID as Output join field.
15. Again, this join gives additional attributes which are not of interest in this stage of the process. For this the Delete Field (Data Mangement) is used to remove these. Only keep the attributes ET_X, ET_Y (the coordinates of the TomTom midpoints), NEAR_FID and IDtomtomchange (indication nearest TomTom midpoint) and POINT_X_1 and Point_Y_1 (coordinates top10nl road part point). Make sure to delete the POINT_X and POINT_Y coordinates. These belong to the previous manual near check.
16. Use the ‘XY To line’ tool. Use ET_X and ET_Y as start fields and Point_X_1 and Point_Y_1 as End fields. These lines graphically indicate the relation between the TomTom lines and road part polygons, in a simplified point-line-point view.
17. Check if the updated points and lines are correct. If this is still not the case, repeat steps 11-13. In case there are still many connections made wrong, a second manual near check can be executed as described in steps 14-16.

Transferring attributes TOP10NL to TomTom midpoints
The next steps encompass the attribute transfer from the remaining TOP10NL road parts to the TomTom midpoints.

18. Open the ArcGIS catalog window and go to the active file geodatabase were the TOP10NL road parts and the TomTom midpoints are stored. It is important that these files are active in the same geodatatabase.
19. Right click on the file geodatabase, select ‘New’ and click Relationship class. Choose the remaining TOP10NL roadparts as Original table/feature class and the TomTom midpoints as destination table/feature class. Give the relationship class the name ‘Remaining_road_parts’ Click next.
20. Choose the following settings: the type of relationship is‘Simple (peer to peer) relationship’, The messages direction is ‘None (no messages propagated), the cardinality is 1 - M (one to many), Choose ‘No’, at the option to choose addtributes to this relationship class.
21. At the Origin table/feature class, the Primary key is OBJECTID and the Foreign key is IDroadpartchange. For the Destination table is still the TomTom midpoints. Click ok. A new relationship class is made within the geodatabase
22. To show the table relationship, open the attribute table of the TomTom mid points and click on related tables .

Output D (part 2): All the remaining TOP10NL road parts have been assigned to the correct TomTom midpoint. Furthermore the attribute data of the TOP10NL has been transferred. Any additional data which the user wants to add later can be easily joined with the use of the TOP10NL ID. Additionally, in model builder some additional layout is added with the use of the ‘make feature layer’ and ‘apply symbology from layer’ tools and .lyr layout inputs.

Appendix D: Traversing arcs Hoogvliet

This attachment has been removed from the public version of the report. The documents are available upon request only. Please contact R.J.W.dekleijn@student.utwente.nl