Master Thesis, Industrial Engineering & Management by Bart Essink

Scenario analysis of a ice and snow control program on the tactical level

TWENTE MILIEU

Schoon, gezond en fris

Department of Industrial Engineering and Business Information Systems (IEBIS)

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Examination committee

Dr. ir. M.R.K. Mes (University of Twente)

Dr. ir. L.L.M. van der Wegen (University of Twente)

Gerbert Stegehuis (Twente Milieu)

UNIVERSITY OF TWENTE.

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Preface

From November 2013 until June 2014, I have been working at Twente Milieu on the topic of snow and ice control. This rapport is the result of my graduation internship in order to obtain my Masters in Industrial Engineering & Management at the University of Twente.

I would like to thank Martijn Mes and Leo van der Wegen, my supervisors from the University of Twente, for guiding me through the process of writing my Master thesis. Their guidance and constructive feedback have been very valuable. I am also thankful for the opportunity Gerbert Stegehuis gave me to conduct my research at Twente Milieu.

Finally, I thank my family and friends for their support during my studies. Your patience, support, and encouragement have been of great help in order to obtain my Masters degree.

Bart Essink

Enschede, July 2014

Summary

Municipalities are, by law, responsible for the maintenance and cleaning of the road network. Snow and ice control is part of this responsibility. Twente Milieu carries out this task on behalf of several municipalities in Twente. This report is about creating insights, on a tactical level, into the snow and ice control process currently used at Twente Milieu. The focus is mainly put on Enschede. These insights can be used to make decisions whether to change certain aspects regarding the snow and ice control in the future.

Activities in the area of snow and ice control mainly take place during the evening or at night. With a budget of more than €500k, for the municipality of Enschede, and the impact it has on traffic safety, it is considered an important task. Table 1 shows some characteristics of the snow and ice control program. It can be seen that the number of salting times varies a lot. From a financial perspective, budgeting is difficult.

Season	2011-2012	2012-2013	2013-2014
Number of salting actions	22	83	19
Salt used (in tons)	1,180	2,771	509

Table 1: Characteristics of the ice and snow control

Snow and ice control program
Enschede determines annually the roads and cycle paths that need to be salted during the winter. A distinction is made between roads that need to be salted within three hours (phase 1) after the first signs of slipperiness, and roads that need to be salted within five hours after these signs appear (phase 2). Twente Milieu determines salting routes based on these roads with corresponding priorities. Determination of salting routes takes place without the use of professional planning techniques or planning software. For example, the salting routes of Enschede are set by dividing the sprinkle map (overview of all roads that need to be salted, Appendix A) into different sections. Subsequently, the salting route within a section is drawn based on experience, logic, and intuition. For this reason, it is not known whether the current routes are optimal and if the use of routing and planning techniques could reduce costs (i.e., minimize driven kilometers) and/or increase safety.

Furthermore, the absence of professional planning techniques makes it rather difficult to assess the effects, both financially and in terms of safety, that arise when (tactical) changes are being made. Organizations need to be aware of cause and effect relations in their decision making process. Examples of such tactical decisions are:

- What happens when there is a 10% reduction of the number of roads that needs to be salted?
- What happens when no prioritization (in terms of time) is made between different roads?
- What happens when less salting vehicles are being used?

This thesis focuses on providing Twente Milieu with insights into the effects of such tactical decisions.

Solution method
An Integer Linear Programming (ILP) model is used to solve the planning problem. Two formulations are presented. The objective function of the first formulation is about cost minimization and

incorporates an integral approach towards route optimization for the whole fleet. The corresponding model appears to be too big to solve in a reasonable timeframe. Thus an alternative formulation is required. The objective function of this model seeks for effective truck usage, i.e., a truck should salt as many roads as possible within a certain time interval. Instead of coming up with a route for the whole fleet at once, the ILP is solved iteratively for every available truck. In other words, a heuristic approach is used to solve an ILP per truck. The ILP provides a starting solution in which most roads are salted. The remaining streets are scheduled with an insertion heuristic. The insertion rule is based on distance minimization.

This solution method is applied to several scenarios such as: varying number of trucks, different depot locations, and allowing violation of road prioritization with corresponding completion times. Per scenario, the solution method calculates the distance travelled per truck, the salting time per truck, and the traversing time per truck. This information is used to compare the scenarios with each other.

Results

Table 2 contains information about every scenario.

Scenario category	Scenario (averages)	Distance travelled (km)	Travelling time (min)	Salting time (min)
Differing depot location	Current depot location (initial solution)	87.08	154.31	93.91
	Depot west	87.19	156.01	92.63
	Depot south	84.51	151.06	94.79
	Depot east	91.35	154.67	93.55
	Depot city centre	78.99	140.52	92.98
Adjusting completion time of phase 1	Normal completion time (initial solution)	87.08	154.31	93.91
	Extended completion time	89.61	157.15	92.74
	Penalty for violating completion time	92.91	161.95	91.57
Differing truck usage	11 trucks (initial solution)	87.08	154.31	93.91
	10 trucks	93.06	166.24	102.32
	9 trucks	118.36	204.50	117.48

Table 2: Overview of all scenarios

One can see that, besides the scenarios in which fewer trucks are used and the scenario in which the depot is located in the city centre, the distance travelled per truck does not differ that much. For the scenarios in which the completion time of phase 1 is eased or extended, this is not that remarkable. This is because Twente Milieu has sufficient trucks to salt the arc network. Easing or extending the completion time could become necessary in case fewer trucks are used. In case Twente Milieu decides to do so, it is recommended to examine this.

Depot location

Locating the depot in the city centre does have a significant impact on the distance travelled per truck. It is recommended to use this knowledge in case the current depot is depreciated. This location becomes more important if fewer trucks are used. If fewer distance must be covered from the depot to a truck's salting area, the chance that the completion time of phase 1 is respected increases. This distance travelled per truck depends on the depot location.

Fewer trucks

Using fewer trucks results in less incurred costs. In the case of 9 trucks, a truck takes, on average, 204.50 minutes to complete its route. 11 trucks take on average 154.31 minutes to complete their route. This is an extension of 33%. In the current situation, trucks take 2 to 2.5 hours to complete their routes. With this extension in mind, it seems permitted to use fewer trucks.

Truck differences

The differences between the trucks per scenario, with respect to the distance covered, the travelling time, and the salting time, are caused by the fact that some districts are more difficult to reach and salt. This effect is mitigated by the seed customers[1] assigned per truck, however this effect cannot be eliminated. Furthermore, it is not necessary to construct equal routes in terms of distance covered, travelling time, and salting time.

Recommendation

Twente Milieu should start with an extensive discussion regarding the organization of the entire snow and ice control program. The subject of this debate is whether different salting routes, i.e., various scenarios could be used in the future. The information retrieved from the solution method can help in this process. Only if there is a consensus among different stakeholders (Management Team, municipalities, and the operation department), further steps could be taken.

At the moment, the discussion with respect to the snow and ice control program is mainly focused on the available financial resources. From the perspective of operational excellence, a better starting point would be to shift the focus from the current snow and ice control program and to ignore signals coming from the municipalities to carry out cost reductions. Improvements and cost reductions should be the result of strategic and tactical decision making processes, not the starting point. There are sufficient points of interest to start the discussion regarding the future of the snow and ice control program. Twente Milieu's mission statement speaks of a waste-free society in 2030. Waste-free is a broad concept and could also be seen in light of minimal fuel consumption, seeking synergy by combining activities, and minimize the usage of vehicles. Furthermore, seeking synergy between municipalities was one of the goals set during the establishment of Twente Milieu. All municipalities are united within Twente Milieu, so it is the designated organization to take the lead in this process.

Twente Milieu's mission statement and the aim of seeking synergy should be leading in the strategic and tactical discussion on winter maintenance. A relevant question is: 'how do we see winter maintenance, in the context of a waste-free society, in 2030 on the level of Twente Milieu?' Only if

[1] A seed customer is a specific road that is assigned to a specific truck in order to guide that truck to a certain district. For example, truck 1 is assigned to the southern part of Enschede, truck 2 is assigned to the western part of Enschede et cetera. The use of seed customers increases the quality of the solution obtained by the iterative ILP procedure.

there is a consensus among stakeholders regarding this question, further steps should be taken. Examples of further actions are: use Operation Research in order to determine depot locations (transboundary or not), determine an economically viable fleet size, set the routes. One should be aware that these actions do not determine how one sees winter maintenance in the future. These actions only give shape to the policy that was set prior to this.

The problem solving approach described above increases the chance of ending up in a desired state. Furthermore, such a method provides a good basis for a new way of working. This basis can also be used to convince all relevant stakeholders.

Chapter 1: Introduction

In this chapter, an introduction on the entire graduation project is given. The chapter starts with an overview of the working activities at Twente Milieu. Thereafter, in Section 1.2, the snow and ice control program at Twente Milieu is introduced followed by the reason for conducting this research, its scope, limitations, and expected contributions to this control program.

1.1 Twente Milieu N.V.

Twente Milieu N.V. is a government-owned company. The shares are owned by seven municipalities in Twente: Almelo, Borne (since October 2013), Enschede, Hengelo, Hof van Twente, Losser and Oldenzaal. Furthermore, these seven towns are also the main customers of Twente Milieu. The main objective of Twente Milieu is not profit maximization but 'impact maximization' (Twente Milieu, 2012). Twente Milieu is a specialist in garbage disposal, managing public space, sewage management, pest control, and ice control. These tasks are carried out in light of offering high societal value for low community costs.

Mission statement and vision

The primary activity of Twente Milieu is in the area of garbage disposal and waste management. This is also reflected in the mission statement (Twente Milieu, 2013):

'Twente Milieu contributes to a clean and healthy environment.'

This mission has been translated into Twente Milieu's dream, namely to establish a waste-free society. In 2030, waste is being processed into raw materials by moving away from the current linear economy towards a circular economy (cradle to cradle) (Twente Milieu, 2013). Nowadays, Twente Milieu uses awareness campaigns in order to change people's and organization's attitude towards waste. Furthermore, a more intelligent garbage collection system, that focuses on waste sorting, is being used in order to shape Twente Milieu's dream.

Ice and snow control

The idea behind a waste-free society can also be applied to other fields in which Twente Milieu is active. In a broad sense, minimizing or even eliminating environmentally harmful activities, such as the inefficient usage of fossil fuel or the unnecessary use of company cars, all contributes to Twente Milieu's mission. This research is in the area of winter maintenance. In the spirit of the previous stated dream, Twente Milieu seeks for collaboration between all municipalities in order to generate efficient salting routes and an effective salting program. Only this contributes to safe traffic conditions and a low carbon footprint for minimal community costs.

Municipalities are, by law, responsible for the maintenance and cleaning of the road network and the public space as defined in the *Wegenwet*[2]. These tasks are carried out by Twente Milieu on behalf of the shareholders (municipalities). Annually, a service level agreement (SLA) is signed in which all

[2]The Wegenwet is a Dutch law in which the responsibilities for managing public roads are arranged. This law states i.e. that the public road network should be in good condition.

tasks and responsibilities of all parties are specified in. The agreements, with respect to the ice and snow program, are as follows (Twente Milieu; Gemeente Enschede, 2013):

- preventing slipperiness on all public roads and cycle paths according to the prioritization list (appendix A) provided by the municipalities;
- salting starts within 45 minutes after signaling slipperiness;
- 24/7 availability of snow & ice fighters between November 1st and March 31e.

During the snow and ice control season, approximately 150 snow & ice fighters and 40 salt spreaders are available (Twente Milieu, 2013).

Key figures

In 2012, Twente Milieu served approximately 400.000 citizens in these seven municipalities. 202.6 kg (x10^6) of waste has been collected and per salting action approximately 1000 km is salted. Some financial figures are presented in Table 3.

Revenue	€28,590,311
Profit	**€792,360**
Employees	**228**
FTE	**215**
Average age	**46.1**
Sick leave	**7.6%**

Table 3: Key figures of Twente Milieu

Organization chart

The management team of Twente Milieu consists of eight people, namely: the director, three location managers (Almelo, Enschede, and Hengelo), a fleet manager, a staff manager, a financial manager and a facility manager. The structure is depicted in Figure 1.

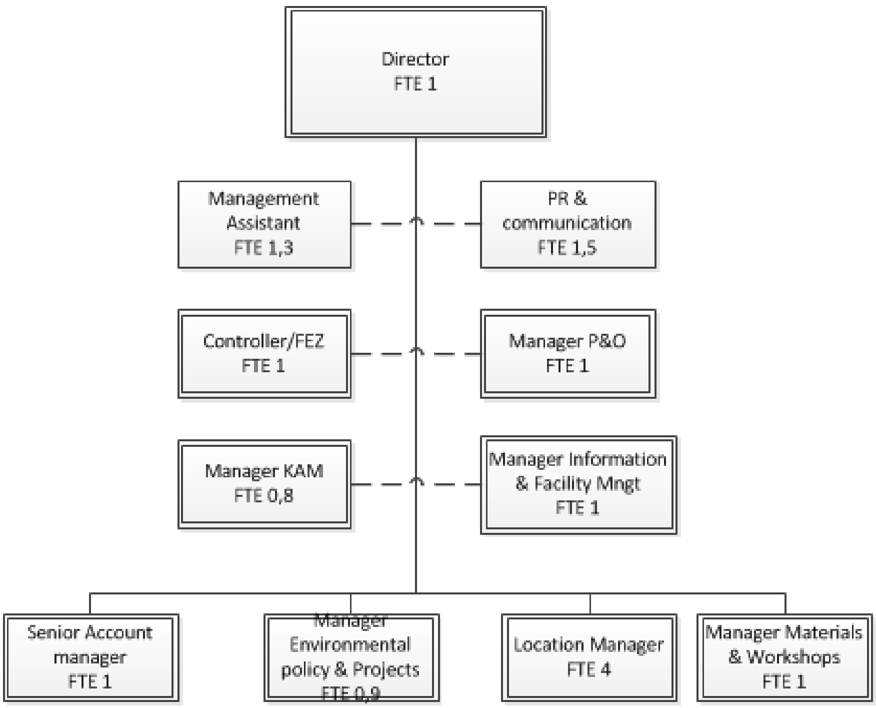

Figure 1: Organization chart

1.2 The snow and ice control program

All five[3] municipalities determine annually the roads and cycles paths that need to be salted during the winter. A distinction is made between roads that need to be salted within three hours after the first signs of slipperiness and roads that need to be salted within five hours after these signs. Twente Milieu determines salting routes based on these roads with corresponding priorities. Such determination of salting routes takes place without the use of professional planning techniques or planning software. For example, the salting routes of Enschede are set by dividing the sprinkle map (Appendix A) into different sections. Subsequently, the salting route within a section is drawn based on experience, logic, and intuition. For this reason, it is questionable whether the current routes are optimal and that the use of routing and planning techniques could reduce costs (i.e., minimize driven kilometers) and increase safety.

Furthermore, the absence of professional planning techniques makes it rather difficult to assess the effects, both financially and in terms of safety, that arise when (tactical) changes are being made. Organizations need to be aware of cause and effect relations in their decision making process. Examples of such tactical decisions are: what happens when there is a 10% reduction of the number of roads that needs to be salted?, what happens when no prioritization (in terms of time) is made between different roads?, what happens when less salting vehicles are being used? This thesis focuses on providing Twente Milieu with insights in the effects of such tactical decisions.

Additionally, it is questionable whether the current method of organizing the snow and ice control program at Twente Milieu is effective. Twente Milieu starts salting all predefined routes as soon as the Province Overijssel starts salting provincial roads and highways or MeteoConsult indicates that roads are becoming slippery. All routes are being salted regardless whether this is actually effective. For example, continuously sprinkling roads during a non-stop snow storm is very ineffective. Municipalities could consider snow plowing *after* the snowstorm and subsequently apply salt on the road. During the snowstorm, only the traffic arteries are kept free of snow. Such an approach is much more cost effective.

1.3 Research motivation

Nowadays, government finds itself in a financially difficult situation. Most budgets are cut and cost minimization has become increasingly important. This also holds for the participating seven municipalities in Twente Milieu. For this reason, Twente Milieu expects budget loss for their ice and snow control program in the near future. It is questionable whether the current way of working and expected cutbacks from the city of Enschede suit each other.

In order to guarantee the traffic safety in the future, funded by tighter budgets, the current snow and ice control program needs to be examined. This is done both on the organizational and technical level as well as the funding model. These three fields of study are explained in more detail in the problem chart.

[3] Twente Milieu does not salt in Losser and Oldenzaal.

1.4 Problem chart

A problem chart is a technique to expose cause and effect relations. It is an illustrative way to make problems tangible and it clarifies the cohesion of problems in which they occur. This helps structuring the problem context. Furthermore, it is a useful tool to discuss the problem(s), because the chance of miscommunication reduces due to the visualization of the web of problems. It is also a means to get the key stakeholders on the same page in order to prevent disagreement, at a later stage, about the problems and the resulting solutions. The problem chart is presented in Figure 2 followed by an explanation per problem in Table 4.

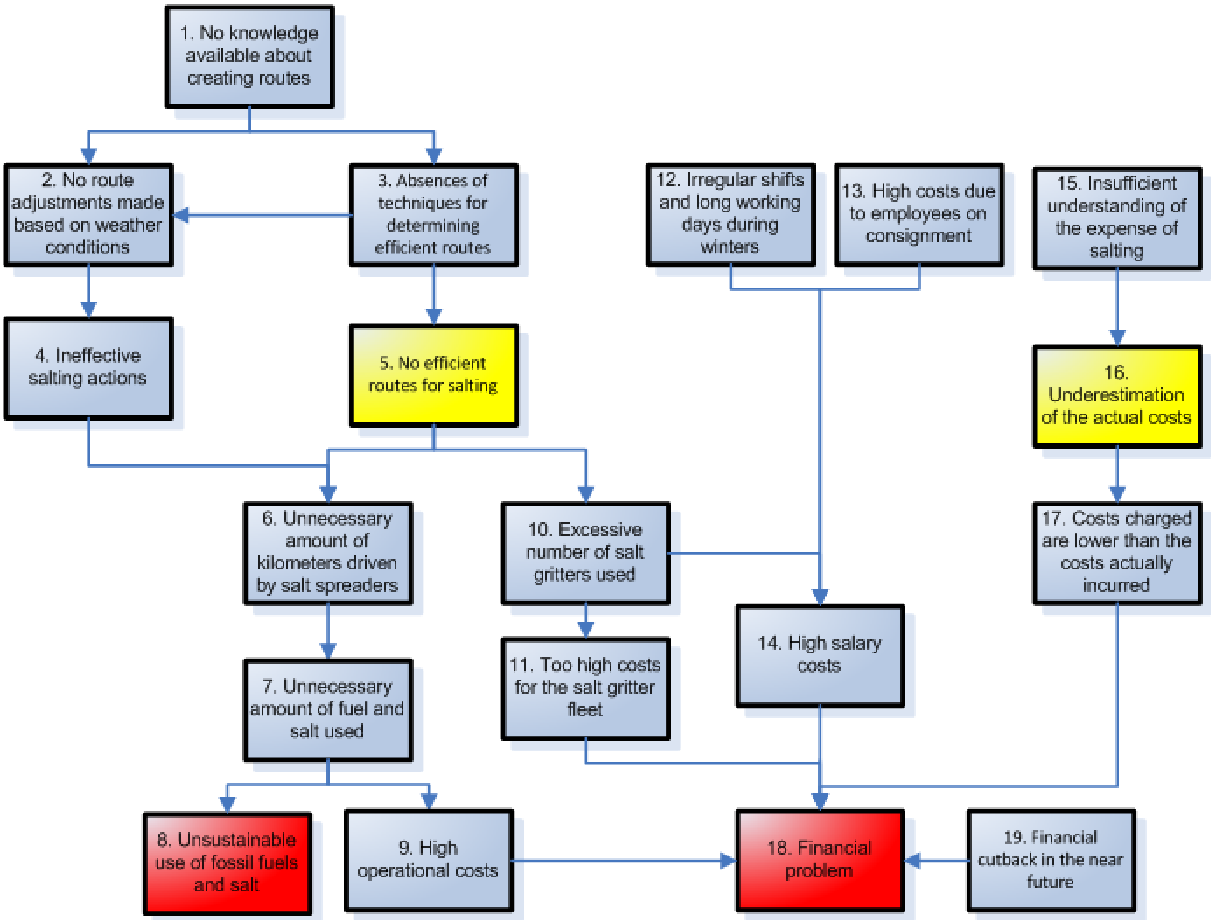

Figure 2: The problem chart

Problem number	Explanation of the problem
1	Twente Milieu has no knowledge about creating routes.
2	All 20 routes are predefined. In case the salt spreaders move out, all routes are being salted.
3	Twente Milieu does not possess advanced planning techniques and software, therefore it is hard to assess cause and effect relations when tactical changes are being considered or implemented.
4	Salting streets during prolonged snowfall (when road usage is low) is ineffective.
5	Current routes are created based on intuition, logic and experience (Sleebos, 2013).
6	Due to the inefficient routes and ineffective salting actions an unnecessary long distance is traveled.

7	Due to the efficient routes and ineffective actions an unnecessary amount of fuel and salt is used.
8	Unnecessary fuel and salt consumption is harmful to the environment and unsustainable.
9	Unnecessary fuel and salt consumption results in unnecessary high costs.
10	Ineffective salting actions and inefficient routes require the use of an unnecessary amount of cars.
11	Most costs are incurred due to the large fleet of salt spreaders.
12	Unpredictable winter conditions results in irregular and long working shifts.
13	A significant number of employees are continuously on consignment service.
14	Consignment services and overwork result in additional salary costs.
15	Twente Milieu has insufficient insights into the costs with respect to all salting activities.
16	The finance department beliefs that the actual costs regarding salting are being underestimated.
17	Underestimation of costs results in lost earnings.
18	This all results in a financial difficulty.
19	A financial cutback is expected in the near future.

Table 4: Explanation of the problems

1.5 Research question

From Figure 2 several problems emerge. Focus is put on problem 1 (no knowledge available about creating routes). Solving this problem provides insights into different cause and effect relations with respect to certain tactical decision that can be made. Solving this problem is in line with the main objectives of this research, namely, to help Twente Milieu (1) to gain insights into the effects of various important factors (e.g., road prioritization, response time, number of vehicles) on the snow and ice control program's efficiency and effectiveness and (2) to provide Twente Milieu with a method in order to assess cause and effect relations with respect to decisions made in the snow and ice control program.

From this, the following research question is formulated:

What is the most efficient and effective way of organizing the ice and snow control program at Twente Milieu?

From this research question, four sub questions follow. Each sub question is discussed in a chapter. The sub questions are:

1. **How is the snow and ice control program currently organized at Twente Milieu?**
   1.1 How does the snow and ice control program work?
   1.2 How does the current decision making process work?
   1.3 Which factors influence decisions?
   1.4 What are the current problems at the snow and ice control program?

Chapter 2 is about sub question 1. The characteristics of the snow and ice control program are discussed along with the current decision making process. This is necessary to understand the snow and ice control process. This process functions as the framework for the rest of the report. The chapter ends with problems arising from the current way of working.

2. **How does literature prescribe the organization of traversing roads?**
    2.1 What are the key factors for determining routes?
    2.2 What kind of models can describe the winter maintenance program?
    2.3 What are the advantages and disadvantages of different models?

The problems from Chapter 2 function as the input for Chapter 3. Sub question 2 is about using literature in order to tackle these problems. Several models are presented that could help solve the problem.

3. **What are the characteristics of a model that constructs routes for the snow and ice control program at Twente Milieu?**
    3.1 Which model is most suitable for Twente Milieu?
    3.2 How can the model be customized to the snow and ice control program?

Chapter 4 is about presenting a model that assists in assessing cause and effects relations on a tactical level. Chapter 5 begins with a set of stand-alone scenarios. Each scenario reflects a potential tactical decision. The output of the model quantifies the effect of a scenario. The scenarios arise from discussions with employees, the job description provided by Twente Milieu, and the problem analysis.

4. **How should winter maintenance be organized in the future?**
    4.1 How many salt spreaders are needed for the salting operations?
    4.2 How should Twente Milieu cope with roads with different prioritization levels?
    4.3 What is the effect of different completion times of certain roads?
    4.4 What is the best location for the salt depot?

Most scenarios are extracted from the problem description provided by Twente Milieu. The result of the different scenarios provides Twente Milieu with insights in the effect of several tactical decisions. It indicates the direction in which the most promising result can be achieved. This sub question is covered by Chapter 5 and Chapter 6.

1.6 Scope of the project

The scope is based on three different aspects: decision, location, operation.

Decision

As already stated in Section 1.2, the absence of sophisticated planning techniques makes it rather difficult to gain insight into the effects of decisions made on a tactical level. Examples of questions that must be answered at a tactical planning level are: Which streets need to be salted? What is the time frame? How much salt spreaders may be used? What is the location of the salt depot? Given the answers on such questions, on an operational level, routes can be constructed.

The scope of this thesis is to provide Twente Milieu with the tools to gain insights in such tactical decisions. Insights into this level are needed to provide the shareholders with information whenever necessary and are a requisite to make well informed decision on an operational level.

As a result, the word route is used in a context of tactical decision making, i.e., it is no predefined sequence of roads that can instantly be driven by the various salt spreaders since traffic regulations are neglected. Rather, it can be seen as a sequence of roads that incorporates all characteristics of the snow and ice control program in order to provide insights on a tactical level. Thus, the routes provide Twente Milieu with valuable information regarding tactical decision making, but adjustments need to be made before day-to-day operations benefit from these insights.

Location

Although Twente Milieu serves five municipalities on snow and ice control, this project mainly focuses on Enschede. We assume that answering all questions stated in Section 1.5 for Enschede provides insights into Twente Milieu as a whole. Enschede is by the far the largest of the five municipalities, therefore it should expose a wide range of problems that probably also arise in the other four towns. Enschede is, in this sense, a suitable research topic to start with.

Operation

Currently, several activities are being considered in the area of ice and snow control. Some routes consist of cycle paths and other routes consist solely of regular roads. Furthermore, Twente Milieu defined snow plow routes which are different from the regular routes. In this thesis, only the routes that consist of regular roads are considered. In other words, cycle routes are being neglected.

Also, Twente Milieu distinguishes between anti-icing and deicing. Traditionally, roads are being salted while they are already slippery (deicing). Nowadays, road management companies move from deicing to anti-icing. Twente Milieu usually salts before roads become slippery (anti-icing). Anti-icing salting operations require less salt usage. This is a decision made on tactical level. From a mathematical perspective, deicing and anti-icing are two different kind of salting actions, because during anti-icing salting actions trucks need to be reloaded several times. This makes a route much less straightforward compared to deicing. During deicing salting actions, reloading salt is not necessary. In 2013-2014 all salting actions were considered as deicing. In 2012-2013 58% of all salting actions were considered as deicing and in 2011-2012 deicing was responsible for 85% of all salting actions. Thus, the focus is set on deicing, not anti-icing.

1.7 Conclusion

This report considers the ice and snow control program at Twente Milieu. Insights into operations are of vital importance in order to manage an organization. Providing such insights is the reason for this research. Due to time limitation and the unavailability of sophisticated routing software the scope is limited to Enschede (instead of Twente), deicing instead of anti-icing, and the provision of insights on a tactical decision making level.

Chapter 2: The snow and ice control program

This chapter covers the first sub question. The main objective of the snow and ice control program is introduced. Furthermore, various topics will be addressed regarding the current situation. Section 2.1 is about how slipperiness occurs and what the effect is on various road surfaces. Section 2 covers the subject of thawing materials. Section 3 is about the current decision making process at Twente Milieu and the factors that influence such decisions. Section 4 deals with the problems that occur due to the current way of working. The chapter ends with a conclusion that is drawn in Section 5.

2.1 Snow and ice control program

The snow and ice control program is intended to make roads, sidewalks, and cycle paths safe to use. Every winter, people die because of slippery roads. For this reason, it is not surprising that the government spends millions of Euros annually on snow and ice control programs. These control programs mainly focus on lowering the freezing point of water.

Roads tend to get slippery when:

- the moisture level on the road or in the air is high;
- the temperature of the pavement is below 0° Celsius.

If these conditions are met, water freezes into a thin slippery layer resulting in much less grip for various traffic users.

2.1.1 Differences in temperature of pavement

Various circumstances (hillside, bridge, tunnel, material of pavement, (un)availability of underground, shadow,(un)availability of sunlight, wind et cetera) can influence the temperature of the pavement.

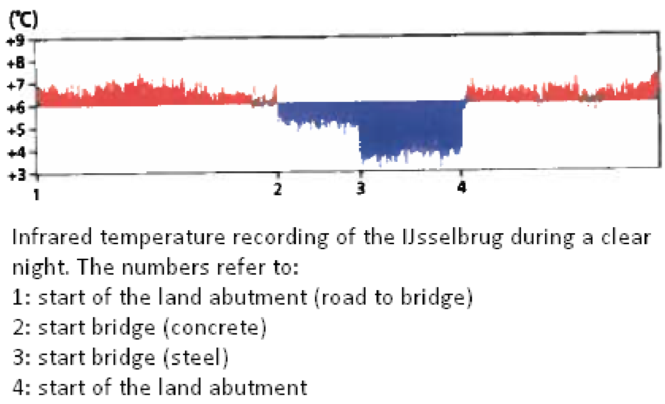

Figure 3: Infrared recording of bridge (CROW, 2008)

An example of these differences is shown in Figure 3wherean infrared image of a bridge is displayed. It is easy to see that the material and the absence of a substrate have influence on the bridge's temperature. This is an important factor to take into account, because it means that authorities in the field of winter maintenance should take the various circumstances and temperatures in the road network into account. These differences are greatest during cold and clear nights, because heat radiating from the road is largest under those circumstances (CROW, 2008). In this context, Twente Milieu pays extra attention to, so called, critical locations in their snow and ice control program. Such locations are not always the coldest, because also the availability of moisture is of importance.

2.1.2 Types of slipperiness

Slipperiness can occur because of freezing of the water on the road surface (called 'black ice'), condensation of moisture from the air, or precipitation.

Black ice is considered very dangerous, because road users can barely see the difference between a wet road surface and a frozen road surface. For this reason, drivers not always adjust their driving behavior.

Condensation occurs when moisture from the air is deposited on the road surface. If the road temperature is lower than the dew point this will result in a wet road surface that eventually could become black ice.

Precipitation (snow, glazed frost, and hail) is the most common cause of slipperiness. The form of precipitation has major influence on the behavior of drivers, therefore on the chance of accidents. For example, snow is easily observed and this generally results in traffic participants adjusting their driving behavior.

2.1.3 Types of pavement

As already stated, the pavement is of influence on the temperature, however it also influences the most effective way (timing of salting, frequency, dosage of salt, technique) to fight slipperiness. The following sections all cover different types of pavement and their reaction on winter conditions.

Dense asphalt concrete and stone mastic asphalt

Dense asphalt concrete and stone mastic asphalt both have a rather dense structure on the top. This makes it quite easy to fight slipperiness. However, in the presence of ruts, see Figure 4, water cannot easily flow to the side of the road. This increases the chance of slipperiness.

Figure 4: A rut

Open asphalt concrete ('ZOAB')

Open asphalt concrete, see Figure 5, is characterized by an open structure on the top. This result in less noise, however the road's temperature easily adapts to the temperature of the surroundings. If temperature drops, open asphalt gets slippery easily. Furthermore, a proportion of the thawing material gets into the pores of the open asphalt reducing the effect of the salt. This effect is mitigated when traffic intensity is high. During winter conditions, open asphalt gets salted more often and more salt is sprinkled on the road.

Figure 5: ZOAB

Pavement

Some examples of pavement are tiles, cobble stones or pavers. The pavement is made up of individual elements, see Figure 6, that are more or less loosely connected to each other. It has the same characteristics as open asphalt concrete in the sense that the pavement's temperature easily adapts to the temperature of the surroundings.

Figure 6: Pavement

Cycle paths

Cycle paths are generally made of pavement or thin asphalt. Due to this structure, its temperature mostly is colder than the main road. Most cycle paths are equipped with cycle tunnels, poles et cetera. This makes salting such paths difficult.

Rail crossing

ProRail's directive specifies that rail crossings are not being salted. Salt can interfere with the electrical relay that is used for the security of the crossing. Salt spreading stops within 10 meters of the rail crossing to prevent this from happening.

Bridges, overpasses et cetera

As already stated, the material (wood, concrete, metal) of which such a building is made off determines how Twente Milieu should prevent it from being slippery.

2.2 Thawing materials

Thaw refers to the process of melting. The thawing material is the actual component that facilitates this process. In the following sections, the effect of thawing materials is explained as well as which type of thawing material is used mostly and which salting strategies are used.

2.2.1 Freezing-point depression

The effect of thawing materials can best be explained by 'freezing-point depression' or cryoscopy. It describes the process of the phenomenon that the freezing point of a solution decreases when a solute (for example salt) and a solvent (for example water) are dissolved.

If the water temperature drops below 0° Celsius a state transition from liquid to solid (ice) takes place. As a matter of fact, the molecular structure of, for example, water changes (see Figure 7). If a solute (for example NaCl or salt) is added to water a solution is obtained. The solution consists of water molecules, sodium ions and chloride ions. Now, if temperature drops to 0° Celsius, the water molecules solidify and arrange in a grid. However, the sodium- and chloride ions prevent the water molecules from forming a perfect grid (ice).

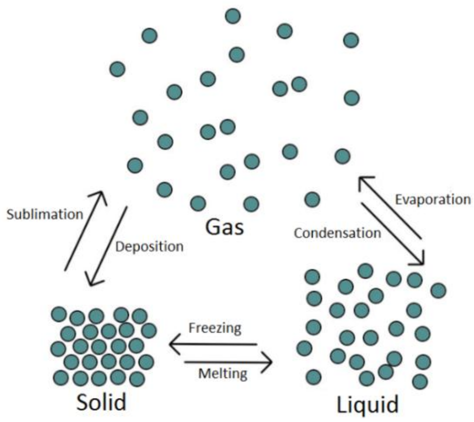

Figure 7: Phase transitions

This means that lowering the freezing point is not about the characteristics of, for example sodium chloride, but about the amount of parts (ions) that prevent the solvent from forming a grid, thus becoming a solid. Appendix A provides more insight into freezing-point depression.

2.2.2 Types of thawing materials

The choice for the deployment of a thawing material depends on several factors, namely (CROW, 2008):

- effectiveness: as a function of melting capacity at a certain temperature, # kg of ice that is melted by 1 kg of thawing material;
- applicability: the freezing-point depression;

- availability: the thawing material should be available in a large amount and at a short notice;
- workability: the material should be easily stored for longer periods without losing its efficacy;
- safety: no need for safety provision to use the product;
- noxiousness: vehicles, roads and the environment are not to be damaged by the product;
- environmental impact: biological impact on the environment should be minimized;
- price: the material is used in large amounts this means that the price is important.

Salt is the most common thawing material used in ice and snow control programs. Various types of salt can be used for this purpose. Sodium chloride (NaCl) is the most common used thawing material, however also Magnesium chloride ($MgCl_2$) and Calcium chloride ($CaCl_2$) are used.

Sodium chloride (NaCl)

Two types can be distinguished: vacuum salt and halite (rock salt). Vacuum salt is characterized by high purity and a uniform particle size distribution. Halite has a more coarse grain and mostly is contaminated with sand, heavy metals et cetera (Akzo Nobel). Vacuum salt is, because of the fine grain, in contrast with halite rapidly effective.

2.3 Current decision making process

Understanding the current decision making process and the determination of the salting routes is important, because it functions as the context for the mathematical model, introduced in Chapter 4. This model functions as a tool for the realization of effective and efficient routes. These two subjects are covered in Sections 2.3.1 and 2.3.2. Section 2.3.3 deals with the factors that are important for the decision whether to start salting roads or not. In the last section, some problems arising from the current way of working are being discussed.

2.3.1 Determination of the routes

Twente Milieu identified twenty different routes in Enschede. These routes are set by one of the winter coordinators by dividing the sprinkle map (Appendix B) into different sections. Every section corresponds with a salt spreader. Subsequently, routes are created based on experience, intuition, and logic. Twente Milieu does not use advanced planning techniques. In that sense, it is questionable whether the current routes are optimal or that the use of routing and planning techniques could reduce costs, i.e., minimize kilometers driven.

The twenty routes consist of eleven routes (circa 50 to 60 kilometers per route) that solely consist of motorways and nine routes (circa 30 to 40 kilometers per route) that also consist of cycle paths and smaller roads. As already stated in Section 1.6, this report is about the eleven motorways routes. All routes take approximately 2 to 2.5 hours to complete.

The municipalities make a distinction between roads in different phases. Roads in phase 1 (highways, arterial roads, roads near schools, industrial areas et cetera) need to be salted within three hours after the first signs of slipperiness appear. Roads in phase 2 (country roads or small residential streets) need to be salted within five hours. Currently, due to the availability of a large fleet of salt spreaders, no distinction is made between roads in phase 1 and phase 2 in the current routes. This large fleet of salt spreaders also makes it possible to salt the whole sprinkle map within three hours. Still, it is beneficially to take a closer look at the snow and ice control planning. Significant budget cuts are expected in the near future and the salt spreaders are mostly responsible for the costs of the snow and ice control. Examining snow and ice control with less salt spreaders will have an effect on road prioritization and vice versa.

2.3.2 Decision making process (on an operational level)

Salting the road network of Enschede can start by three different events, namely: (1) the province Overijssel informs Twente Milieu that it started salting provincial roads, (2) Twente Milieu decides to start the salting operation based on own observations from employees or information provided by MeteoConsult[4] (Appendix C) or (3) because Twente Milieu chooses to follow Rijkswaterstaat when they start salting highways.

The salt spreaders usually are operational within 45 minutes after one of these events occurs. This time buffer is particularly relevant during the night, when employees first have to arrive at Twente Milieu. All prescribed routes are salted regardless of whether this is considered effective or not. The salt spreaders continuously work until the roads are safe.

This decision making process is depicted in Figure 8.

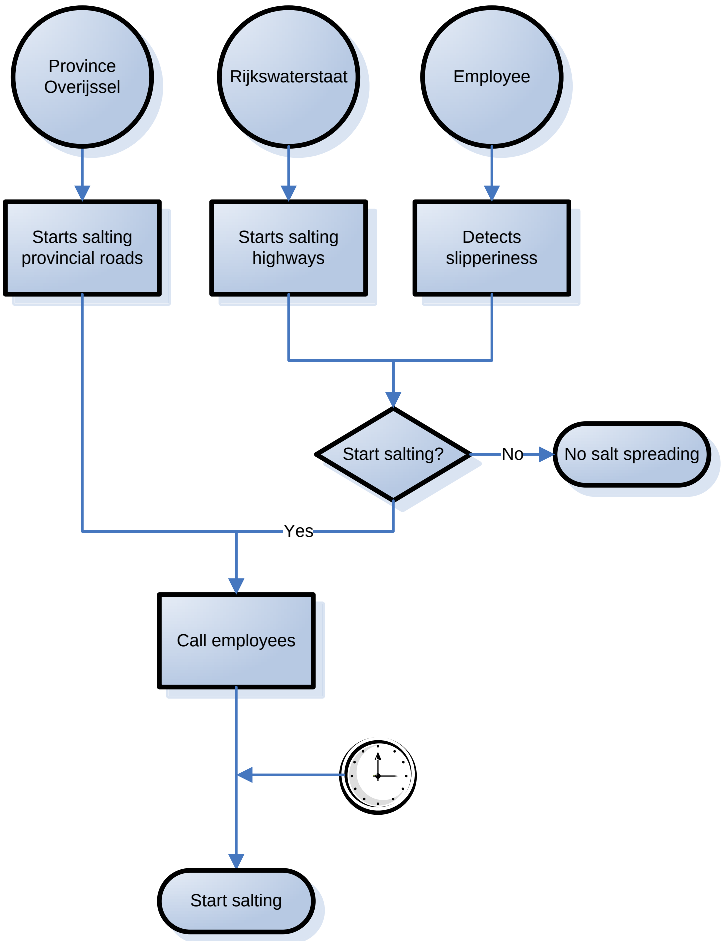

Figure 8: Operational decision making process

[4]MeteoConsult is part of MeteoGroup, the largest private sector weather business. MeteoConsult provides Twente Milieu with information about road conditions on a daily bases. Appendix B gives an overview of the information that is provided.

2.3.3 Important factors

The decision regarding the start of the salting operation, regardless whether it is based on own observations or information provided by MeteoConsult, is based on the weather conditions and timing. Important factors are: expected type of precipitation, expected traffic intensity and the current time. For example: deicing on a Monday at 2 AM has major impact on the employees due to the fact that their night's rest is split in two (before the work shift and between the end of the work shift and the new work day that starts at 7:30 AM). Furthermore, the low traffic intensity at 2 AM impedes the working of salt on the road.

Another important factor is related to liability. Twente Milieu is, through the Wegenwet, responsible for winter maintenance. Twente Milieu has a so called *inspanningsverplichting*[5], this is in contrast with a *resultaatsverplichting*[6] (CROW, 2008). This means that Twente Milieu is obligated to do its utmost best to keep the roads from being slippery. It is allowed to give certain roads priority based on economical or environmental factors, however such decisions should be in line with applicable standards. This means that the snow and ice control program should be in accordance with recognized standards, otherwise there is a chance that Twente Milieu will be held responsible for damage suffered by road users.

2.4 Conclusion

This chapter was about the first sub question, namely: How is the snow and ice control program currently organized at Twente Milieu? In order to answer this question, several subjects in the context of the ice and snow control program were discussed. This gives an idea about the effects of temperature and precipitation on different kinds of pavement. Furthermore, the current decision making process regarding winter maintenance and the resulting shortcomings are discussed. The following list summarizes these shortcomings regarding the current ice and snow control program:

- Twente Milieu is, due to the absence of sophisticated planning tools, currently not able to determine the effects of modifications in the sprinkle map, changes in policy or other adjustments.
- Currently, only two scenarios are being considered: salt all routes or salt nothing. This decision is made regardless of the question whether salting every road is effective. For example: during a non-stop snowstorm of 30 hours it is rather questionable if a continuous salting action is effective.
- The decision to start all salting operations is not subject to strict guidelines, rather based on (subjective) observations in combination with experience.
- It is questionable whether the current way of working and expected cutbacks from the city of Enschede suit each other.
- The current routes were established without the use of planning and/or routing techniques, therefore it is questionable whether these are most efficient given the sprinkle map.
- Every municipality has its own salting routes. This is in contrast with the objectives, seeking collaboration between shareholders, posed when Twente Milieu was established. This problem lies outside the scope of this research.

[5] An obligation to guarantee best efforts.
[6] An obligation to guarantee a certain result.

The mathematical model from Chapter 4 will provide insights regarding the questions raised above. These insights should subsequently be used in the process of making the Service Level Agreements with the municipalities and finally operational routes for the salting vehicles.

Chapter 3: Literature review

In this chapter, an overview of the existing literature in the field of routing problems is presented. The review helps with getting insights into different types of routing models. Section 3.1 gives an overview of the set of generalized routing models. Subsequently, in Section 3.2, difficulties with these models are discussed. This section also covers ways to overcome these difficulties. Section 3.3 is about how literature prescribes the characteristics of good routes. In the last section the conclusion regarding this literature review is given.

3.1 Routing problems

Much has been written about routing problems. Two types of routing problems are distinguished: node routing and arc routing. The first type is about travelling from node (e.g., city or intersection) to node with respect to some objective (e.g., minimizing total travelled distance or minimize total costs). Two well-known problems within this class are the Travelling Salesman Problem (TSP) and the Vehicle Routing Problem (VRP). Such kinds of problems are not being addressed in this thesis, because the snow and ice control program is about servicing streets (arcs), not nodes. Thus, the problem Twente Milieu faces can be classified as an arc routing problem.

3.1.1 Arc routing problems

Arc routing problems are generally about servicing (salting, sweeping, plowing, et cetera) a set R of required edges or arcs in an underlying network $G = (V, A \cup E)$ with nodes V, directed arcs A and undirected edges E as presented in Figure 9 (Assad & Golden, 1995). The graph could consist of arcs and/or edges. The cost of traversing and servicing an arc (or edge) plays an important role in this class of problems. Typically, objectives of solving such problems are: minimize the sum of the costs of traversing non-required edges or minimize the total costs of servicing all required edges.

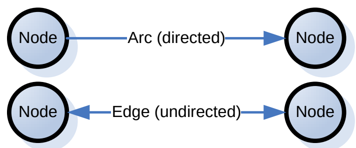

Figure 9: difference between arc and edge

The network $G = (V, A \cup E)$can be seen as a general representation of all arc routing problems. Assad & Golden (1995) presented Table 5in order to summarize some important features of well-known arc routing problems. These problems differ in underlying graph and the required set R.

Problem	A	E	Required edges R	Complexity	Comments
Undirected Postman Problem (UPP)	ϕ	*	R = E	P	Solved by matching algorithm in O(n^3) or less
Directed Postman Problem (DPP)	*	ϕ	R = A	P	Solved by flow problem in O(n^3)
Mixed Postman Problem (MPP)	*	*	R = $A \cup E$, $A \neq \phi, B \neq \phi$	NPC	Remains NP-complete even if all edge costs are equal; solvable if G is an even connected graph
Rural Postman Problem (RPP)	ϕ	*	R ⊂ E	NPC	Solvable if G_R is connected
Directed Rural Postman Problem (DRPP)	*	ϕ	R ⊂ A	NPC	Solvable if G_R is connected

Stacker Crane Problem (SCP)	*	*	R = A	NPC	Remains NP-complete even if all edge costs are equal
Windy Postman Problem (WPP)	ϕ	*	R = E	NPC	Edge costs depend on direction of traversal; solvable if G is connected and even
Capacitated Arc Routing Problem (CARP)	ϕ	*	R $\subset$ E	NPC	Explicitly capacity constraint on each cycle with respect to edge demands (as in VRP)
Capacitated Postman Problem (CAPP)	ϕ	*	R=E	NPC	Same as the CARP but all edges must be services

Table5: Overview of arc routing problems. Explanation: * = arbitrary set, P = polynomial time, NPC = NP complete, n = number of nodes, G_R = set of required edges.

Many real routing problems can be transformed into one of these more standard problems that have a corresponding integer linear programming (ILP) formulation. Linear programming seeks to achieve a best outcome (i.e., minimizing costs) in a mathematical model whose requirements are presented by linear relationships. Using literature in this field is useful, because much research already has been conducted regarding these problems. They have been studied in the area of ILP modeling and the construction of various types of heuristics. One needs to make a set of assumptions in order to translate the actual problem into one from Table 5. Now, the ILP models and heuristics that correspond to the standard problem can be applied in order to generate a solution. Obviously, it should be checked whether the obtained solution holds in reality with respect to the underlying set of assumptions.

3.1.2 Types of arc routing problems

The Undirected-, Directed-, and Mixed Postman Problem (UPP, DPP and MPP)

An example of the UPP and the DPP is a mailman who visits the post office in order to collect mail and subsequently must traverse every street in order to deliver the mail. Eventually, the mailman returns to the post office (Edmonds & Johnson, 1973). The UPP and the DPP seek to find an optimal route; objective is to minimize total distance covered. The mixed postman problem is a combination of these two problems; the road network consists of roads where both unidirectional (arc) and bi-directional (edge) traffic is allowed.

The (Directed) Rural Postman Problem (D)RPP

These problems can be seen as a practical extension of the previous problems. Here, a subset of the arcs/edges needs to be served instead of all.

Stacker Crane Problem (SCP)

Consider a stacker crane that must load containers into a ship. The capacity of such a crane is one (only one container can be lifted at a time). Given the locations of the containers (demand), a route can be constructed.

Windy Postman Problem (WPP)

Again, consider the postman problem as addressed earlier. Now, the cost of traversing an arc depends on direction of crossing the arc (with or against the wind). More precisely, cost c_{ij} and c_{ji} differ, where i,j ∈ EUA.

Capacitated Arc Routing Problem (CARP) and the Capacitated Postman Problem (CAPP)
This problem has similarities with the RPP. However, this set of problems takes a truck's capacity into account. This makes the problem much harder to solve. The CAPP differs from the CARP in the sense that the CAPP requires all edges to be served, while the CARP requires a subset of E to be served.

3.1.3 Types of objective functions

The different models also vary in terms of their objective function. Three different categories are distinguished, namely, profitable problems, orienteering problems, and prize-collection problems (Benavent, Corberán, Gouveia, Mourão, & Pinto, 2013). Profitable problems are about finding a route in which the difference between the total collected profit and the distance travelled in maximized. In the second case, the objective function is about maximizing the collected profit with a constraint that arranges for the maximum costs (for example distance covered) does not exceed a certain limit. Prize-collection problems are about looking for a route with minimum costs at a least given amount of profit.

3.2 Subtour elimination constraints

All models above need subtour elimination constraints to make the model feasible. However, such constraints make the model hard to solve. In Section 3.2.1 this set of constraints is discussed. In Section 3.2.2some heuristics are presented that could solve the problem. Section 3.2.3 is about an alternative way to deal with this set of constraints.

3.2.1 Subtour elimination difficulties

The goal of the ILP, cost minimization, presents a solution in which all arcs that need to be serviced are traversed. Furthermore, so called flow constraints force the construction of a route (leaving a node/arc corresponds with entering a node/arc). This can be seen in Figure 10. Due to the model's goal, the required traversal of intermediate arcs is omitted resulting in an infeasible solution. This phenomenon is similar to teleporting which is obviously not possible. Subtour elimination constraints prevent this from happening.

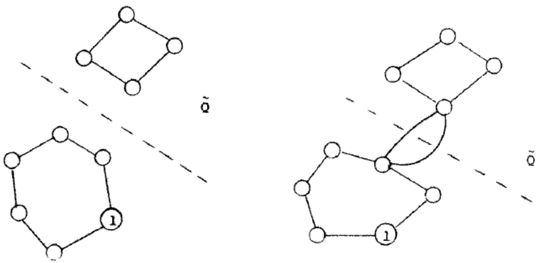

Figure 10: Illegal tour and legal tour

Subtour elimination brings in a new problem, namely the excessive computing power needed to solve the related extensive set of constraints. The number of constraints increases exponentially with the number of nodes (Golden & Wong, 1981). As a result, most problems have too many restrictions in order to be solved. Therefore, it is not uncommon to use heuristics instead of an ILP model to solve problems.

3.2.2 A stepwise subtour elimination restriction

An alternative way of modeling the subtour elimination problem is by introducing the concept of steps. This idea is derived from a helicopter position paper (Van Urk, 2012). In this paper, the next position of a helicopter depends on the current location and intermediate elapsed time. This idea can be translated to the current problem. However, unlike a helicopter a truck depends on existing infrastructure. Such a step is similar with visiting train stations. For example, from station Enschede Drienerlo only the stations Enschede and Hengelo can be visited in one 'step'. The road map of Enschede can be translated in such 'stations' as well. Subsequently, a restriction needs to be drawn that forces the model to add arcs (stations) in the route that are adjacent to the last arc (station) in the route. The idea is basically to construct a closed tour that starts and ends at a depot. Every next street in the tour can be selected out of a set of streets that are reachable in one step from the current position of the truck. This prevents, so called, teleportation or the phenomena that a truck is at two different locations at the same time. In essence, this stepwise approach is not the same as the classical subtour elimination constraints, but rather a method to cope with the same problem, namely disconnected tours.

This idea is also used in a PhD report on movements in civil airspace (Persiani, 2011).

3.3 Heuristics

Due to the complexity involved with solving routing problems many researchers use heuristics. These heuristics can have different starting points. Some start with a feasible solution and work towards a better solution while making improvements. Other heuristics start with adding an arc to the solution, based on a certain criterion, until all arcs are serviced.

Golden & Wong constructed a heuristic for the CARP of the first type. There are many other heuristics. Advantages of these heuristics are that they have been proven in different cases and that they find feasible near-optimal solutions in polynomial time, thus can be used in the case of Twente Milieu. Disadvantages are that the heuristics cannot be used immediately in the case of Twente Milieu, because some characteristics are neglected. For instance, prioritization is mostly not incorporated. Some research has been conducted regarding road prioritization (Demodaran, Krishnamurthi, & Srihari, 2008). However, such heuristics neglect other important features, such as capacity restrictions. No heuristic has been found that dealt with both the capacity restrictions and prioritization of arcs/edges.

To overcome the disadvantages of both solving techniques a combination can be used. As the number of variables and constraints increases exponentially with the amount of nodes/arcs in the network it would help to reduce this amount.

3.4 Conclusion

This chapter was about the second sub question, namely: How does literature prescribe the organization of traversing roads? The literature review gave insight in the different generalized models in the area of arc routing. Different starting points result in different models. It is obvious that most real world problems have elements that are incorporated in different models, therefore the problem Twente Milieu faces cannot be easily translated into one of these models. Also the difficulty of handling the extensive set of subtour elimination constraints makes it hard to solve real world problems.

Chapter 4: Model setup

In Section 4.1, the problem of Twente Milieu is being translated into one of the generalized problems from the previous chapter. Furthermore, a set of assumptions is presented in Section 4.2. Model characteristics are covered in Section 4.3. The mathematical model is presented in Section 4.4. Subsequently, Section 4.5 is about problems that arise from this formulation and how these can be tackled. Section 4.6 clarifies the solution method that is applicable to the snow and ice control program at Twente Milieu. Finally, in Section 4.6, is about initializing the parameters.

4.1 Twente Milieu's arc routing problem

This section is about translating the problem Twente Milieu faces into one of the generalized models. In Section 4.1.1 the characteristics of the snow and ice control program, in the context of arc routing, are explained. Section 4.1.2 is about a corresponding generalized arc routing problem.

4.1.1 Characteristics of the snow and ice control program

The problem can be seen as follows: the trucks of Twente Milieu traverse arcs/edges (roads) in order to serve (salt) them (R $\subset A \cup E$). Vehicle capacity may not be exceeded, for example, total 'demand' of salt of all arcs/edges within a route may not exceed a vehicle's salt capacity. Furthermore, costs (kilometers driven, vehicles (drivers) used and salt used) are minimized. However, some extra constraints should be incorporated for the model to be applicable on Twente Milieu, namely: (1) some arcs/edges need to be served within 3 hours (phase 1) and some arcs within 5 hours (phase 2), (2) Some arcs/edges should be served more than once due to their width, and (3) traffic regulation should be taken into account.

This problem can be translated into a corresponding ILP problem. As stated in Section 3.1.1, (Integer) Linear programming seeks to achieve a best outcome (i.e., minimizing costs) in a mathematical model whose requirements are presented by linear relationships. In the case of winter maintenance, one could construct an objective in which the total kilometers driven by all trucks are minimized. The ILP seeks to achieve a best outcome while respecting several linear constraints such as, completion time of roads in phase 1 may not be exceeded, truck capacity should be respected, et cetera. Section 4.4 is about an ILP that captures all relevant factors associated with the snow and ice control program at Twente Milieu.

4.1.2 Translating the problem

The problem shows similarities with the MPP (see Section 3.1). However, the MPP lacks capacity (and time) constraints and requires the traversal of all arcs and/or edges instead of a predefined set R. When associated heuristics or ILP restrictions are used, adjustments in the sprinkle map (Appendix A) need to be made. The solution's quality heavily depends on the adjustments made in the sprinkle map.

On the other hand, the CARP (see Section 3.1) can be used. This model does take the capacity constraints into account, but not the time constraints associated with the two different phases. Furthermore, only two way streets are considered. Thus, the road network of Enschede needs to be translated into an undirected graph. This may be reasonable for main roads and secondary roads, but certainly not for all roads. This means that, after the partitioning and route construction, one should check whether the routes are still feasible due to this assumption. At the moment, this is not a problem, due to the fact that information on a tactical level must be provided instead of operational routes.

As explained in Chapter 3, both heuristics and ILP models can be used to solve the problem Twente Milieu faces. This research is about using an ILP model that captures all elements. Both elements from the MPP and the CARP are used in this model. An ILP is used instead of a heuristic, because ILPs provide an exact solution while a heuristic seeks for an approximation.

4.2 Set of assumptions

The routing problem that arises from the salting activities at Twente Milieu (Section 4.1) cannot directly be translated into one of the problems shown in Table 4 (Section 1.4). First, some assumptions need to be made. From the perspective of delivering insights on a tactical level, it is allowed to make an extensive set of assumptions. Some assumptions do not have an effect on the amount of kilometers driven, however, some assumption do have an effect on the routes.

Assumptions

- only one type of salt is used;
- only fixed costs for salt storage are taken into account, not variable;
- there is enough salt present during winters;
- not all roads are taken into account. See Section 4.3.3;
- depreciation cost, based on mileage and driven kilometers, is excluded;
- all routes begin and end at the same depot;
- arcs are traversed completely or not;
- the speed of the salt spreader is always the same and is independent of driving or salting;
- only personnel costs that can directly be linked to salting are taken into account (no consignation costs, planning et cetera);
- the number of employees used for the salting operation equals the number of trucks used plus an addition of two employees;
- the model does not take into account that traversing an already served arc is safer than traversing one that still needs to be served;
- traffic regulations (one-way street, turn right/left is forbidden) are not taken into account;
- a road can be salted from both directions;
- fuel restriction is neglected[7];
- amount of salt sprinkled per arc only depends on the length of the arc, not the width.

4.3 Model characteristics

Before the ILP model can be presented, model characteristics should be clarified. Several characteristics are distinguished. Section 4.3.1 is about dealing with nodes and arcs. Subsequently, in Section 4.3.2, the road network is treated followed by the arc network in Section 4.3.3 and the arc distances in Section 4.3.4.

[7] Salt capacity and time restriction are tighter than fuel restriction.

4.3.1 Nodes and arcs

The number of constraints increases exponentially with the number of nodes (Golden & Wong, 1981) (Section 3.2.1). One way to decrease this number of constraints is to swap the nodes and arcs. This can be illustrated as follows. In the case of arcs, let X_{ikt} be one if location ($i \in I$), an arc, is being traversed by truck ($k \in K$) at time interval ($t \in T$). In the case of nodes, let X_{ijkt} be one if truck ($k \in K$) traverses between node ($i \in I$) and node ($j \in I$) during time interval ($t \in T$). It can be seen that in the latter case an extra index is used. This extra index causes increased complexity and requires excessive computational power.

A depot location is by definition a node, however if arcs are used instead of nodes the depot location must be replaced by an arc as well. The depot location is represented by an arc with a small distance.

Stepwise approach

The closed tour constraints make use of steps. Within one step a truck may only reach an adjacent arc to the arc it is in now. This is explained in Figure 11. This figure contains a portion of the road map of Enschede. Intersections function as nodes and an arc consists of two nodes. By introducing a parameter it becomes clear whether two arcs are adjacent or not. An arc is adjacent if and only if a common node is shared. For example (see Figure 11): node 1 and 2 are connected by arc C and this arc is adjacent with and reachable from arc A in one step. On the contrary, this does not hold for arcs B and C. The whole road map is translated into such a set of arcs with an accompanying set of parameters that provides information regarding the contiguity of arcs that can be reached within one step.

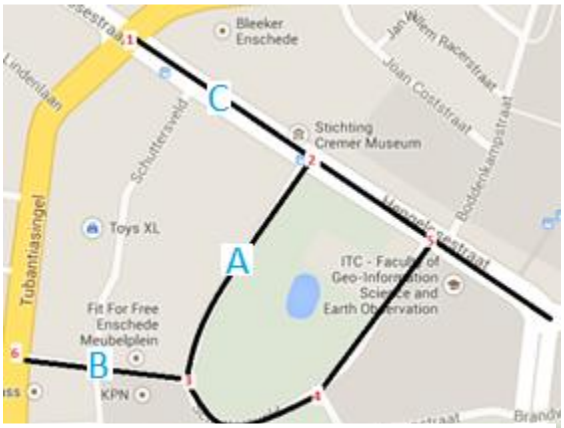

Figure 11: Translation of the road map

Introducing the corresponding constraint that ensures closed tours (Section 3.2.3) clarifies this. The first formula represents the case in which nodes are used, the second formulation uses arcs instead of nodes.

$$X_{ijkt} \leq \sum_{a \in A_{ij}=1} X_{aikt-1} \qquad \forall i,j,k,t \qquad\qquad X_{ikt} \leq \sum_{j \in A_{ij}=1} X_{j,k,t-1} \qquad \forall i,k,t$$

Set A_{ij} contains information on the accessibility from one arc to another arc in one time interval. This accessibility is explained by Figure 11. Furthermore, index a also represents the nodes. It can be seen that using arcs as a starting point instead of nodes drastically decreases the number of constraints required for the closed tours.

4.3.2 The road network

Obviously, all roads marked on the sprinkle map need to be traversed. However, salt spreaders might also use other roads in order to drive an efficient and continuous route. In order to reduce computational complexity, the mathematical model will not consider all roads within the city of Enschede. A subset of this extensive class of roads is determined based on the following rules:

- all roads marked on the sprinkle map;
- all roads with a speed limit of at least 50 kilometers per hour that can (visually) contribute to effective routes;
- all road segments where the speed limit is at least 50 kilometers per hour, that have a temporary lower speed limit due to particular circumstances (i.e., the presence of a school);
- roads that are required to make the arc network connected.

4.3.3 The arc network

The network that is used is presented in Figure 12. All red dots represent an intersection (node). The coordinates of the nodes are retrieved with GPS Visualizer. Subsequently, these coordinates can be translated into corresponding X- and Y-values (or: *Rijksdriehoekstelsel*) such that they can be depicted on a map.

The Rijkshoeksdriehoekstelsel is a coordination system for the Netherlands. The origin is located in Amersfoort, *Onze Lieve Vrouwetoren*. The conversion method translates GPS coordinates, which are based on a sphere, into corresponding X- and Y-values which are based on a plain surface area. The method of Schreutelkamp & Strang van Hees (2001) will be used for this transformation. The method has a maximum error margin of two meters (Schreutelkamp & Strang van Hees, 2001), which is sufficient.

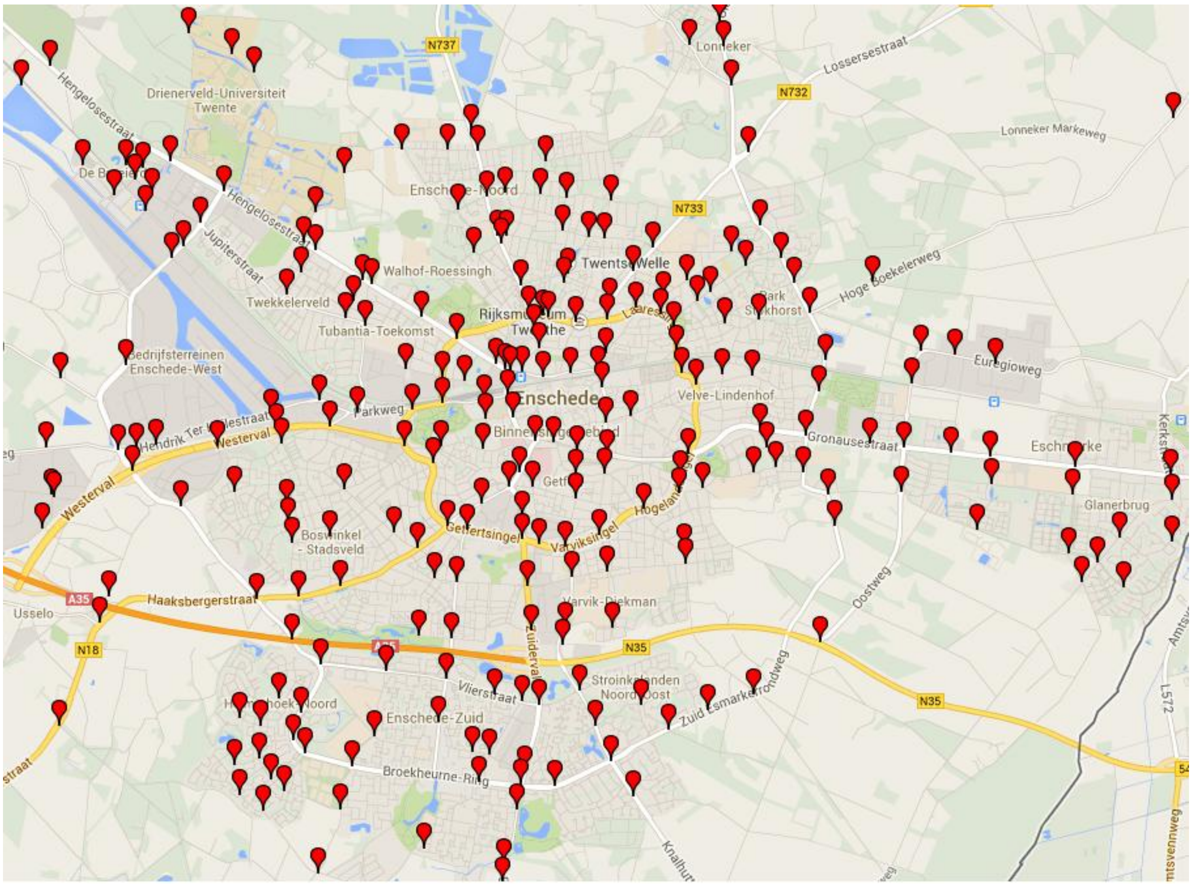

Figure 12: Node network of Enschede (GPS Visualizer)

The transformed X- and Y-values with corresponding distances are used in order to graphically represent a modeled route.

4.3.4 Arc distances

Mostly, researchers do not use network distance (or: 'real' distances) while conducting research in the area of routing. Retrieving network distances for an entire arc network takes quite some time. Euclidean distances tend to be used instead of network distances due to the previous reason, for simplicity, and based on the assumption that the difference between these distances tend to be a constant (or: circuity factor) (Levinson & El-Geneidy, 2007). Multiplying this circuity factor with the Euclidean distance provides an estimate for the network distance. This assumption only holds when variation in the network is minimal. Since nearly all arcs are located in an urban area, the assumption holds for the network of Enschede. Figure 13 gives a visual explanation on the difference between Euclidean and network distances.

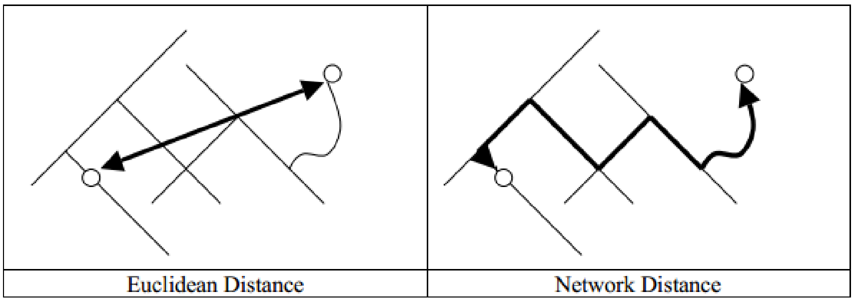

Figure 13: Difference between Euclidean distance and network distance (Levinson & El-Geneidy, 2007)

Much research has been conducted to determine the circuity factor. Levinson & El-Geneidy calculated this constant and found a circuity factor of 1.20. The X- and Y-values from all intersections from Figure 13 and the circuity factor of 1.20 can be used to estimate the network distance of each arc based on the coordinates of the two nodes that construct the arc.

4.4 The ILP model

This section is about the ILP used in order to generate routes for the trucks. As already stated in Section 1.6, routes that consist of cycle paths are outside the scope of this report. However, for the sake of completeness, the model also incorporates different types of streets and different types of salt spreaders. When the model is solved, cycle paths with corresponding salt spreaders are excluded.

First, all decision variables, parameters and indices are explained. Next, the objective function and the constraints will be elaborated on. The location represented by an arc ($i \in I$) of a truck ($k \in K$) at time interval ($t \in T$) is represented by the binary decision variable R_{ikt}. The binary decision variable X_{ikt} has the same characteristics, but describes whether a location is salted by a certain truck at a certain time interval or not. The set A_{ij} captures the possibility to travel from arc i to arc j in one time interval. The set L_a consists of all arcs from phase 1 and set L_b contains the arcs from phase 2.

An overview of the entire model:

Indices:
k = salt spreaders[8];
i,j= arcs (0 is the depot location);
t = steps (start at 1).

Decision variables:
R_{ikt} = 1 if arc i is being traversed by salt spreader k at step t, 0 otherwise;
X_{ikt} = 1 if arc i is being salted by salt spreader k at step t, 0 otherwise.

Parameters:
Trucks
n = number of trucks (20 trucks);
type 1 = big trucks (k=1,…11);
type 2 = small trucks (k=12,…20).

Fixed costs for salt spreaders and salt storage
vk_k = fixed costs for truck k;
vkoz = fixed costs for salt storage.

Price
pz = price per ton salt;
pb_k = fuel consumption (in Euros) per kilometer of truck k;
pp = standard personnel costs per person per hour.

Routes
r_i = time (in hours) in order to traverse arc i;
c_i = length (in kilometers) of arc i;
h_i = salt demand (in tons) of arc i;
y_i= number of times arc i should be salted;
z_{ik} = 1 if arc i can be salted by truck k;
A_{ij}= 1 if arc i can be reached from arc j in one step;
L_a = set containing all arcs from phase 1;
L_b = set containing all arcs from phase 2.

Capacity
CapA = time (in hours) in which phase1 needs to be salted;
CapB = time (in hours) in which phase2 needs to be salted;
Cap_k = salt capacity (in tons) of truck k.

Maximum
T = maximum number of steps.

[8] Two types of salt spreaders are being distinguished, namely, big (type 1) and small (type 2) ones. Big ones cannot cross cycle paths and small salt spreaders, for example, cannot salt the Hengelosestraat.

Model:

The model consist of two parts, namely, the objective function that is about minimizing total costs and some restrictions in order to meet certain elements that are inextricably linked to the snow and ice control problem. Examples are: respect truck capacity and the completion time of arcs from phase 1.

$$\min Z = pp\left(\sum_{i}\sum_{k}\sum_{t} r_i R_{ikt} + \frac{1}{2}n\right) + \sum_{k} vk_k + vkoz + pb_{k \in type\ 1}\sum_{i}\sum_{k \in type\ 1}\sum_{t} c_i R_{ikt} + pb_{k \in type\ 2}\sum_{i}\sum_{k \in type\ 2}\sum_{t} c_i R_{ikt} + pz\sum_{i}\sum_{k}\sum_{t} h_i X_{ikt}$$

The objective function minimizes the personnel costs, fixed costs per salt spreader, fixed costs for salt storage, total fuel consumption costs and total salt consumption costs. In the personnel costs an extra 30 minutes per employee is added as a call out fee.

s.t.

$$\sum_{k \in type\ 1}\sum_{t} X_{ikt} \geq y_i \sum_{k=1}^{11} z_{ik} \qquad \forall i \qquad (4.1)$$

$$\sum_{k \in type\ 2}\sum_{t} X_{ikt} \geq y_i \sum_{k=12}^{20} z_{ik} \qquad \forall i \qquad (4.2)$$

Constraints (4.1) and (4.2) ensure that all arcs that require service (including the associated number of services) are being served.

$$R_{ikt} \geq X_{ikt} \qquad \forall i, k, t \qquad (4.3)$$

Constraint (4.3) makes sure that if an arc is served the arc is also traversed.

$$\sum_{i}\sum_{t} h_i X_{ikt} \leq Cap_1 \qquad \forall k \in type\ 1 \qquad (4.4)$$

$$\sum_{i}\sum_{t} h_i X_{ikt} \leq Cap_2 \qquad \forall k \in type\ 2 \qquad (4.5)$$

The salt capacity of the salt spreaders is respected via constraints (4.4) and (4.5).

$$\sum_{i \in \mathrm{L_a}}\sum_{t > CapA} X_{ikt} \leq 0 \qquad \forall k \qquad (4.6)$$

$$\sum_{i \in \mathrm{L_b}}\sum_{t > CapB} X_{ikt} \leq 0 \qquad \forall k \qquad (4.7)$$

Via constraints (4.6) and (4.7) the predefined time restrictions for serving specific arcs are regulated.

$$R_{0k1} = 1 \qquad \forall k \qquad (4.8)$$

$$R_{0kT} = 1 \qquad \forall k \qquad (4.9)$$

Constraints (4.8) and (4.9) ensure that every route begins and ends at the depot.

$$R_{ikt} \leq \sum_{j \in \mathrm{A_{ij}}=1} R_{jkt-1} \qquad \forall i,k,t \tag{4.10}$$

Constraint (4.10) ensures closed tours.

$$\sum_{i} X_{ikt} \leq 1 \qquad \forall k,t \tag{4.11}$$

$$\sum_{i} R_{ikt} \leq 1 \qquad \forall k,t \tag{4.12}$$

Restrictions (4.11) and (4.12) ensure that trucks can only be at one place at a time interval. This holds both for traversing and salting.

$$X_{ikt} \in \{0,1\} \tag{4.13}$$

$$R_{ikt} \in \{0,1\} \tag{4.14}$$

Constraints (4.13) and (4.14) require all decision variables to be binaries.

The ILP does not incorporate the possibility for trucks to reload salt at the depot if needed. This is a reasonable assumption, because during anti-icing, salting trucks have enough capacity to salt their routes. Deicing requires trucks to reload. So, if deicing is taken into account this needs to be incorporated into the model.

The model above (with 350 arcs and 11 trucks) is not solvable with CPLEX. No solution was retrieved even after 70 hours of computation time on an 8 GB RAM and 64 bits computer. Enschede, Hengelo, and Almelo are considered too large in order to solve this model. Due to the execution of several test runs with smaller sets of arcs, it is assumed that the model is solvable for Borne, Hof van Twente, Losser, and perhaps Oldenzaal. In order to retrieve a solution for the city of Enschede, a heuristic is used in combination with a simplified ILP. This solution method is presented in Section 4.5.

4.5 Alternative solution methods

The ILP from Section 4.4 is too large in order to solve it for Enschede. The model needs to be divided into smaller parts in order to be solved. This section is about several ways of doing so. In all alternatives, the trucks (index k) are excluded from all the variables and parameters, e.g., Cap_k changes to Cap. Subsequently the ILP is solved iteratively per truck. In other words, during each iteration, a truck salts some roads and after a certain criterion is met, the truck returns to the depot and another iteration is started, i.e., a new truck starts salting. As a result, the decision variable will change to R_{it}. Its value is 1 if a location ($i \in I$) is traversed at a certain time interval ($t \in T$) and 0 otherwise. The same holds for the salting variable which is changed to X_{it}.

Section 4.5.1 is about maximizing the truck usage. In Section 4.5.2, emphasis is put on excluding the salting variable. The alternative formulation from Section 4.5.3 focuses on an artificial reward in case an arc is salted.

4.5.1 Maximizing truck usage

Constraints (4.1) and (4.2) made sure that all arcs that needed to be salted were salted by a truck. If the trucks are excluded from the ILP such a formulation will not hold, therefore the model must be adjusted. One could seek for an objective function that maximizes truck usage. This leads to the following two objective functions, namely,

$$Max\ z = \sum_{it} h_i X_{it}$$

and

$$Min\ z = Cap - \sum_{it} h_i X_{it}$$

These two formulations are quite similar. The second formulation is preferred due to the direct link with the truck capacity. However, as stated before, truck capacity exceeds current salt demand of each route. If the ILP is solved iteratively per truck, one could retrieve a solution in which the first number of trucks salt most of the network and the last trucks are not needed. To prevent this, the model will not use the actual truck capacity, but an artificial restrictive salt quantity that ensures workload balance and makes sure that all trucks are required. This is further elaborated on in Section 4.7.4.

This formulation belongs to the engineering problems that were discussed in Section 3.1.3.

4.5.2 Releasing salting variable

One could also simplify the model by releasing the salting variable. This drastically reduces the number of variables. However, somehow the model needs to assure that arcs still be salted by the trucks. This can be done by formulating the objective function as minimizing the absolute difference between the number of times an arcs needs to be served and the number of times an arcs is traversed, or:

$$Min\ z = \left| \sum_i (y_i - \sum_t X_{it}) \right|$$

The parameter y_i represents the total number of times arc i must be salted. Unfortunately, this formulation results in a nonlinear equation, thus cannot be used here. This problem formulation is part of the profitable problems from Section 3.1.3.

4.5.3 Rewarding a salted street

Another formulation results in the following objective function:

$$Min\ z = \sum_i \sum_t (R_{it} - parameter \cdot X_{it})$$

The main idea is to reward if an arc is salted. Unfortunately, this formulation brings in a new parameter. This is an artificial parameter that is used to model the problem. The quality of the solution will depend on the value of this parameter, therefore much effort needs to be put in determining a reasonable value for this parameter. Furthermore, there is no guarantee that such a value can be found. Due to these disadvantages this problem formulation will not be used. This problem formulation can also be combined with a constraint that ensures that at least a certain number of arcs will be salted by a certain truck. This brings in the same disadvantage, namely, this number of arcs must be determined. The values of these parameters will heavenly influence the solution, making the formulation not ideal.

Such an objective formulation is called a profitable model (Section 3.1.3). In case a minimum amount of arcs must be salted per truck, the model becomes more of an orienteering problem.

4.5.4 Conclusion

The formulation from Section 4.5.2 cannot be used in an ILP formulation, thus cannot be used as a simplified objective function. The artificial reward introduced in Section 4.5.3 has some disadvantages. These disadvantages do not occur if truck usage is maximized (Section 4.5.1). Furthermore, from a different perspective, maximizing truck usage can be seen as a translation of the previous objective function, namely, minimizing costs. So, the second formulation from Section 4.5.1 will be used.

4.6 The solution method

In Section 4.6.1, seed customers are introduced in order to increase the quality of the solution. In Section 4.6.2, the mathematical method to support the snow and ice control program in Enschede is presented. Section 4.6.3 deals with the values awarded to the different parameters.

4.6.1 Seed customers

The concept of seed customers is used in order to avoid, so called, cherry picking. Cherry picking means that during the first iteration, the truck will salt all roads that are closest to the depot. During the second iteration, the truck will do the same. As a consequence, it will be quite difficult to generate a route for the last trucks. Seed customers are used in Vehicle Routing Problem (VRP) heuristics in order to cope with this problem (Hosny, 2011). A seed customer, for a truck, is a specific arc (i) that must be traversed by that truck. Mostly, these seed customers are selected such that the workload in terms of distance travelled is somehow balanced. These seed customers aim to solve this problem by balancing the difficulty of obtaining a feasible solution (route).

Seed customers are determined by dividing the sprinkle map in as much parts as there are trucks available. Consequently, in every part, an arc is set as seed customer that has the longest distance with respect to the salt depot and other seed customers.

In this case, seed customers are defined as a single arc. However, one could also select a set of arcs to designate it as seeds. In practice this means that most streets within a certain neighborhood will be assigned to a specific truck. In such a way, a so called cluster-first route-second method is used. Seeds are used for clustering arcs, subsequently, a Travelling Salesman Problem (TSP) needs to be solved in order to obtain the most efficient route given the seed customers.

An advantage is that the ILP must solve a smaller set of arcs. Furthermore, from a managerial point of view it could be interesting to cluster arcs based on districts. However, creating clusters can be difficult. Furthermore, it would be hard to start salting main roads, unless they lie between the depot and the predefined clusters.

Here, a seed is defined as a single arc (i) in order to provide the ILP with a large solution space. Since the objective is to expose cause and effect relation instead of providing operational solutions, managerial issues, such as clustering, is not an issue. The seed arc is used in order to balance the difficulty of obtaining a feasible solution (route) and to provide the ILP with a large solution space.

4.6.2 The model

Section 4.6.2 is about how the model works. The solution method can be subdivided into three separate parts, namely, the ILP that is solved iteratively per truck and two improvement heuristics. The ILP is covered in Section 4.6.2.1. Preliminary runs have shown that due to the restrictive number of steps, not all arcs are served after the ILP is executed. Thus, Section 4.6.2.2 is about executing two heuristics that make sure that the whole arc network is salted. The solution method is depicted in Figure 14.

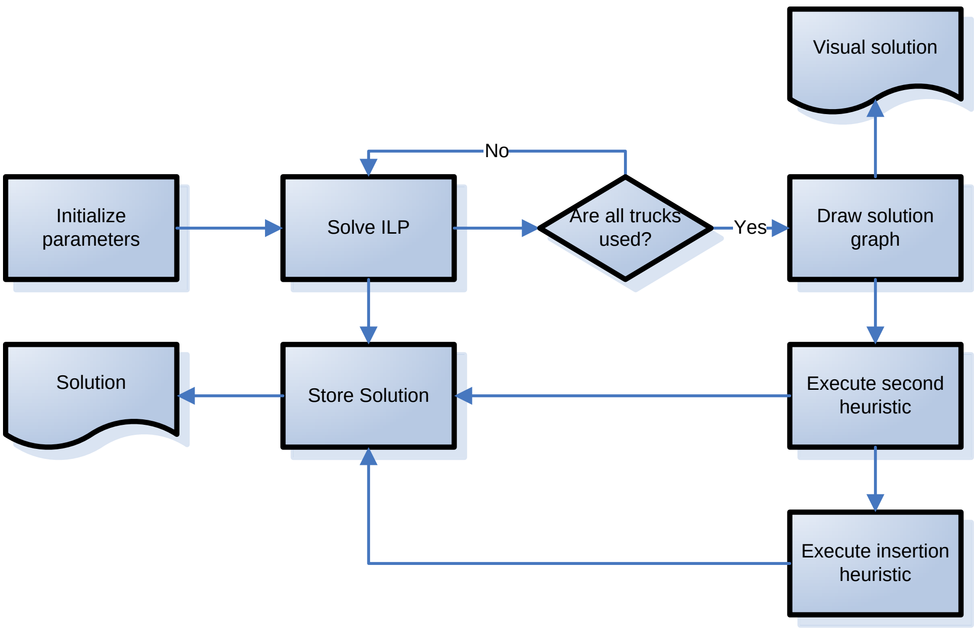

Figure 14: Solution method

4.6.2.1 The ILP

The mathematical model that corresponds with the iterative solution method of the ILP is about maximizing truck usage. The objective function is as follows:

$$\min Z = Cap - \sum_{i} \sum_{t} h_i X_{it}$$

Effectiveness can be seen as maximizing truck usage. Truck usage must be seen in terms of salt used.

s.t.

$$\sum_{t} R_{it} \leq y_i \qquad \forall i \tag{4.15}$$

$$\sum_{t} R_{seed,t} \geq 1 \tag{4.16}$$

Restriction (4.15) allows a truck to salt an arc a limited number of times. It is derived from restrictions (4.1) and (4.2), however no distinction need to be made with respect to different truck types. Restriction (4.16) compels the truck to traverse an arc seed. This seed prevents cherry picking and seeks for finding a balance with respect to the workload. Seeds are explained in Section 4.6.1.

$$X_{it} \leq R_{it} \qquad \forall i, t \tag{4.17}$$

Salting an arc is only possible if that specific arc is traversed at the same time interval. This is arranged via restriction (4.17). The restriction corresponds with restriction (4.3) from the previous model.

$$\sum_{i} \sum_{t} h_i X_{it} \leq Cap \tag{4.18}$$

Every truck has limited salt capacity. This is respected by restriction (4.18). The restriction is similar with restrictions (4.4) and (4.5) from the previous model.

$$\sum_{i \in \mathrm{L_a}} \sum_{t > CapA} X_{it} \leq 0 \tag{4.19}$$

$$\sum_{i \in \mathrm{L_b}} \sum_{t > CapB} X_{it} \leq 0 \tag{4.20}$$

Arcs in phase 1 need to be salted before the completion time of phase 1. This is ensured by restriction (4.19). Restriction (4.20) is about respecting the completion time of phase 2. These restrictions are derived from restrictions (4.6) and (4.7).

$$R_{0,1} = 1 \tag{4.21}$$

$$R_{0,T} = 1 \tag{4.22}$$

A truck should start and stop at the depot. This is ensured by restrictions (4.21) and (4.22). These restrictions correspond with restrictions (4.8) and (4.9).

$$R_{it} \leq \sum_{j \in \mathrm{A_{ij}} = 1} R_{j,t-1} \qquad \forall i, t \tag{4.23}$$

Restriction (4.23) ensures closed tours. If a truck is at location i at step t, it should have been at location j (where j is accessible from location i in one time interval) at step t-1. Set A_{ij} contains information regarding the accessibility, within one time interval, from one arc to another arc. Restriction (4.23) is similar with restriction (4.10) from the previous model.

$$\sum_{i} X_{it} \leq 1 \qquad \forall t \tag{4.24}$$

$$\sum_{i} R_{it} \leq 1 \qquad \forall t \tag{4.25}$$

Restrictions (4.24) and (4.25) ensure that trucks can only be at one place at a time interval. This holds both for traversing and salting. The formulation is also used in the previous model by restrictions (4.11) and (4.12).

$$X_{it} \in \{0,1\} \tag{4.26}$$

$$R_{it} \in \{0,1\} \tag{4.27}$$

All decision variables are binaries, since a truck can either be at a certain location at a certain time interval or not. This is captured in restrictions (4.26) and (4.27). The restrictions show similarities with restrictions (4.13) and (4.14).

4.6.2.2 Completing the arc network

It would be most preferable to present an ILP in which CPLEX (the solver used by AIMMS) solves a route for all trucks at once. Such a model is presented in Section 4.4. In this model, route effectiveness is guaranteed, because the decision whether to assign a certain arc to a truck influences the route of other trucks. Unfortunately, CPLEX experiences difficulties if such a model needs to be solved, therefore an ILP is solved iteratively for every truck (Section 4.6.2.1). In other words, the ILP seeks a route for the first truck and returns to the depot. All streets that are salted by this truck are omitted from the set of arcs that need to be salted and the solution is stored. Subsequently, the ILP seeks a route for the second truck, et cetera. In order words, if truck 1 salts arc i twice then the parameter y_i is reduced by two. In such a case, it is assured that arc i will not be salted by any other truck in case y_i initially was two. This new value of y_i is used for the next iteration.

Unfortunately, after several runs it has become clear that not all arcs will be served after the ILP is solved for all trucks. This is a result from the limited computational time, assigning a limited number of steps per truck in order to retrieve a feasible solution, and the method that is used. Thus, after the ILP is solved iteratively a heuristic is executed. This covering heuristic first checks for every truck if an arc is traversed that still needs to be salted. If capacity is sufficient, the arc is assigned to that truck. Unfortunately, the ILP does not ensure that these arcs are salted due to the limited computation time assigned per iteration. The mathematical notation of the covering heuristic, for all i, is as follows:

$$\sum_{t} X_{it} = 0 \cap \sum_{t} R_{it} = 1 \cap (\sum_{it} X_{it}) + d_i \leq Cap \cap R_{i \in \mathrm{L_a}, t < CapA} = 1 \rightarrow X_{iT'} = 1$$

where T' represents the step that corresponds with the variable $R_{iT'}=1$.

After this step an insertion heuristic is executed. This heuristic checks for every arc that still needs to be salted, which route consists of an arc that is closest to this arc (Figure 15). In other words, the heuristic finds the most promising location in a route in which an arc, that not has been served yet, can be inserted. At this location in the tour, the arc is inserted and a closed tour is created.

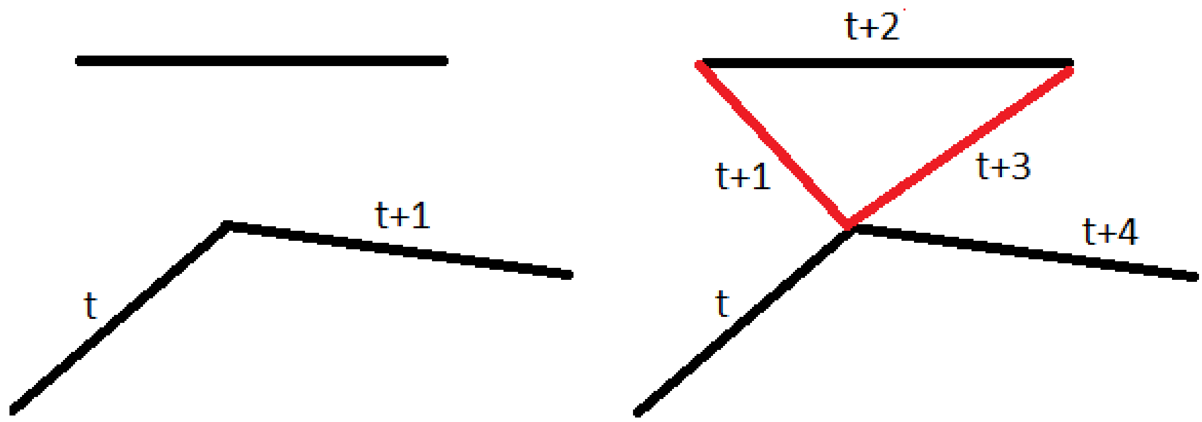

Figure 15: Insertion heuristic

Also the remaining truck capacity is taken into account as well as the road prioritization. Unfortunately, due to the nature of the insertion heuristic some roads from phase 1 eventually will be salted after the completion time of phase 1. For example, if arc X from phase 1 is inserted just before the completion time and subsequently arc Y is inserted in the route of the same truck prior to arc X it could be that arc X will be salted after the completion time. In other words, arc X is 'pushed' by the insertion of arc Y (in case arc Y is inserted prior to arc X). It is expected that the percentage of arcs from phase 1 that eventually will exceed the completion time of phase 1 will stay within the limits, thus no improvement heuristic will be executed in order to repair the obtained solution. Furthermore, this phenomenon will be experienced by all scenarios. This makes it possible to compare the results from all scenarios with one another.

4.6.2.3 Summary

As already stated, the solution method is depicted in Figure 14 in Section 4.6.2. At first all parameters are initialized and passed to the ILP model. This model is iteratively solved per truck. The model stores per truck and per step if an arc is traversed and/or salted. Furthermore, if an arc is salted the parameter yi is adjusted. This iterative procedure results in a graphical representation of the solution. After this procedure, the covering heuristic is executed that checks if there are arcs that still need to be salted are being traversed. If this is the case, with respect to the capacity and completion time of phase 1, the arc is salted. Again the solution is stored. Finally, the third heuristic is executed that inserts remaining arcs with respect to the problem characteristics and also the solution is stored again.

4.7 Initializing parameters

This section is about explaining the values of certain parameters. Section 4.7.1 is about determining the number of steps assigned per truck. In Section 4.7.2 the completion time of phase 1 is converted to steps. The solving time per iteration is explained in Section 4.7.3. Section 4.7.4 is about the salt capacity per truck. Finally, in Section 4.7.5 the truck speed is set.

4.7.1 Number of steps

The number of steps heavily influences the solving time of CPLEX. Moreover, at some point solving the model becomes impossible, therefore setting this parameter requires extensive testing. The ILP has been solved many times by iteratively increasing the solving time per iteration and the number of available steps per truck. If the number of steps increases to 100, CPLEX will not find a feasible solution regardless of the solving time assigned per iteration. Thus, every truck will have 100 steps at its disposal.

The above also holds for the number of arcs. However, this number is a direct result from the road map of Enschede and cannot be influenced that easily.

4.7.2 Completing phase 1

The total distance of all arcs that needs to be salted is 211 km. The total distance covered by the trucks in the current situation is 750 km. This means that each arc is traversed, on average, approximately 3.55 times. This can be incorporated into the model by increasing the allowable number of steps a truck may take, however this drastically increases the computation time of the model. Preliminary runs have shown that it is not possible to retrieve a solution while setting the steps sufficiently high in order to capture the entire network. In order to obtain a result, the model serves all arcs twice instead of, on average, 3.55. It is assumed this is sufficient in order to draw conclusions. However, this decision does have an impact on the completion time of phase 1 which is 180 minutes. This completion time of phase 1 corresponds with salting the entire network (every arc on average 3.55 times). If this number is reduced to 2, the completion time must be changed. The completion time is adjusted, based on these two ratios, to $\frac{2}{3.55} \cdot 180 = 101.4$ minutes. Unfortunately, because of the model formulation, this threshold has to be formulated as a number of steps instead of time. Since, a truck takes on average 0.96 minutes to traverse an arc, a truck may only salt arcs from phase 1 during the first 97 steps $(= 101.4 \cdot 0.96)$ of its route.

This threshold is slightly smaller than the maximum number of steps per available truck. This is a problem for the scenario in which the completion time is formulated as a soft constraint, therefore the completion time will artificially be set at a lower number for all scenarios. This leaves the opportunity to model the completion time as a soft constraint.

Since the objective is to gain insights in cause and effect relations in the tactical decision making process instead of constructing routes for the snow and ice control program, it is permitted to deviate from the actual winter maintenance process, e.g., a scenario may differ from the actual process, however the extent in which the scenario differs must be somehow the same as in comparison with other scenarios in order to draw conclusions with respect to cause and effects relations. So, it is important that this completion time is equal in all scenarios. Furthermore, the solution method can be subdivided in three different heuristics. The first heuristic is the most efficient, therefore scenarios are comparable if the percentage of arcs covered by the first heuristic is similar to the other scenarios. Numerous runs have been conducted in order to determine a completion time that maximize the number of arcs covered by the first heuristic and at the same time provide the opportunity to model the soft constraint formulation. The completion time will be set at 67 steps. In Chapter 5, one can see that the number of arcs covered by the first heuristic per scenario are similar, thus the scenarios are comparable with each other.

4.7.3 Solving time

The initial solution has been used in order to determine the solving time per iteration. The solving time should at least ensure that every iteration results in a feasible solution. Furthermore, percentage improvement (measured as percentage of total covered network), due to the increased solving time, is considered to decrease as the solving time increases. The information from Table 6 is used in order to gain insight in this effect in order to set the solving time per iteration.

Solving time per iteration	4,500 seconds	6,000 seconds	7,500 seconds	9,000 seconds	10,500 seconds	12,000 seconds
Trucks with feasible solution	8	8	8	11	11	11
Percentage of network covered	48.34%	48.34%	48.34%	67.48%	67.48%	67.48%

Table 6: Solving time

The solving time per iteration is set at 12,000 seconds for all experiments.

4.7.4 Salt capacity

This parameter can be influenced manually. Completing time of phase 1, solving time, and the number of steps are somehow influenced by the model. Total salt capacity of the fleet must exceed the total demand of network of Enschede in order to generate a feasible solution. It is obvious that due to travelling time, trucks with a sprinkle area near the depot use more salt than trucks that have a more remote sprinkle area. Setting the salt capacity per truck can be used in order to balance the workload.

In the present situation (anti-icing), salt capacity is not restrictive. In order to retrieve balanced routes and to keep conditions constant during all experiments (see Section 4.4), truck capacity is set at the total amount of salt needed to serve the total network divided by all available trucks. Subsequently, this amount is multiplied by 105%. So, the capacity per truck is set at 5% more than the average amount of salt needed per truck in order to serve the entire network. This ensures constant conditions. Furthermore, an unbalanced workload is allowed within certain limits.

4.7.5 Truck speed

For practical reasons, the truck speed is set as a constant. The average vehicle speed is 35 km/h (Kloppers, 2014).

4.8 Conclusion

This chapter started with combining two generalized models (MPP and CARP) from Chapter 3 in order to model the specific routing problem Twente Milieu faces and to answer the third sub question. The creation of closed tours is controlled by introducing the element of steps that lead salt spreaders only to adjacent roads. Concepts from the MPP and the CARP, the closed tours, and a predefined set of assumptions lead to the introduction of an ILP. Due to the ILP's complexity, we are not able to solve the model for the network of Enschede. As a result, a heuristic is introduced in order to solve the ILP iteratively per truck. Also the objective function is changed. Cost minimization is replaced by maximizing truck usage.

This iteratively procedure works, however not all roads will be served after all iterations. Therefore, we combined the ILP model with a heuristic in order to serve the remaining roads. The resulting solving method is the starting point for modeling several scenarios that will provide Twente Milieu with insights in their snow and ice removal process. The result of these scenarios will be presented in the next chapter.

Chapter 5: Experimental results

This chapter is about the experimental results that were obtained from running various scenarios. Each scenario reflects a potential tactical decision, for example, relocate the salt depot or use 10 trucks instead of 11. Each scenario is about changing only one parameter in the planning model. The output of the model quantifies the effect of changing that parameter. These effects can be used in the discussions regarding the future of the snow and ice control program. The scenarios arise from discussions with employees, the job description provided by Twente Milieu, and the problem analysis. The different scenarios were briefly discussed in Section 1.5 and are part of the research questions.

The ILP generates information that can be used to make a visual representation of the routes. This information cannot be directly used by Twente Milieu, because, arcs inserted by the last two heuristics are not displayed in the graph and the route does not provide any information on an operational level. To give an impression, in Figure 17, the routes generated by the ILP for eleven trucks are presented.

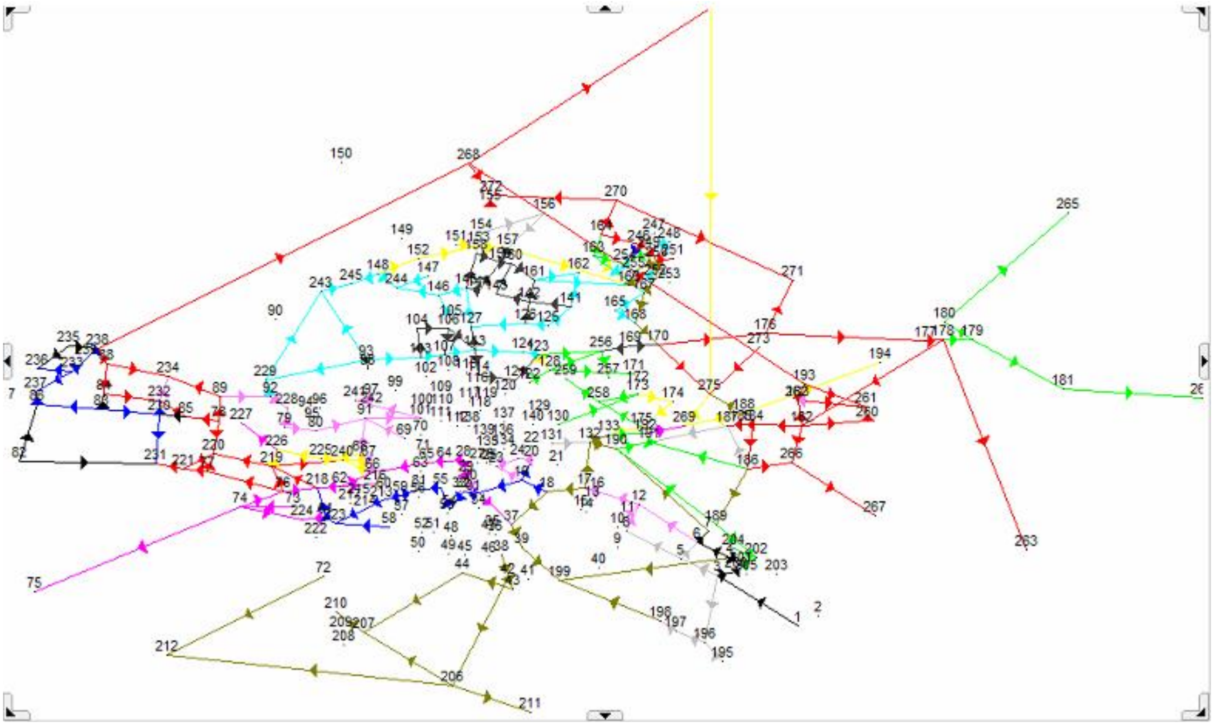

Figure 17: Representation of the ILP solution

In Section 5.1, the following information will be provided per scenario: distance covered per truck, salting time per truck, traversing time per truck, remaining salt per truck, the percentage of arcs in phase 1 that are salted after the completion time of phase 1, and the effective salting time (salting time divided by travel time). This information is used, per scenario, as Key Performance Indicators (KPIs). These KPIs can be used to compare the scenarios based on objective measurements. The last two KPIs provide information about the quality of the solution. The others provide information regarding distance covered and time consumed per truck. These KPIs with respect to the quality are important to assess whether scenarios can be compared with each other. Due to the insertion heuristic, some arcs from phase 1 are salted after the completion time of phase 1 as they get shifted as more arcs are inserted in the same tour (Section 4.6.2.2). Therefore, if this percentage differs much among scenarios, these scenarios become incomparable. Another measurement for quality is the percentage of arcs that are salted by the ILP. The ILP is the most efficient way of modeling routes, because the ILP minimizes deadheading. The insertion heuristic negatively influences the amount of deadheading, because two arcs must be driven in order to salt the inserted arc.

The information that forms the KPIs arises from the solution method depicted in Figure 14 and explained in Section 4.6.2.2. In other words, it is the result from, first, iteratively solving the ILP per truck, secondly, executing the covering heuristic that checks whether arcs that are traversed can be salted at once, thirdly, carrying out the insertion heuristic that inserts all remaining arcs in the constructed routes.

In Section 5.2, an overview of the score on the different KPIs per scenario is presented. Furthermore, conclusions are drawn with respect to these scores.

5.1 Experimental results per scenario

Every subsection covers a different scenario. The scenarios can be classified as follows, (1) differing depot location, (2) adjusting the completion time of phase 1, and (3) differing the number of trucks used. First, all relevant information regarding the different scenarios is presented followed by an analysis regarding the score of the KPIs.

5.1.1 Location of the salt depot

Twente Milieu possesses four different locations in Enschede. The aim of this research is not to determine the best depot location, but to show cause and effect relations with respect to a certain depot location. For this reason, every location corresponds with a scenario without examining whether this location is considered good. The four locations are all located at the outskirts of Enschede. This makes them somehow comparable. Furthermore, the city centre is used as depot location in a fifth scenario.

At first, all information regarding the four locations is presented. At second, a comparison is made in order to compare the results.

Current location (Marssteden 37, Enschede)

Truck	Distance travelled (km)	Travel time (min)	Salting time (min)
1	58.68	100.11	80.04
2	74.91	128.54	80.15
3	64.90	110.79	80.27
4	120.61	206.76	79.74
5	85.22	146.09	79.95
6	90.19	165.70	100.09
7	103.86	192.54	105.30
8	70.85	125.29	91.02
9	90.65	173.82	132.37
10	108.26	171.00	82.36
11	89.76	176.77	121.77
μ/σ	87.08/18.97	154.31	93.91

Table 7a: Current location

Percentage covered by ILP (%)	67.48%
Roads from phase 1 violated (%)	12.05%

Table 7b: Current location

Location West (Binnenhaven 152, Enschede)

Truck	Distance travelled (km)	Travelling time (min)	Salting time (min)
1	56.85	96.42	81.56
2	111.96	191.93	80.00
3	110.48	189.39	79.99
4	80.30	137.65	79.94
5	104.79	179.64	79.97
6	92.00	167.91	101.65
7	95.75	170.56	92.40
8	71.78	133.12	100.25
9	67.99	126.08	95.00
10	77.41	145.36	108.22
11	89.80	178.05	119.94
μ/σ	87.19/18.00	156.01	92.63

Table 8a: Depot location west

Percentage covered by ILP (%)	64.82%
Roads from phase 1 violated (%)	11.90%

Table 8b: Depot location west

Location South (Vlierstraat 105, Enschede)

Truck	Distance travelled (km)	Travelling time (min)	Salting time (min)
1	70.52	120.90	79.88
2	82.22	140.40	80.14
3	74.10	127.03	79.96
4	76.68	131.99	81.55
5	78.55	142.78	94.04
6	82.18	141.00	80.12
7	90.33	155.58	82.22
8	100.61	188.66	121.53
9	84.80	155.33	96.56
10	103.00	190.55	129.85
11	86.58	167.45	116.90
μ/σ	84.51/10.25	151.06	94.79

Table 9a: Depot location south

Percentage covered by ILP (%)	63.61%
Roads from phase 1 violated (%)	14.14%

Table 9b: Depot location south

Location East (Lenteweg 44, Enschede)

Truck	Distance travelled (km)	Travel time (min)	Salting time (min)
1	57.53	100.13	81.72
2	122.60	210.00	80.041
3	83.50	143.15	79.98
4	98.05	169.91	84.05
5	87.13	149.36	79.99
6	70.70	129.27	102.32

7	74.84	129.51	82.43
8	105.33	178.221	114.08
9	94.84	165.62	96.76
10	103.48	155.20	108.87
11	106.87	171.05	118.77
μ/σ	91.35/18.81	154.67	93.55

Table 10a: Depot location east

Percentage covered by ILP (%)	64.05%
Roads from phase 1 violated (%)	10.42%

Table 10b: Depot location east

All scenarios in which the depot location is varied can be compared, i.e., the percentage covered by the ILP and the percentage of roads violated from phase 1 are considered similar. The solutions seem somewhat the same. Distance travelled, travelling time, and salting time are about equal. This could be the result of the potential locations of the depot which are located on the outskirts of the city. For this reason, another scenario is suggested, namely, to locate the depot in the city center. Twente Milieu does not possess land in this area. Furthermore, also from a managerial point of view it is questionable whether the city center is a preferable location for a depot due to the chance of congestion during winter conditions. On the other hand, the city center is located near the Singel, other important traffic arterial roads, and, on average, relatively little distances needs to be covered in order to reach different areas in Enschede.

Location city centre

Truck	Distance travelled (km)	Travel time (min)	Salting time (min)
1	105.76	181.29	79.99
2	87.59	149.98	80.00
3	65.12	111.64	80.00
4	63.77	109.32	79.99
5	80.19	150.44	99.59
6	67.84	124.99	92.13
7	74.74	136.98	101.19
8	83.73	136.57	101.08
9	85.87	145.00	105.00
10	59.96	118.37	90.91
11	94.28	181.13	112.99
μ/σ	78.99/14.23	140.52	92.99

Table 11a: Depot location city centre

Percentage covered by ILP (%)	67.15%
Roads from phase 1 violated (%)	8.04%

Table 11b: Depot location city centre

It can be seen that the percentage arcs covered by the ILP and the number of roads from phase 1 that are violated differ at most 4%. This number is incalculable and for that reason are the solutions comparable.

Conclusion

It can be seen that the depot location certainly influences the efficiency (distance covered, travelling time, and salting time) of the salting routes. This is caused by the effect that trucks need to cover less distance in order to reach their seed customer and to complete their rout. This effect will remain even if the depot location will be combined with one of the other scenarios. The location of the depot will become more important if, for example, Hengelo and Enschede will share a depot, because the depot location acts as an important starting point for all routes.

One could assume that, due to the seed arcs, the variance between the trucks with respect to the distance covered is more of less the same. This does not hold for the depot in the city centre and the depot located in the south of Enschede. In the case of the city centre, this is not remarkable. If one assumes that the arc network, seen from the center point, is homogeneous, all trucks will experience the same degree of difficultness with respect to their route. For the depot located in the south, this is not the case. However, the depot in the south is located less remote with respect to the other locations. This result in a lower standard deviation and a lower average distance covered.

5.1.2 Road prioritization

The following two scenarios are about examining the effect of the completion time of phase 1 on the solution. The first scenario is about a soft formulation of the constraint that arranges arcs from phase 1 to be salted before the completion time of phase 1. In other words, arcs from phase 1 may be salted after the completion time of phase 1, however in that case some penalty is incurred.

The second scenario is about extending the completion time of phase 1 with 30 minutes.

Scenario with soft constraint formulation

Truck	Distance travelled (km)	Travelling time (min)	Salting time (min)
1	81.84	140.30	79.99
2	147.88	253.51	79.97
3	85.68	146.87	79.99
4	100.31	171.97	79.94
5	69.77	118.91	80.02
6	97.62	177.65	94.36
7	83.71	145.87	87.99
8	93.64	165.46	99.68
9	91.04	161.95	106.99
10	85.40	151.62	113.64
11	85.06	147.36	104.70
μ/σ	92.91/20.04	161.95	91.57

Table 12a: Soft constraint formulation

Percentage covered by ILP (%)	66.59%
Roads from phase 1 violated (%)	18.45%

Table 12b: Soft constraint formulation

Extended completion time phase 1

Truck	Distance travelled (km)	Travelling time (min)	Salting time (min)
1	109.81	188.25	79.99
2	79.32	136.20	80.26
3	75.74	139.69	92.43
4	90.26	154.85	80.39
5	71.63	122.31	80.13
6	92.37	161.59	90.87
7	91.39	159.48	91.72

8	117.57	194.10	95.38
9	79.77	152.06	104.85
10	69.58	135.18	93.93
11	108.23	184.98	130.23
μ/σ	89.61/16.33	157.15	92.74

Table 13a: Extended completion time phase 1

Percentage covered by ILP (%)	**68.58%**
Roads from phase 1 violated (%)	**12.20%**

Table 13b: Extended completion time phase 1

The scenarios 'Extended completion time phase 1' and 'Soft constraint formulation' are about evaluating the effect of the completion time of phase 1 on the solution. It can be seen that the interventions do not lead to better solutions. This seems remarkable, since these scenarios are formulated less severe than the current situation. However, in the current situation the completion time of phase 1 seems to be sufficiently large to salt the arcs from phase 1. Easing or extending the completion time becomes useful if the interplay between the arc network and the number of trucks used to salt the network form a tension field, i.e., if fewer trucks are used the completion time becomes more important. At this moment, this is not the case.

Note: the percentage of roads from phase 1 that violate the completion time is higher. This is not surprising, since this is incorporated into the scenario.

5.2.3 Number of trucks

Currently, Twente Milieu uses 11 trucks to salt the network. The following scenarios are about examining the snow and ice control program with less available trucks.

Current situation (11 Trucks)

Truck	Distance travelled (km)	Travel time (min)	Salting time (min)
1	58.68	100.11	80.04
2	74.91	128.54	80.15
3	64.90	110.79	80.27
4	120.61	206.76	79.74
5	85.22	146.09	79.95
6	90.19	165.70	100.09
7	103.86	192.54	105.30
8	70.85	125.29	91.02
9	90.65	173.82	132.37
10	108.26	171.00	82.36
11	89.76	176.77	121.77
μ/σ	87.08/18.97	154.31	93.91

Table 14a: Current situation (11 trucks)

Percentage covered by ILP (%)	**67.48%**
Roads from phase 1 violated (%)	**12.05%**

Table 14b: Current situation (11 trucks)

10 trucks

Truck	Distance travelled (km)	Travel time (min)	Salting time (min)
1	80.28	137.46	87.99
2	95.80	163.35	88.06
3	94.15	161.40	87.85
4	79.59	142.86	97.04
5	101.20	173.54	88.05
6	90.77	165.61	108.07
7	103.31	177.40	111.09
8	93.77	175.91	116.70
9	92.91	174.14	114.61
10	98.83	190.74	123.78
μ/σ	93.06/7.92	166.24	102.32

Table 15a: 10 trucks

Percentage covered by ILP (%)	62.87%
Roads from phase 1 violated (%)	14.88%

Table 15b: 10 trucks

9 trucks

Truck	Distance travelled (km)	Travel time (min)	Salting time (min)
1	134.49	230.55	95.97
2	162.92	250.22	123.77
3	106.72	182.96	95.95
4	107.85	199.16	115.80
5	99.63	170.80	95.89
6	120.29	208.39	106.47
7	118.14	203.77	162.30
8	105.25	184.20	116.16
9	109.98	210.47	144.97
μ/σ	118.36/19.65	204.50	117.48

Table 16a: 9 trucks

Percentage covered by ILP (%)	55.42%
Roads from phase 1 violated (%)	20.83%

Table 16b: 9 trucks

It is not remarkable that as the number of trucks used decreases, the distance covered, travelling time and salting time, per truck, increases. However, this (relative) growth is much higher when 9 trucks are used compared to the situation in which 10 trucks are used. Unfortunately, this is very likely caused due to the low percentage of roads covered by the ILP. The ILP is more efficient than the insertion heuristic due to the fact that the insertion heuristic requires some travelling before the inserted road can be salted. This flaw does not emerge if the ILP is executed (Section 4.3.4).

One would expect to see the following growth in the distance covered in the scenario where 10 trucks are used: $93.06 + \frac{93.06}{11} = 95.00$. This distance does not differ that much from the actual average distance covered in the case of 10 trucks. It is also explicable that the percentage roads from phase 1 that are violated, with respect to the completion time, are slightly higher. There is less time available for all these streets. On the other hand, trucks have more time at their disposal (number of steps available is higher), this increases the effective salting time. This is also because the area around the depot will be salted quite rapidly. So, as the number of iterations increases, the trucks must traverse to an area that has not been salted yet. In order to do so, some roads need to be traversed that have already been salted.

The low percentage covered by the ILP could also implicate that the KPI with respect to distance covered, of the scenarios of 10 and 9 trucks, should have been better in comparison with the current results. This is because the heuristic provides results that are worse in comparison with the ILP. In other words, if more arcs are inserted with the insertion heuristic, the actual solution is worse due to the model, not because of the issues associated with the scenario settings.

Total distance covered

The tables that hold information regarding the performance of the different scenarios provide insights into the distance covered per truck. As already stated, the average distance covered per truck increases as the number of trucks used decreased. However, the total distance covered differs from the previous observation. Table 17 gives an overview of the total kilometers driven per scenario in which the number of trucks is varied.

Truck	Total distance covered (km)
11	1021.95
10	930.61
9	1065.27

Table 17: Overview of total kilometers driven

It can be seen that if 10 trucks are used the total kilometers driven decreases. This effect does not continue if the number of trucks used is set to 9. One would aspect that if the number of trucks decreases the total distance covered by the trucks also decreases. This is caused by less deadheading, i.e., less distance needs to be covered before a truck enters an area that needs to be salted. However, as can be seen in the scenario with 9 trucks, this is not always the case. Apparently, at a given moment, the trucks must traverse to an area that has not been salted yet. In order to do so, some roads need to be traversed that have already been salted. It is assumed that this effect can be mitigated if the depot location is changed and/or if a truck does not get a seed arc appointed, but a whole set of seed arcs. In this case, remote areas (seeds) are salted entirely and the ILP could not come up with a feasible route in which some remote arcs still need to be salted. This causes substantial deadheading costs. However, a set of seed arcs causes another problem, namely, which arcs need to be appointed to which seed. The big question is: when does one seed stops and when does another seed begins? In order to provide the ILP with a large solution space, an arc seed is appointed to a truck instead of a whole set of seed arcs.

The position of the depot influences the chance of increased deadheading. In this report, only stand alone scenarios are being considered. However, it is recommendable to examine the effect of the depot location with respect to the number of trucks used. This gives a better understanding of the interplay between the depot location and the fleet size with respect to a given arc network. Especially, if environmental and financial aspects are being considered, lowering the total kilometers driven may be a goal on its own.

5.2 Overview KPIs per scenario

In Table 18, an overview of the average scores of the three KPIs per scenario is presented.

Scenario category	Scenario (averages)	Distance travelled (km)	Travelling time (min)	Salting time (min)
Differing depot location	Current depot location (initial solution)	87.08	154.31	93.91
	Depot west	87.19	156.01	92.63
	Depot south	84.51	151.06	94.79
	Depot east	91.35	154.67	93.55
	Depot city centre	78.99	140.52	92.98
Adjusting completion time of phase 1	Normal completion time (initial solution)	87.08	154.31	93.91
	Extended completion time	89.61	157.15	92.74
	Penalty for violating completion time	92.91	161.95	91.57
Differing truck usage	11 trucks (initial solution)	87.08	154.31	93.91
	10 trucks	93.06	166.24	102.32
	9 trucks	118.36	204.50	117.48

Table 18: Overview of all scenarios

One can see that, beside the scenarios in which fewer trucks are used, the distance covered per truck does not differ that much. For the scenarios in which the completion time of phase 1 is eased or extended, this is not that remarkable. As already stated, the current network in combination with the available truck is sufficient, thus easing or extending the completion time of phase 1 is not necessary. This could become necessary in case fewer trucks are used. In case Twente Milieu decides to do so, it is recommended to examine this.

Depot location

Locating the depot in the city centre does have a significant impact on the distance travelled per truck. It is recommended to use this knowledge in case the current depot is depreciated. This location becomes more important if fewer trucks are used. If fewer kilometers must be covered from the depot to a truck's salting area, the chance that the completion time of phase 1 is respected increases. This distance heavenly depends on the depot location.

Fewer trucks

Using fewer trucks results in less incurred costs. In the case of 9 trucks, a truck takes, on average, 204.50 minutes to complete its route. 11 trucks take on average 154.31 minutes to complete their routes. This is an extension of 33%. In the current situation, trucks take 2 to 2.5 hours to complete their routes. With this extension in mind, it seems permitted to use fewer trucks.

Truck differences

The differences between the trucks per scenario, with respect to the distance covered, the travelling time, and the salting time, is caused by the fact that some districts are more difficult to reach and salt. This effect is mitigated by the seed customers assigned per truck, however this effect cannot be eliminated. Furthermore, it is not necessary to construct equal routes in terms of distance covered, travelling time, and salting time.

Chapter 6: Conclusion, recommendations and discussion

Conclusion

This report started with an introduction regarding the snow and ice control organized at Twente Milieu. The aim of the report is to provide Twente Milieu with insights into different cause and effect relations with respect to tactical decisions (scenarios) that can be made in the area of improving the snow and ice control program in the future. Examples of such decisions are: the usage of less salt spreaders or the relocation of the salt depot.

This is done in order to answer the following research question:

What is the most efficient and effective way of organizing the ice and snow control program at Twente Milieu?

For every scenario, an ILP model and two improvement heuristics have been used in order to model salting routes on a tactical level[9]. KPIs, such as distance covered per truck, salting time per truck, and travel time per truck have been used in order to compare the various scenarios.

This question will be answered based on the results obtained from the different scenarios. First, a quick glance at the different scenarios is presented. Finally, the question is answered in the recommendation section.

Completion time phase 1

The arc network can be divided in two phases. Phase 1 has priority over phase 2, i.e., phase 1 needs to be salted within a certain time frame, just as phase 2. Two scenarios are about the completion time of phase 1. These scenarios indicate that there is no need for adjustments in the road network and/or adjusting the completion time of phase 1. This is positive, since changing one of these will have a negative effect on the traffic safety and requires a municipality policy change.

Fleet size

The results obtained from the solution method indicate that there is room for cost reductions. Making use of the available time for roads in phase 2 and simultaneously lower the number of trucks used during salt gritting will lead to fewer costs made for the vehicle fleet. Such a decision has major impact on the snow and ice control program and the organization. Negative side effects are that in the case of a vehicle break down there are fewer possibilities for other trucks to take over. Furthermore, especially during night shifts, truck drivers must start earlier. This may result in personnel that are fatigued during their regular work[10]. However, fewer people are tired from a nights shift during their regular work. Twente Milieu should decide whether such effects are acceptable.

[9] Routes are not operational, since adjustments have been made in order to model the ice and snow program. For example, traffic regulation is not incorporated in the model.
[10] Most truck drivers are garbage collectors during the day.

A positive effect is as the number of trucks used decreases, the fixed costs decreases as well. Most of the costs associated with the snow and ice control program are fixed costs. Examples of variable costs are: fuel, maintenance, and personnel costs. These costs cannot be influenced easily. However, if fewer trucks are used, it can be assumed that maintenance costs increases. It is debatable whether total fuel and personnel costs increases as well.

Depot location

The solution method revealed that the depot location does have an impact on the snow and ice control program. Since the current depot has not been depreciated yet and collaboration between municipalities, with respect to the usage of the same depot, in the area of winter maintenance has not been discussed, there is currently no need to relocate the depot. This does not imply that examining whether a relocated depot in the future can be beneficial for Twente Milieu. This is further elaborated on in the section on recommendations.

Results

Table 19 contains an overview of the results of all scenarios. The goal of this report is not to define how winter maintenance should be organized at Twente Milieu, rather to expose cause and effect relations with respect to tactical decision making. It can be seen that these scenarios actually influence the three KPIs.

Scenario category	Scenario (averages)	Distance travelled (km)	Travelling time (min)	Salting time (min)
Differing depot location	Current depot location (initial solution)	87.08	154.31	93.91
	Depot west	87.19	156.01	92.63
	Depot south	84.51	151.06	94.79
	Depot east	91.35	154.67	93.55
	Depot city centre	78.99	140.52	92.98
Adjusting completion time of phase 1	Normal completion time (initial solution)	87.08	154.31	93.91
	Extended completion time	89.61	157.15	92.74
	Penalty for violating completion time	92.91	161.95	91.57
Differing truck usage	11 trucks (initial solution)	87.08	154.31	93.91
	10 trucks	93.06	166.24	102.32
	9 trucks	118.36	204.50	117.48

Table 19: Overview of all scenarios

Note: kilometers per truck increases as the number of kilometers per truck decreases. However, with respect to the total number of kilometers driven, the solution with 10 trucks scores better in comparison with the scenario in which 11 trucks are used.

Recommendations

This thesis is written as a result of a request of Twente Milieu to examine the snow and ice control plan currently employed. The focus has been put on the usage of Operations Research techniques. However, many other aspects such as the business perspective are important as well. Therefore, the focus should not be solely on KPIs retrieved from the solution method. It is easy to raise questions like: 'are the current salting routes efficient?' Such thinking should not be leading in the process of evaluating the snow and ice control process. In particular, because salt gritting can have a major impact on the reachability of Enschede during winters and the number of (deadly) accidents.

From the perspective of operational excellence, a better starting point would be to shift the focus from the current snow and ice control program and to ignore signals coming from the municipalities to carry out cost reductions. Improvements and cost reductions should be the result of strategic and tactical decision making processes, not as the starting point. One could end up in operational issues and/or not being able to think outside the scope in order to break through the status quo. Budgets act as a framework for the snow and ice control program in the future, therefore one should check whether strategic and tactical decisions fit in this framework. Only then can we avoid that financial resources function as the starting point of the discussion. There are sufficient points of interest to start the discussion regarding the future of the snow and ice control program. Twente Milieu's mission statement speaks of a waste-free society in 2030. Waste-free is a broad concept and could also be seen in the light of minimal fuel consumption, seeking synergy by combining activities, and minimize the usage of vehicles. Furthermore, seeking synergy between municipalities was one of the goals set during the establishment of Twente Milieu. All municipalities are united within Twente Milieu, so it is the designated organization to take the lead in this process.

Twente Milieu's mission statement and the aim of seeking synergy should be leading in the strategic and tactical discussion on winter maintenance. Relevant questions are: 'how do we see winter maintenance, in the context of a waste-free society, in 2030 on the level of Twente Milieu?' One could decide to organize winter maintenance per municipality. However this should be the result of an informed decision instead of the result from how winter maintenance was organized in the past.

Regardless of the previous decision, a next question becomes relevant, namely, where a depot should be located? This is especially important if winter maintenance (and waste collection) is organized transboundary. The solution method showed that the quality of a route, i.e., depends on the location of the depot. Such an effect also occurs when winter maintenance is organized at the level of Twente Milieu as a whole. In fact, it could lead to a situation in which fewer depots are needed, which leads to direct cost savings. The decision regarding the depot(s) location should be made parallel with determining the number of trucks needed and the completion time of the different phases. The sprinkle map and strict completion times must be respected. So, the location of the depot(s) along with the number of available trucks must ensure that these requirements are met.

A last decision that must be made on a tactical level is about the routes. At the moment, Twente Milieu has routes for snowplowing and routes for deicing/anti-icing. One could decide to adjust routes according to specific external conditions. For example, during the night one could neglect completion times. Most anti-icing salting activities take place at night. At night, traffic intensity is low. Twente Milieu could, in accordance with municipality Enschede, neglect the completion time of phase 1 at night. The completion time should be set before the morning rush hour in order to ensure road safety. This makes it possible to use far less trucks than currently used. It could also lead to a situation in which employees work all night and are dismissed from their day-to-day operations the following days.

Another example is during severe traffic congestion. Salt spreaders come to a hold in a traffic jam, for example as a result of snow. One could decide to alter routes in order to avoid such traffic congestion and focus on roads that still need to be salted and are accessible before salting congested roads. Such scenarios can be drawn beforehand, because the same roads tend to congest.

Operational level
Only after a clear strategy is formulated, the focus can be put on operational issues. Important operational issues are: the allocation of costs in case winter maintenance is organized transboundary, the establishment of the routes, and the type of shift system that suits winter maintenance.

Short term
The previous recommendations focus on establishing a long term vision and act upon it. Benefits will become visible in the long run. But, creating a long term vision must not prevent Twente Milieu to set goals in the short term. Especially, if modifications in the short term contribute to and are in line with long term goals.

If Twente Milieu decides to make modifications in their snow and ice control program, these will focus on cost reductions. Based on the scenario analysis, the most effective way, but at the same time also the most risky way, of doing this is lowering the number of salt spreaders used. This can be done without violating the completion time of phase 1.

Summary of recommendations
Twente Milieu should start with an extensive discussion regarding the organization of the entire snow and ice control program. The subject of this debate is whether different salting routes, i.e., various scenarios could be used in the future. The information retrieved from the solution method can help in this process. Only if there is a consensus among different stakeholders (Management Team, municipalities, and the operation department) further steps could be taken. These further steps can be:

- define a vision with respect to the snow and ice control program;
- determine whether snow and ice control can be organized transboundary;
- decide whether, in the future, the location of the salt depot is ideal. On the basis of the current results, this does not appear to be beneficial. However, if Hengelo (and/or other municipalities) are being served from the same location, this could become beneficial;
- determine whether depots may be shared by municipalities;
- determine the location(s) of the depot(s);
- determine how much trucks should be made available during anti-icing and deicing salting actions;
- determine if this number can be different regarding the time of the salting action (night or day);
- determine whether to further examine the first ILP (Section 4.3.4) for a smaller community (for example: Losser);

- making contact with a software developer in order to help with the construction of a route planning tool that can be used for operational purposes;
- take the financial department into consideration, because changing the snow and ice control program will be reflected in the amount charged by Twente Milieu and depreciation costs of the trucks;
- make specific agreements about on which conditions one should decide to start salting activities. Currently, this decision is based on intuition, experience and logic. However, this could lead to two undesirable incentives, namely, (1) truck drivers are eager to sprinkle often due to the extra wages than can be earned, and (2) the variable costs charged for salt gritting are currently not in line with the actual costs. The current costs are too high and the fixed costs are too low. From a financial perspective, salting is beneficial. Both situations can lead to a situation in which issues that are not primarily concerned with road safety influence the decision to start salting.

Discussion

Several parts of the solution method are discussed in this section. The discussion is subdivided into three parts. The goal of the discussion is two-sided, namely, to appoint certain points for improvement and to make recommendations with respect to implementing the method.

Method used

The mathematical model used gives insights into cause and effect decisions made on a tactical level. Unfortunately, model limitations make it impossible to incorporate all effects. Furthermore, the model could not guarantee that all roads from phase 1 where salted within the corresponding time limit.

Seed selection

Currently, seed customers are defined as a single arc. However, one could also select a set of arcs to designate it as seeds. From a managerial point of view it could be interesting to cluster arcs based on districts. In this case, the chance that street within the same district are salted within a short period of time. This reduces the chance that drivers will be surprised by streets that have not been salted (yet).

If Twente Milieu decides to adopt the recommendations mentioned earlier, it is suggested to use a set of seed arcs when coming up with operational routes.

Depot location

Four locations were examined in the scenario analyses. These locations were not picked based on an extensive research. The goal was to expose the link between the depot location and KPIs of routes, not on determining the optimal depot location. One could try to seek an ideal location for the depot. This can be done by calculating the weighted salt demand based on distance to a potential location. An ILP model can be used for this. It is also possible for the model to look at more than one possible depot location.

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Appendix A: Freezing-point depression

The following formula can be used to calculate the freezing-point depression:

$$\Delta T_{FP} = K_{FP} \cdot \frac{n}{m_0} \cdot i = K_{FP} \cdot m \cdot i$$

ΔT_{FP} = freezing-point depression.

K_{FP} = 1,853 °C kg/mol for water. The cryoscopic constant (depends on the properties of the solvent).

n = # mol of solute in the solvent.

m_0 = mass of the solvent.

i = Van 't Hoff factor (number of ion particles per individual molecule of solute, e.g., i = 2 for NaCl[11], 3 for $BaCl_2$).

Example

A solution consists of 200.000 g of NaCl (molar mass 58,44 g/mol (Nederlandse Vereniging voor Onderwijs in de Natuurwetenschappen, 2013)) with 800kg of H_2O.

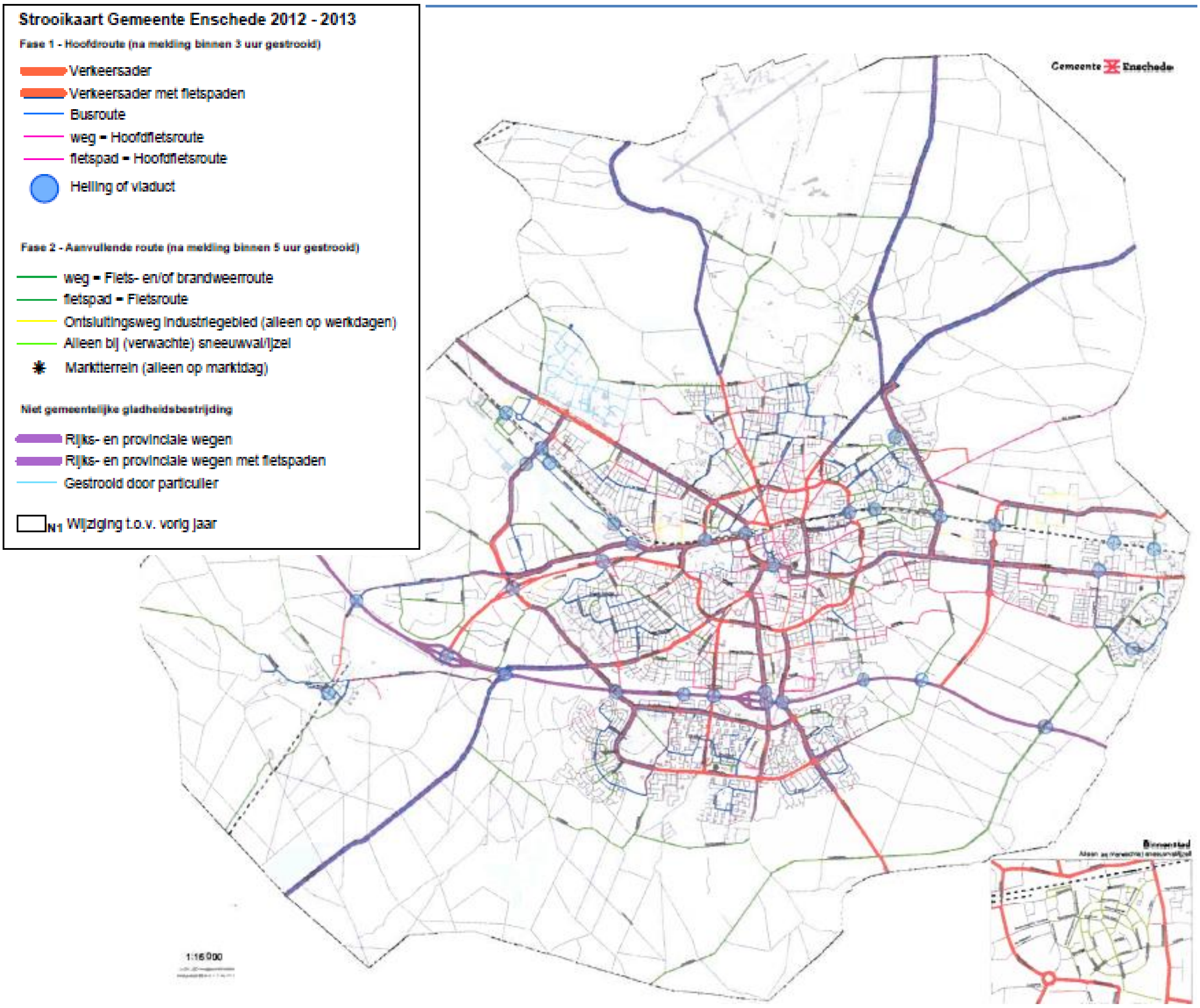
$$m = \frac{200.000}{800} = 250 \text{ g NaCl per } 1{,}0 \text{ kg } H_2O$$

$$\Delta T_{FP} = 1{,}853 \cdot \frac{250}{58{,}44} \cdot 2 = 15{,}85\ °C$$

This means that, in theory, NaCl as a thawing material is effective until -15,85 °C. However, as soon as NaCl is applied to the road surface snow starts to melt, therefore the amount of water increases resulting in a lower concentration of sodium- and chloride ions. This mitigates the effect of NaCl on the freezing-point.

[11] NaCl will turn into Na^+ and Cl^- when resolved in H_2O. This doubles the amount of particles in the water. Hence, the Van 't Hoff factor is 2.

Appendix B: Sprinkle map



Appendix C: MeteoConsult

Twente Milieu can log in onto the website of MeteoConsult in order to obtain information as depicted below. Based on this information an estimation can be made whether salting at night is necessary or not. When the expected temperature at night is higher than 5°C all employees retrieve an SMS in which states that their consignment duty is off.

Datum en tijd	Weertype	Neerslag kans (%)	Neerslag (mm/uur)	Sneeuw (cm/uur)	Temp. 1.5m (°C)	Wegdek		Brug		Dauwpunt (°C)	Rel. Luchtv. (%)	Bewolking (8-sten)	Wind richting	Wind kracht (bft)	Max. wind stoot (km/u
						Temp. (°C)	Conditie	Temp. (°C)	Conditie						
woensdag 20 november 2013															
09:00	Zonnig	0	0.0	0	0.5	0.0	Nat	-2.8	Bevriezing	-0.1	96	1/8	ZZW	2	12
10:00	Licht bewolkt	0	0.0	0	2.3	0.9	Nat	-0.5	Bevriezing	1.2	92	2/8	ZZW	2	17
11:00	Licht bewolkt	0	0.0	0	3.5	2.5	Nat	2.3	Nat	1.9	89	2/8	ZZW	2	21
12:00	Licht bewolkt	10	0.0	0	4.6	4.0	Nat	4.6	Nat	2.1	83	2/8	ZZW	2	25
13:00	Licht bewolkt	10	0.0	0	5.5	5.1	Droog	6.1	Nat	1.8	77	2/8	ZZW	3	27
14:00	Licht bewolkt	15	<0.1	0	5.7	5.5	Droog	6.5	Nat	1.6	75	2/8	ZZW	3	29
15:00	Licht bewolkt	10	<0.1	0	5.5	5.2	Droog	6.1	Nat	1.6	76	3/8	Z	3	31
16:00	Licht bewolkt	10	0.0	0	5.0	4.5	Droog	5.3	Droog	1.5	78	3/8	Z	3	33
17:00	Half bewolkt	10	<0.1	0	4.0	4.0	Droog	4.6	Droog	1.4	83	4/8	ZZO	3	32
18:00	Zwaar bewolkt	20	<0.1	0	2.9	3.8	Droog	4.1	Droog	1.3	89	6/8	ZZO	3	31
19:00	Zwaar bewolkt	25	<0.1	0	2.3	3.7	Droog	3.7	Droog	1.2	92	7/8	ZZO	3	33
20:00	Lichte regen en sneeuw	30	<0.1	0	2.6	3.6	Natte sneeuw	3.2	Natte sneeuw	1.0	90	8/8	ZZO	3	33
21:00	Lichte regen en sneeuw	40	<0.1	0	3.2	3.6	Natte sneeuw	3.0	Natte sneeuw	0.9	85	8/8	ZZO	3	34
22:00	Lichte regen en sneeuw	40	<0.1	0	3.4	3.5	Natte sneeuw	2.8	Natte sneeuw	0.7	83	8/8	ZZO	3	35
23:00	Lichte regen en sneeuw	40	<0.1	0	3.1	3.3	Natte sneeuw	2.6	Natte sneeuw	0.6	83	8/8	ZZO	3	34
donderdag 21 november 2013															
00:00	Lichte regen en sneeuw	40	<0.1	0	2.8	3.1	Natte sneeuw	2.4	Natte sneeuw	0.4	84	8/8	ZZO	3	33
01:00	Lichte regen en sneeuw	40	<0.1	0	2.5	2.9	Natte sneeuw	2.2	Natte sneeuw	0.1	85	8/8	ZO	3	31
02:00	Lichte regen en sneeuw	30	<0.1	0	2.1	2.7	Natte sneeuw	2.0	Natte sneeuw	-0.3	84	8/8	ZO	3	29