Transport logistics for a biogas plant

An approach for an optimal collection of manure from local farms by the planned biogas plant Biogas Väst Skaraborg AB

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Degree project/Independent project • 30 credits
Swedish University of Agricultural Sciences, SLU
Faculty of Natural Resources and Agricultural Sciences/Department of Economics
Agriculture Programme - Economics and Management
Degree project/SLU, Department of Economics, 1543 • ISSN 1401-4084
Uppsala 2023

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Credits:	30 credits
Level:	Second cycle, A2E
Course title:	Master thesis in Business Administration
Course code:	EX0906
Programme/education:	Agriculture Programme - Economics and Management
Course coordinating dept:	Department of Economics
Place of publication:	Uppsala
Year of publication:	2023
Copyright:	All featured images are used with permission from the copyright owner.
Title of series:	Degree project/SLU, Department of Economics
Part number:	1543
ISSN:	1401-4084

Keywords:	VRP, IRP, VRPB, IRPB, logistics, optimising, biogas

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Abstract

Vehicle routing problems (VRPs) are a prevalent concern for businesses that rely on effective logistics to collect and transport items. Biogas Väst, a company that collects liquid manure from local farms and returns residue, is facing a VRP that includes both linehaul and backhaul operations. Biogas Väst's challenges is an inventory routing problem with backhaul (IRPB).

This thesis focuses on the construction of a mathematical model based on a version of IRP given by Berg (2020) to address the goal of transporting manure from farms to the biogas plant. Backhaul operations were added to the model, inventory and transportation data was acquired from Biogas Väst to verify relevance to their specific environment. While the resulting model is a simplified version of the real-world problem, it can be used to build heuristics to determine the best routing plan.

The research method entailed examining the problem and collecting data from Biogas Väst to inform the model's development. The model was subsequently tested and analysed, demonstrating that some changes is required to make it suitable for Biogas Väst. The thesis's goal is to develop a model which can be used for determining the optimal routing plan, which strives to improve Biogas Väst's logistical operations and overall efficiency. The result for testing the model became 27,3 hours. This was scaled to fit the real case which resulted in a requirement of 3,66 vehicles which drives 13,5 hours daily.

The IRPB with linehaul and backhaul is a difficult challenge that necessitates careful consideration of several elements, including vehicle capacity, travel distance, and timing limitations. The mathematical model established in this thesis is a good beginning for approaching a practical solution for this problem, but further effort is needed to produce a practical solution that suits the specific demands of Biogas Väst.

Keywords: VRP, IRP, VRPB, IRPB, logistics, optimising, biogas

Table of contents

List of tables

List of figures

Abbreviations

VRP	Vehicle routing problem
VRPB	Vehicle routing problem with backhaul
IRP	Inventory routing problem
IRPB	Inventory routing problem with backhaul
NP-hard	Non-deterministic polynomial-time hardness

1. Introduction

In this chapter the background and motivation for the thesis are presented, as well as the aim and research questions.

1.1 Background and motivation

Sweden has established a challenging climate target to attain net-zero greenhouse gas emissions by 2045, followed by achieving negative emissions whereby emissions of greenhouse gases are less than zero (Regeringskansliet, 2022). This measure would contribute towards reducing the atmospheric concentrations of greenhouse gases. The purpose behind this objective is to fulfil Sweden's commitment due to the Paris Agreement, which aims to limit global warming to 1.5 degrees Celsius above pre-industrial levels.

To attain the desired temperature goal, the Swedish legislature has embraced 16 environmental objectives from the United Nations (Energigas, 2022a). Among these goals, biogas has been identified as having a positive impact on at least eight of them, for example limited climate change, no overfertilization and a healthy agricultural land. This is because biogas, in addition to its ability to substitute for fossil fuels, generates residue which in turn serves as a biofertilizer. If residue replaces mineral fertilizers, more carbon can be concealed in the soil, and the production of mineral fertilizers, known for its high energy demand, can be reduced. As a result, the use of biogas has the potential to contribute significantly to the reduction of greenhouse gas emissions and the achievement of Sweden's environmental goals. In 2021, the total consumption of biogas in Sweden was 4.8 TWh, with domestic production accounting for 2.3 TWh (Energigas, 2022b). The national government has set a target to increase biogas usage to 15 TWh by 2030. This goal aligns with the EU's renewable energy directive and Sweden's climate policy, which emphasize the importance of decarbonizing the energy sector.

Vara municipality shares the national vision for increased biogas production and aims to establish additional biogas facilities. The Varaslätten region presents a promising opportunity for biogas production due to its high concentration of animal producers and the resulting availability of manure as feedstock, see *Figure 1*. By converting animal waste into biogas, the region can reduce methane emissions from manure and generate renewable energy. However, the expansion of biogas production requires a comprehensive approach to address technical, economic, and social challenges. Technical barriers such as the lack of reliable gas infrastructure and difficulties in achieving high biogas yields must be overcome. Economic challenges include high capital costs, the need for government incentives, and the competition with other renewable energy sources. Moreover, social considerations such as stakeholder engagement, land-use conflicts, and environmental impacts should also be addressed. In conclusion, the promotion of biogas production in the Varaslätten region and Sweden presents a significant opportunity for renewable energy generation and CO2 reduction. Successful implementation of biogas facilities requires careful planning and stakeholder engagement to address technical, economic, and social barriers. (Vara kommun, 2013)

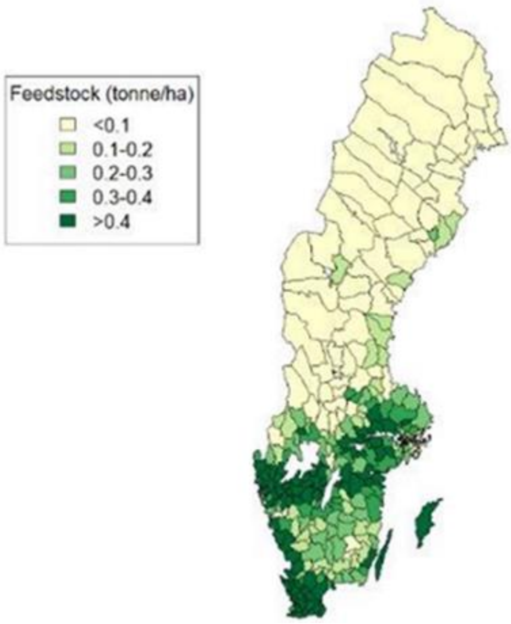

Figure 1. Density of feedstock, ton per hectare, total land area (Nordin, 2022)

The local agricultural community in Vara recognized the potential of a biogas plant and has therefore formed an economic association with the aim of constructing their own facility. The association evolved into an investor-owned firm in which the farmers have ownership. According to the firm the biogas plant will operate using manure as the main substrate, which will be supplied by over 65 farmers, providing a daily input of 1000 cubic meters. The plant will produce liquid biogas as its main product, which will be sold, while the remaining residues will be returned to the farmers to serve as biogas fertilizer. The location of the plant was selected using a "localization optimization" process, making sure that the location is close to optimal regarding the locations of the farms.

The logistics of transporting manure from the farms to the plant (backhaul) and returning the residue back to the farms (linehaul) will be a crucial challenge for Biogas Väst. An illustration of this can be seen in *Figure 2*. Given an input of 1000 cubic meters per day and an equivalent output, there will be over 30 trips between different farms and the plant daily. The farms are located at varying distances from the plant, ranging from 4 km to 44 km with an average of 22.8 km. As such, an effective logistics plan is necessary to manage the timing and location of the transportation of the manure and residue. Implementing such plan will result in significant economic benefits and environmental advantages due to a reduction in drivetime.

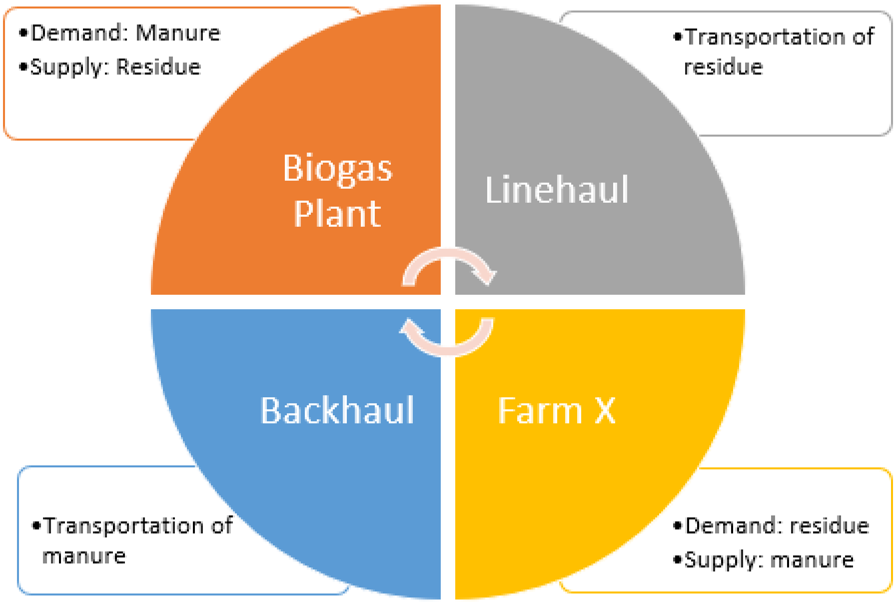

Figure 2 Illustration of transportation process.

1.2 Empirical problem

In this part, the empirical problem is stated. The subsections are divided into time periods, different types of manure, deliveries and pickup, storage capabilities and road conditions.

1.2.1 Time periods

The highest gas yield in biogas production is obtained from fresh manure (Jordbruksverket, 2022). As manure ages on the farm, the methane and CO2 levels are reduced. Both methane and CO2 are essential components in the formation of biogas (Energigas, 2017). Therefore, time is a crucial factor for transporting the manure from the farms to the biogas plant. The earlier the manure is placed in the digester, in terms of days, the greater the quantity of biogas that can be obtained per kilogram of manure. Different types of manure also have varying gas yields and qualities (Ek, 2007).

This implies that Biogas Väst aims to collect manure as early as possible, with some farms' manure given priority due to the type of animal production they have. As a result, a target has been set to limit the manure's storage time on farms to a maximum of two weeks. This leads to the division of a calendar year into 26 periods, with each period comprising of two weeks.

1.2.2 Different types of manure

The farms will provide different types of manure, with the production types being cows/cattle and pigs. Each production line produces liquid manure, solid manure or both, and there are possible of various combinations of manure types delivered by each farm. Both cows/cattle and pigs may deliver only liquid or solid manure or a combination of both.

1.2.3 Deliveries and pickups

Biogas Väst has developed a preliminary plan which specifies that the vehicle fleet will require two trucks for the conveyance of liquid manure and composted residues, with an additional truck dedicated solely to the collection of solid manure. The trucks assigned to transport liquid manure are anticipated to operate in a two-shift system, Monday through Friday, whereas the truck assigned to collect solid manure will operate on a less frequent schedule. It is predicted that there will be greater demand for the delivery of composted residues than the number of farmers supplying manure. As a result, it is expected that the trucks will need to deliver composted residues to some farms while collecting manure from others.

1.2.4 Storage capacity

To ensure proper management of agricultural waste, farms that supply manure and accept returns of residues are required to have at least two containment structures. The well designated for manure collection must be of a minimum size of 500 cubic meters. Since residue is used as fertilizer during the spring and fall and Biogas Väst does not have an excess of storage for the residue. Storage is needed at the farms for the residue in between the fertilization periods.

Given that the size of the containment structures used for manure collection will vary between farms, and the herds of livestock maintained by these farms will also vary, it is expected that the containment structures will reach their maximum capacity at different times.

1.2.5 Road conditions

One challenge that may occur is the difference in road quality throughout the year. Some roads may become unusable due to severe snowfall, especially during the winter season. As a result, a crucial topic is whether it would be more effective to deprioritize some of the more remote farms during periods of increased snow risk, and instead shift resources to better-connected farms during these times. Once favourable road conditions have been restored, compensatory measures can be implemented to meet the demands of the "paused" farmers.

Similar circumstances may occur when specific highways have heavy vehicle limitations, which are most likely to occur during the spring season. In such instances, affected farms will most likely be managed similarly to the winter scenario described above. Similarly with the winter scenario, once the road limits are removed, compensatory measures can be introduced to fulfil the requirements of any farms that may have been deprioritized during the limited period.

1.3 Theoretical problem

The vehicle routing problem (VRP) is commonly used in transportation optimization. The problem often includes products from one depot which is to be transported to many different customers by a vehicle, while minimising costs with regards to number of vehicles used, travelling measured in time or distance (Baker & Ayechew, 2006). The classical example aims to construct routes of a homogenous vehicle fleet which is to serve a set of customers. Different variants of the VRP include VRP’s with backhaul, time windows, pickup and delivery among others (Toth & Vigo, 2001). Furthermore, there are combinations of these variants to fit the selected case.

The literature of transport optimisation includes variants of the VRP such as the inventory routing problem IRP which includes the inventory aspect (Bell et al, 1983, Fokkema et al, 2020, Berg, 2020). VRP's has also been used in analysing municipal waste collection which is to be transported to for example biogas plants (Höke, M.C. & Yalcinkaya, S., 2021). This study could be seen as an extension of (Berg, 2020) which analysed manure transports from farms to the biogas plant as an IRP. This study will include, the backhauling aspect, transforming the IRP into an IRPB using Biogas Väst as a real-life case scenario. IRPB is a variation of the VRP which has not been analysed in a large range in the literature. (Arab et al, 2020) made a multiperiod and multiproduct IRPB model which was solved by meta heuristics methods. (Arab et al, 2020) has also in another article included the risk factor within a IRPB which considers the total cost of the operation as well as the transportation risks. Since the literature of IRPB's is limited, this study aims to contribute as a case study of a transportation problem which considers inventory management as well as large quantities of product. This study can also be used as a template along with meta heuristics to analyse larger quantities of data for similar types of transportation problems.

1.4 Aim and research questions

The aim of this thesis is to develop an optimization model that can be used by Biogas Väst in their transport planning, as well as expanding the literature of the IRPB as a practical case study. The model will aim to identify the most optimal route for delivering digestate to farms, while simultaneously identifying the optimal solution for delivering manure back to the biogas plant. The primary research question is as follows:

- Given a set of locations for linehaul and backhaul customers, what is the optimal route, measured in time?

The research question will be supported by the following sub-questions:

- With a given vehicle capacity, how many trucks are required to cover the supply of manure and demand for digestate?
- What is the optimal collection and delivery schedule for manure and residue from and to specific farms?

The model will consider various factors such as transportation costs, distances, time constraints and inventory capacities. The results of this study will provide Biogas Väst with insights that can help them optimize their transport planning and reduce their environmental impact. This research will contribute as a case study to the field of optimization in transportation and logistics which can be used to further elaborate on problems facing similar scenarios, the study may also be used to develop meta heuristics to get close to an optimal solution for the real-case problem.

1.5 Structure of the study

In this part, the structure of the study will be presented, *see Figure 3*. In the first chapter, a background to the study and problem formulations linked to the subject of the study are obtained. The purpose of the study and research questions are also found here. Furthermore, in chapter two there is a literature review where the various theories are presented, these are vehicle routing problem, vehicle routing problem with backhaul, inventory routing problem, and finally inventory routing problem with backhaul. Chapter three explains the study's method. Here you will find how the optimization model is structured, quality assurance, ethical aspects and more. In the fourth chapter the model will be tested, followed by discussing and analysing the model. In the final chapter you will find a conclusion as well as further research.

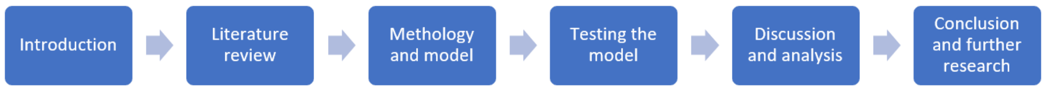

Figure 3 Structure of the study

2. Literature Review

In this chapter, the origins of the IRPB are presented as well as the different variations of the VRP. Transport logistics is an important component of modern economies because it allows for the efficient movement of goods and people over great distances. It includes the planning, management, and coordination of diverse modes of transportation and infrastructure. Transport logistics is critical in fueling economic growth and sustaining global trade, from transporting raw materials to distributing finished goods. The sector is constantly evolving to suit the demands of a linked world, thanks to technological breakthroughs and an emphasis on sustainability.

Lots of studies have already been made on transport logistics, however not specific on biogas transportation with vehicles. Other areas where the subject have been investigated is for example:

- Brar and Saini's (2011) study explore the literature on Milk Run Logistics and provides an outline of how it is used in industrial organisations, particularly in the automobile sector. Milk run logistics benefit the supply chain by lowering transportation costs, travel time, and fuel usage. The research also looks at how direct shipments affect traffic and the environment. Implementing milk run logistics in congested traffic situations gives suppliers more control over the procurement process while also reducing the number of vehicles on the road, easing traffic conditions. The research also emphasises the favourable effect of milk run logistics on lowering CO_2 emissions, which benefits environmental policy.

- Fiorino et al (2015) investigates the multimodal transportation and storage of soybeans and maize, with an emphasis on the journey from farms to ports. Resources, locations, and interferences all have a substantial impact on this complex system, considering elements such as harvest seasonality, climatic fluctuations, road conditions, truck availability, and warehouse possibilities. A simulation model was created to evaluate and identify optimal solutions under future circumstances. The model integrates train, barge, and ship logistics, and a localization analysis revealed the best logistical warehouse locations. The model delivers precise and valuable insights into system performance by modelling the entire chain, guiding future investments in the process.

- The Forestry Routing Optimisation Model (FRoM) is introduced in this study as a modified version of the Vehicle Routing Problem (VRP) optimised for wood logistics (Monti et al, 2020). FRoM is a single integer mixed linear programming model that mixes simple and numerous truck displacements towards the stands. It considers issues like crane and truck scheduling, fleet reduction, minimising overtime, eliminating half-load transportation, and optimising distance travelled within a defined planning horizon.

2.1 The vehicle routing problem (VRP)

The vehicle routing problem (VRP) is a well-studied and very important combinatorial optimization problem where the goal is to find the optimal route for a set of vehicles with a certain number of customers (Toth and Vigo, 2002). The problem was first introduced over 60 years ago and since then has had hundreds of new algorithms and models attached to it to find the optimal solution for various VRP problems. The great interest in VRP is due to its complexity and the practical benefit that can be generated. The research of VRP has led to the existence of many different variants that are intended for different situations, such as:

- The inventory routing problem (IRP): inventory management is included (Bell et al. 1983).
- The VRP with backhaul: the routing problem includes both deliveries and pick-up (Koç and Laporte 2018).
- The VRP with time windows: a routing problem where customers need the product in a certain timeframe (Koç and Laporte 2018).
- VRP’s with a heterogeneous vehicle fleet: more than one type of vehicle, for instance with different loading capacities (Taillard, E. 1999).

Since there is no known algorithm that can solve VRP optimally in polynomial time due to its NP-Hard nature (Kallehauge et al., 2005), it is virtually impossible to solve it precisely for bigger instances of the problem using current technology. This implies that heuristics are frequently used to identify workable methods.

2.2 The inventory routing problem (IRP)

The Inventory Routing Problem (IRP) was first introduced by Bell et al. (1983) and has undergone significant development since then. The IRP, according to Campbell, Clarke, and Savelsbergh (2002), involves the distribution of a single product, where trucks depart from a single facility and deliver to a predetermined set of customers over a specific time horizon. Each customer has their own inventory with a predetermined maximum level, and the objective of IRP is to ensure that customers are provided with the product to avoid stockouts. The problem can be modelled with three main parameters: delivery timing, delivery quantity, and route selection. Delivery timing refers to determining when each customer should receive the product, while delivery quantity involves determining how much product to deliver to each customer. Route selection involves identifying the most efficient route for the delivery trucks to take. Compared to the Vehicle Routing Problem (VRP), which is based on customer orders, IRP is based on customer usage. By considering the customers' inventory levels, IRP can improve the efficiency of the distribution system, reduce delivery costs, and enhance customer satisfaction. As a result, IRP has become an important research area in logistics and supply chain management.

The Inventory Routing Problem (IRP) has been the focus of a significant amount of research, resulting in numerous proposed solutions. Coelho et. al (2014) conducted a comprehensive literature review in their paper "Thirty Years of Inventory Routing," in which they presented a simple yet precise algorithm for solving the IRP. This algorithm was initially developed by Archetti et al. (2007) and has since been refined by Adulyasak et al. (2013) and Coelho and Laporte (2013). The algorithm can address complex scenarios where multiple customers' demands are met by multiple vehicles that transport a product from one depot. The proposed algorithm's effectiveness is attributed to its ability to account for various factors such as delivery schedules, transportation costs, and vehicle capacities, while still optimizing inventory and routing decisions.

2.3 The Vehicle routing problem with backhaul (VRPB)

Vehicle Routing Problem with Backhauls (VRPB) is an extension of the classical VRP in which a fleet of vehicles must service a group of customers from a central depot (Casco et al. 1988). However, in VRPB, the customers are divided into two categories: linehaul-customers and backhaul-customers. Linehaul-customers require delivery of a product from the depot to a designated location, while backhaul-customers require pickup of their product from their designated location.

The objective of VRPB is to combine linehaul and backhaul operations in a way that minimizes the total distance travelled by the fleet of vehicles.

To achieve this objective, several constraints must be satisfied. First, each customer must be visited by exactly one vehicle. Second, the capacity of each vehicle must not be exceeded. Third, the vehicles must start and end their routes at the depot. Fourth, backhaul-customers can only be visited after all linehaul-customers have been served. Finally, the number of vehicles in the fleet is assumed to be fixed, and all vehicles have the same capacity.

Koç and Laporte (2018) conducted a literature review on the development of VRPB variants from the 1980s to 2017. The reviewed studies have contributed to the identification and investigation of several critical extensions to the classical VRPB, including multiple trips by vehicles, time windows, multiple depots, and heterogeneous fleet. However, the authors suggest that there are still significant opportunities for further research in exploring more specific and complex VRPB variants that are tailored to different real-world applications. Overall, the literature review highlights the ongoing efforts to address the challenges and opportunities in the field of VRPB and paves the way for further research to advance the development of practical and efficient VRPB solutions.

2.4 The inventory routing problem with backhaul (IRPB)

IRPB is a sort of distribution problem that combines aspects from many theories to improve the efficiency and cost-effectiveness of a distribution operation. IRPB, like VRPB, includes classifying consumers into linehaul and backhaul categories. The goal of IRPB is to provide a routing and pickup strategy that can be used to both types of consumers while considering various operational restrictions such as vehicle capacity, distance, and the customer's product usage. (Arab et al, 2020). *Figure 4* illustrates the development of the VRP which turns into an IRPB.

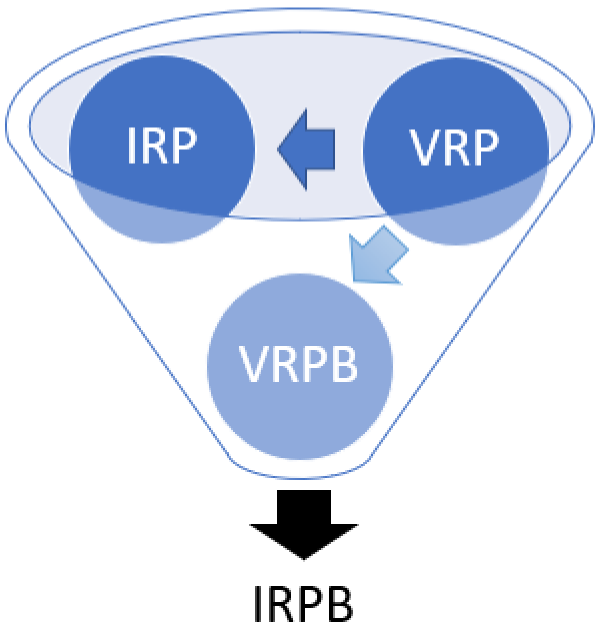

Figure 4 Model development from VRP into IRPB

3. Methodology and model

In this section the methodology will be listed as well as a model description and how the model was developed.

3.1 Methodology

In social studies there are two main methods of research: quantitative and qualitative (Bryman & Bell, 2011). Quantitative studies are based on numeric data and statistical analysis to test hypotheses and generalize findings for larger populations. This method of research typically includes a structured data collection process such as experiments or surveys and requires large sample sizes to achieve statistical validity. The research is independent of the researcher and the data is by result used to measure reality in an objective way (Williams, 2007). Through analysing the collected data through an objective lens, the quantitative research creates meaning.

Qualitative studies are based on non-numeric data such as interviews, focus groups or observations to examine complex phenomena in depth (Bryman & Bell, 2011). These types of studies aim to understand the social context or the meaning from the perspective of the participants rather than measuring large sets of numerical data (Bryman & Bell, 2011, Williams, 2007).

Both methods have their strengths and weaknesses, and it depends on the phenomena or the nature of the study to decide which is suited best (Bryman & Bell, 2011). In general, qualitative studies are suited for exploring complex social phenomena and receiving detailed descriptions. While quantitative method is more suited when answering questions which require generalization and measurements. The approach in this study naturally falls within the quantitative method since the results comes from large sets of data which are analysed through a mathematical model.

3.2 Model description and assumptions

In this chapter, the model is described as well as made assumptions.

Sets

Vertices are defined as the locations, such as the biogas plant as well as the farms. To simplify the problem, the manure and residue stores has been assumed to be located the same place and are reachable all year round.

There are 65 farms which are to deliver manure to the biogas plant, although this number is likely to be changed in the future once Biogas Väst is up and running. There will be additional farms which will not produce any manure for the biogas plant but demand residue. Since the IRPB is NP-hard only a small sample is used in testing the model. NP-hard problems are characterized as having many possible optimal solutions which are hard to solve (Kallehauge et al., 2005). The computer would likely run out of memory before any optimal solution would be found. By scaling down the problem by 100 the data was kept proportionate while also being able to solve the model in a short amount of time. To keep the farms anonymous in this report and not publish any sensitive information it was decided to instead make up imaginary data representing daily production and distances close to the real-case scenario.

Four farms were selected based on the following criteria to ensure an accurate representation of the real-case problem:

- Production Diversity: The farms were chosen to exhibit a diverse range of pig and cow manure production. This variation allows the model to capture the different scenarios associated with transporting manure from farms with varying production types.

- Distance: A variety of distances were considered when selecting the farms. This includes farms located nearby, farms situated far away, and farms located at intermediate distances. By incorporating different distances, the model can account for the logistical complexities that arise from transporting products across varying travel lengths.

- Production Quantity: The chosen farms represent a range of production quantities. This includes farms with large, medium, small, and no manure production. By considering farms with different production scales, the model can accurately capture the transportation dynamics associated with farms of varying sizes and levels of manure output.

- Residue Demand: Some farms exclusively receive deliveries of residue and, therefore, do not produce any manure for the biogas plant. The same goes the other way, some farms produce manure for the biogas plant but does not demand any residue. This criterion ensures that the model considers the diverse demand related to product management and transportation.

By considering these criteria during testing, the model aims to with four farms represent the real case and their transportation requirements, thereby improving the accuracy of its predictions and suitability for the real-case scenario. The following farms were chosen:

Table 1 Farms selected for testing the model

Farm nr	Manure production per period in m^3 (residue demand period 4)	Distance in km (drivetime in hours*)	Inventory capacity in m^3 for manure and (residue) respectively
1	80 (280)	5 (0.166)	500 (1820)
2	20 (0)	10 (0.333)	500 (720)
3	0 (160)	15 (0.5)	500 (1040)
4	40 (92)	20 (0.666)	500 (1040)

Arcs are the roads the vehicles used to transport residue and manure between farms and the biogas plant. *The drivetime has been calculated with the average speed of 30 km/hour which has been obtained from Biogas Väst. It is assumed in this model that the arcs will be available all year round, while some roads will likely not be available in the real case due to weather conditions etc.

Routes are the routes which one vehicle takes to transport residue and manure, to be able to meet the quantities transported in this model there are six routes.

The ***time period set*** is decided to match the number of periods of a year. One period is set to two weeks. There are four periods or two months included in the testing of the model. The reasoning for this is that the biogas plant wants the manure while it has not been laying at the farm more than two weeks. By setting each period to two weeks this requirement can easily be implemented.

Parameters

1. C_{ij}represent the *cost of transporting* goods along the arc, this is measured in hours. The drivetime does not include loading and unloading of vehicle.

2. g_i represent the *manure inventory holding capacity* of each vertex. According to the legal regulations outlined by Jordbruksverket (2019), farms with more than 100 animals are restricted to storing manure for a maximum of eight months for cows and ten months for pigs. For simplicity, and in the absence of additional data on inventory capacity, this model assumes that all farms have adequate storage capacity for the manure they annually produce. Note that the amount of manure produced is scaled down by 100 in testing the model. Biogas Väst is planning on having 3000 m^3 of storage capacity.

3. q represent the *vehicle capacity* which is set at a level of 35 m^3 for all vehicles, as agreed upon during the meeting with Biogas Väst.

4. l_i and l_i' represent the *initial inventory level* for manure and residue of both the farms and the plant, this is assumed to be zero to align with the starting period of the plant.

5. d_i^t represent the annual *demand for manure* by Biogas Väst. This is 365,000 m^3, which has been scaled down by 100 in testing the model. The demand for each period was calculated by dividing the annual production by 26.

6. $d_i'^t$ represent the annual *demand for residue* which is matched to the annual production of manure on each farm minus 5% to account for the weight loss during the processing stages in the plant. Since all farms does not wish to receive their share of residue, the numbers have been adjusted at random to cover some whom demand more residue than which is delivered and some farms who demand less. Since farms only demand residue during the fertilizing periods the sum of all production is demanded in period four.

7. r_i^t represent the quantity of *manure produced* by each farm in each period, this is calculated by dividing the sum of all farms annual production by 365 and multiplying by 14. Then it was distributed into four farms representing small, medium and no producers. The values were also scaled down by 100 in testing the model.

8. $r_i'^t$ represent the ***residue production*** by the biogas factory, this is measured as the total input of manure multiplied by 95%. There is a loss in mass of about 5% during the process of making biogas. This value is also downscaled.

Variables

In this model the following variables are used:

1. I_i^t and $I_i'^t$ represent the inventory level of each vertex at the end of each period.
2. P_i^{kt} and $P_i'^{kt}$ represent the quantity of manure and residue transported between each vertex.
3. Y_i^{kt} represent the frequency with which each farm is visited during each period.
4. X_{ij}^{kt} and X_{i0}^{kt} represent the selection of optimal routes to minimize the distance travelled.
5. Q_i^{kt} and Z_i^{kt} represent whether a vehicle linehauls or backhauls at a farm.

3.2.1 Limitations and assumptions

The "Limitations and Assumptions" section of this thesis outlines the constraints and underlying assumptions that might affect the validity, reliability, and generalizability of the research findings.

One significant limitation is that no actual farms will be used in the study due to regulations made during the meeting with Biogas West. The location of the farms and their supply of manure are classified as confidential. Instead, four simulated farms will be used. While the simulated farms have been designed to mimic real-world conditions as closely as possible, there may be some differences between the simulated and actual farms that could affect the study's results. Another significant limitation is that many assumptions will be made in the optimization model. Solid manure is excluded in this model since that will be taken care of by another vehicle. Farms with solid manure can however demand the residue which is transported with the same vehicles the liquid manure is transported by. Another assumption is that certain road condition is not taken into consideration since they would be close to impossible to account for in the model. These assumptions may not fully capture the complexities of real-world conditions and could potentially affect the accuracy of the results.

Additionally, the testing of the model will not include as many farms as there are in the real case. Instead, four farms will be used to ensure that the testing model works. Afterwards, the client can use this model to input the actual farms. While this approach is practical given the constraints of the study, it may affect the generalizability of the results to the larger population of farms. Due to time constraints, the sample size for this study will be limited. While efforts have been made to ensure that the sample is representative of the population, the small sample size may affect the generalizability of the results.

Overall, it is important to keep these limitations and assumptions in mind when interpreting the results of this study. By acknowledging these potential constraints and biases, readers can better understand the strengths and weaknesses of the research findings.

3.3 Model development

The IRP model proposed in Coelho, Cordeau, and Laporte (2014) is a well-known exact algorithm for solving delivery problems from a single location to several destinations. The IRP model is intended to optimise both inventory management and routing decisions at the same time by calculating the best delivery routes for a fleet of vehicles while respecting inventory levels at each destination. Our problem in question, however, is slightly different in that it entails deliveries and pickups from several places to a single destination.

To transform the IRP model into an IRPB, three key modifications were introduced. The first change involved adding new parameters and variables that specifically address the backhauling of manure. These included factors such as inventory holding capacity, production, demand, initial inventory level, inventory level at the end of each period, the amount backhauled from each farm, and whether a vehicle has backhauled or linehauled from a farm in each period.

The second change was to modify and add constraints to the model to account for backhauling and inventory levels of manure. Inventory constraints (2) $I_0^t = I_0^{t-1} + r^t - \sum_{k \in K} \sum_{i \in V} q_i^{kt}$ and (4) $I_i^t = I_i^{t-1} + \sum_{k \in K} q_i^{kt} - d_i^t$ proposed by Coelho et al. (2014) were replicated. These were transformed from one-to-many into many-to-one to suit the backhauling requirements. Constraint (3) $I_0^t \geq 0$ was no longer necessary in this model since it was already covered by constraint (5) $I_i^t \geq 0$, which was kept unchanged. Constraint (6) $I_i^t \leq C_i$ was also retained without modifications. Constraint (7) $\sum_{k \in K} q_i^{kt} \leq C_i - I_i^{t-1}$ was slightly modified to ensure that the vehicle could not pick up more manure than what was available at the farm. Constraint (8) $q_i^{kt} \geq C_i Y_i^{kt} - I_i^{t-1}$ was not included in the revised model since it was not applicable. The other constraints were kept the same. Finally, constraints (5), (6), (7), (9) $q_i^{kt} \leq C_i \, y_i^{kt}$, and (10) $\sum_{i \in V'} q_i^{kt} \leq Q_k \, y_0^{kt}$ were replicated and modified to incorporate backhauling into the model.

The third and final modification to the IRP model involved adding constraints that were specific to our problem. Biogas Väst wanted to avoid contamination risk, so a constraint that restricts each vehicle to backhaul from only one farm each route was included. Additionally, Biogas Väst wants to collect the manure within two weeks of its production to minimize methane losses in the manure. Since each period in our model represents two weeks, a constraint was implemented to ensure that all manure produced is backhauled each period. By incorporating these additional constraints, the revised IRP model is now better suited to the specific backhaul and linehaul problem which aligns with Biogas Väst's objectives.

Sets:

$V = \{0, \dots, n\}$ $\quad$ $vertex\ set\ 0 = depot,\ V' = farms$
$A = \{(i,j):\ i,j\ \in\ V,\ i < j\}$ $\quad$ $arcset$
$K = \{1, \dots, k\}$ $\quad$ $routeset$
$T\ =\ \{1, \dots, t\}$ $\quad$ $time\ period\ set$

Parameters:

$cij =\ drivetime\ between\ vertex\ i\ to\ vertex\ j\ (arc(i,j)\quad (i,j)\ \in\ A$
$q\ =\ vehicle\ capacity$
$g_i =\ manure\ inventory\ holding\ capacity\ at\ vertex\ i \quad i\ \in\ V$
$l_i\ =\ initial\ manure\ inventory\ level\ at\ vertex\ i \quad i\ \in\ V$
$r_i^t\ =\ manure\ produced\ at\ farm\ i\ \ in\ period\ t \quad i\ \in\ V',\ t\ \in\ T$
$d_i^t\ =\ manure\ demanded\ at\ vertex\ i\ \ in\ period\ t \quad i\ \in\ V,\ t\ \in\ T$
$g'{}_i^t\ =\ residue\ inventory\ holding\ capacity\ at\ vertex\ i \quad i\ \in\ V$
$l'{}_i\ =\ initial\ residue\ inventory\ level\ at\ vertex\ i \quad i\ \in\ V$
$r'{}_i^t\ =\ residue\ produced\ at\ vertex\ i\ \ in\ period\ t \quad i\ \in\ V'\ t\ \in\ T$
$d'{}_i^t\ =\ residue\ demanded\ at\ farm\ i\ \ in\ period\ t \quad i\ \in\ V',\ t\ \in\ T$

Variables:

$I_i^t = manure\ inventory\ level\ at\ vertex\ i\ at\ period\ t \quad i\ \in\ V,\ t \in T$
$I'{}_i^t = residue\ inventory\ level\ at\ vertex\ i\ at\ period\ t \quad i\ \in\ V,\ t\ \in\ T$
$P'{}_i^{kt}\ =\ amount\ linehauled\ to\ farm\ i\ on\ route\ k \quad i\ \in\ V',\ k\ \in\ K,\ t\ \in\ T$
$P_i^{kt}\ =\ amount\ backhauled\ to\ farm\ i\ on\ route\ k \quad i\ \in\ V',\ k\ \in\ K,\ t\ \in\ T$
$X_{i0}^{kt}\ =\ \{0{,}1{,}2\} =\ how\ many\ times\ a\ vehicle \quad i\ \in\ V',\ k\ \in\ K,\ t\ \in\ T$
$travels\ the\ arc\ on\ route\ k\ betweenfarm\ i\ and\ the\ depot\ on\ period\ t$
$X_{ij}^{kt}\ =\ \{0{,}1\}\ =\ how\ many\ times\ a\ vehicle \quad i\ \in\ V',\ k\ \in\ K,\ t\ \in\ T$
$travels\ the\ arc\ \ on\ route\ k\ betweenfarm\ i\ and\ farm\ j\ on\ period\ t$
$Z_i^{kt}\ \{0{,}1\} = 1\ if\ a\ vehicle\ backhauls\ from\ farm\ i \quad i\ \in\ V',\ k\ \in\ K,\ t\ \in\ T$
0 otherwise
$Q_i^{kt}\ \{0{,}1\} = 1\ if\ a\ vehicle\ linehauls\ to\ farm\ i \quad i\ \in\ V',\ k\ \in\ K,\ t\ \in\ T$
$0\ otherwise$
$Y_i^{kt}\ \{0{,}1\} =\ 1\ if\ vehicle\ k\ visists\ vertex\ i\ otherwise\ 0\ i\ \in\ V,\ k\ \in\ K,\ t\ \in\ T$

Formulation:

$$(1)\ Min\ \sum_{(i,j)\in A}\sum_{k\in K}\sum_{t\in T} c_{ij}\, X_{ij}^{kt}\ +\ \sum_{i\in V'}\sum_{k\in K}\sum_{t\in T} Z_i^{kt}\cdot 0.25\ +\ \sum_{i\in V'}\sum_{k\in K}\sum_{t\in T} Q_i^{kt}\ \cdot\ 0.25$$

Subject to:

Inventory constraints:

(2) $I_0^t = I_0^{t-1} + \sum_{i \in V'} \quad + \sum_{k \in K} P_i^{kt} - d_0^t \qquad \forall\, t \in T$

(3) $I_i^t = I_i^{t-1} + r_i^t - \sum_{k \in K} P_i^{kt} \qquad \forall\, i \in V',\, t \in T$

(4) $I_0'^t = I_0'^{t-1} + r_i'^t - P_i'^{kt} \qquad \forall\, t \in T$

(5) $I_i'^t = I_i'^{t-1} + P_i'^{kt} - d_i'^t \qquad \forall\, i \in V',\, t \in T$

(6) $I_i^0 = I_i \qquad \forall\, i \in V$

(7) $I_i'^0 = I_i' \qquad \forall\, i \in V$

(8) $I_i^t \leq g_i \qquad \forall\, i \in V,\, t \in T$

(9) $I_i'^t \leq g_i' \qquad \forall\, i \in V,\, t \in T$

Vehicle constraints:

(10) $\sum_{k \in K} P_i^{kt} \leq I_i^{t-1} + r_i^t \qquad \forall\, i \in V',\, t \in T$

(11) $\sum_{k \in K} P_i'^{kt} \leq g_i' - I_i'^{t-1} \qquad \forall\, i \in V',\, t \in T$

(12) $P_i^{kt} \leq g_i Y_i^{kt} \qquad \forall\, i \in V',\, k \in K,\, t \in T$

(13) $P_i'^{kt} \leq g_i' Y_i^{kt} \qquad \forall\, i \in V',\, k \in K,\, t \in T$

(14) $\sum_{i \in V' k \in K} P_i^{kt} = \sum_{i \in V'} r_i^t \qquad \forall\, t \in T$

(15) $P_i^{kt} \leq qZ_i^{kt} \qquad \forall\, i \in V',\, k \in K,\, t \in T$

(16) $P'^{\,kt}_{\,i} \leq qQ_i^{kt} \qquad \forall\, i \in V',\, k \in K,\, t \in T$

(17) $\sum_{i \in V'} Z_i^{kt} \leq 1 \qquad \forall\, k \in K,\, t \in T$

(18) $\sum_{i \in V'} P_i^{kt} \leq qY_0^{kt} \qquad \forall\, k \in K,\, t \in T$

(19) $\sum_{i \in V'} P_i'^{kt} \leq qY_0^{kt} \qquad \forall\, k \in K,\, t \in T$

(20) $\sum_{j \in V,\, i<j} X_{ij}^{kt} + \sum_{j \in V, i>j} X_{ij}^{kt} = 2Y_i^{kt} \qquad \forall\, i \in V,\, k \in K,\, t \in T$

(21) $\sum_{i\in\rho}\sum_{j\in\rho,\, i>j} x_{ij}^{kt} \;\le\; \sum_{i\in\rho} y_i^{kt} \;-\; y_m^{kt}$

$$\rho \subseteq V',\ k \in K,\ t \in T,\ m \in \rho$$

Binary and integer constraints:

(22) $I_i^t \ge 0$ $\forall\, i \in V,\ t \in T$

(23) $I_i'^t \ge 0$ $\forall\, i \in V,\ t \in T$

(24) $P_i^{kt} \ge 0$ $\forall\, i \in V',\ k \in K,\ t \in T$

(25) $P_i'^{kt} \ge 0$ $\forall\, i \in V',\ k \in K,\ t \in T$

(26) $X_{i0}^{kt} \in \{0,1,2\}$ $\forall\, i \in V',\ k \in K,\ t \in T$

(27) $X_{ij}^{kt} \in \{0,1\}$ $\forall\, (i,j) \in V',\ k \in K,\ t \in T$

(28) $Y_i^{kt} \in \{0,1\}$ $\forall\, i \in V,\ k \in K,\ t \in T$

(29) $Z_i^{kt} \in \{0,1\}$ $\forall\, i \in V',\ k \in K,\ t \in T$

(30) $Q_i^{kt} \in \{0,1\}$ $\forall\, i \in V',\ k \in K,\ t \in T$

Description:

The objective function (1) minimizes the total time cost, which include time spent in transit as well as the time required for loading and unloading the vehicles. Constraints (2)-(3) defines inventory levels of manure at the depot and farms respectively while constraints (4)-(5) define the inventory level of residue at each vertex. Constraints (6)-(7) specify the initial inventory level depending on product type, and (8)-(9) ensures that the inventory level does not exceed the inventory capacity at each farm and depot, again depending on the product. To maintain consistency of available stock, constraints (10)-(11) restrict the vehicles from transporting more products than what is available in stock during each period, while constraints (12)-(13) ensures that the vehicles need to visit a farm to linehaul or backhaul. Constraint (14) ensures that all manure that is produced each period is backhauled by a vehicle, while constraints (15)-(16) impose limitations on each vehicle’s carrying capacity. Constraint (17) restricts each vehicle to only backhaul from one farm each period. Constraints (18)-(19) ensure that the vehicle visits the depot that period. Constraint (20) ensures that if a vehicle visits a farm, it also leaves it (opposite for the depot). Constraint (21) eliminates subtours. Constraints (22)-(30) ensures non-negative, integer and/or binary.

3.4 Quality assurance

It is crucial for the researcher to show the calibre of their work in research and studies. As a result, several requirements must be met for the study to be understood correctly and with reliability (Bryman & Bell, 2011). Depending on whether the study is qualitative or quantitative in character, these requirements often change. In a quantitative essay, reliability and validity play a major role in achieving high quality (ibid).

Validity is an important factor to evaluate in research since it determines whether the indicators employed accurately measure the target idea. Face validity, according to Bryman & Bell, (2011), is a minimal criterion that involves determining if the measures effectively capture the concept. Typically, this is assessed by consulting specialists in the field. Multiple experienced supervisors reviewed the development of the AMPL-file and its solutions in this study, assuring face validity by connecting the measures with the idea of attention.

Bryman & Bell, (2011) define reliability as the consistency of a metric. It is made up of three components: stability, internal reliability, and inter-rater stability. Stability is defined as consistent outcomes throughout multiple testing times, which is frequently examined using a "test-retest" approach. The findings of the test-retests were consistent, showing good dependability. The studied phenomenon remains steady over time. Retests align with original test results from the optimisation process in the absence of such revisions.

This study also acknowledges objectivism's ontological position, which maintains an objective world independent of social actors. Taking a positivistic epistemological position, the study examines the topic using empirical evidence and theory (Creswell, 2009). The researcher's influence on data is thought to be small, whereas a systematic technique assures replicability for comparable results. Overall, these perspectives strengthen the study's credibility and add to our understanding of biogas generation. The purpose of these terms is to ensure that the paper's results are as accurate as possible, and that the data is replicable (Mohajan, 2017). In this study the files used for testing the model is available, making sure that the results can be replicated, *see Appendix A.*

3.5 Ethical considerations

It is critical to examine ethical issues in all sorts of research (Bryman & Bell, 2011). Most universities and colleges have ethical norms in place to protect researchers and research participants from undesirable effects and possibly legal consequences. The major goal of ethical considerations is to avoid harming participants, which can happen if they are not properly informed about their involvement in the study or what their agreement involves.

The integrity and reliability of study findings are greatly influenced by research ethics. Ethical guidelines give a foundation for researchers to undertake ethical and responsible research (ibid). These rules are intended to protect study participants' dignity, autonomy, and well-being while also ensuring that the research contributes to the public good.

Informed consent is a crucial ethical criterion in research (ibid). To give informed consent, participants must be given comprehensive and accurate information about the study's goal, methods, potential dangers, and benefits, as well as their right to withdraw from the study at any time. Participants must also be able to comprehend this information and freely consent to participate without compulsion or undue influence. Failing to get informed permission can result in major ethical violations and damage the research's validity.

In considering the present study and the company's wishes, it has been decided that no actual farms will be included. This judgement is predicated on the fact that the farms are unaware of the study, making it impossible to acquire informed permission from them. As a result, the study will centre on a simulated farm setting, allowing researchers to investigate research topics and hypotheses while following to ethical rules and principles of responsible research conduct.

Finally, ethical issues are an important part of every study project. Researchers must guarantee that their work follows ethical rules and principles, as this not only safeguards participants but also contributes to the research's legitimacy and validity. Researchers can maximise the advantages of their work while avoiding potential harm to participants, society, and the environment by conducting research in an ethical and socially responsible manner.

4. Testing the model and results

For testing and solving the model, AMPL (a mathematical programming language), a modelling program used to describe and solve mathematical problems was used. CPLEX version 22.1.1.0 was used as the solver. Appendix A shows the AMPL-files for the model. The model was solvable, and a solution was found. In *Figure 5* and *Figure 6* on the next page an illustrated solution of the results can be found. *Figure 5* shows which routes each vehicle takes and the amount transported between vertexes. A vehicle leaves the depot on a route (R1-6) to either linehaul or backhaul. If the vehicle is on a linehaul, all deliveries must be made before the vehicle can backhaul. The arrows represent the route and how much is carried by the vehicle. On a linehaul trip to farms there is only residue in the load and to the plant there is only manure. The total cost became 27.3 hours.

Figure 6 illustrates the residue inventory levels after each period at all vertexes. Period 4 represent the fertilization period where farms spread the residue on the field, thus there are no residue left in storage. Manure is also not visible in the figure since the biogas plant demand all manure produced each period, meaning that no manure is left in the storage.

Due to the complexity of computing the subtour constraint (21) in AMPL and considering that only a small fraction of the farms was included in testing the model, it was decided not to include this constraint in the initial solution. Instead, during the testing phase, specific constraints to eliminate any potential subtours was incorporated as needed. The details of this approach are provided in *Appendix A*, where it can be observed that no subtour constraints were necessary in testing the model.

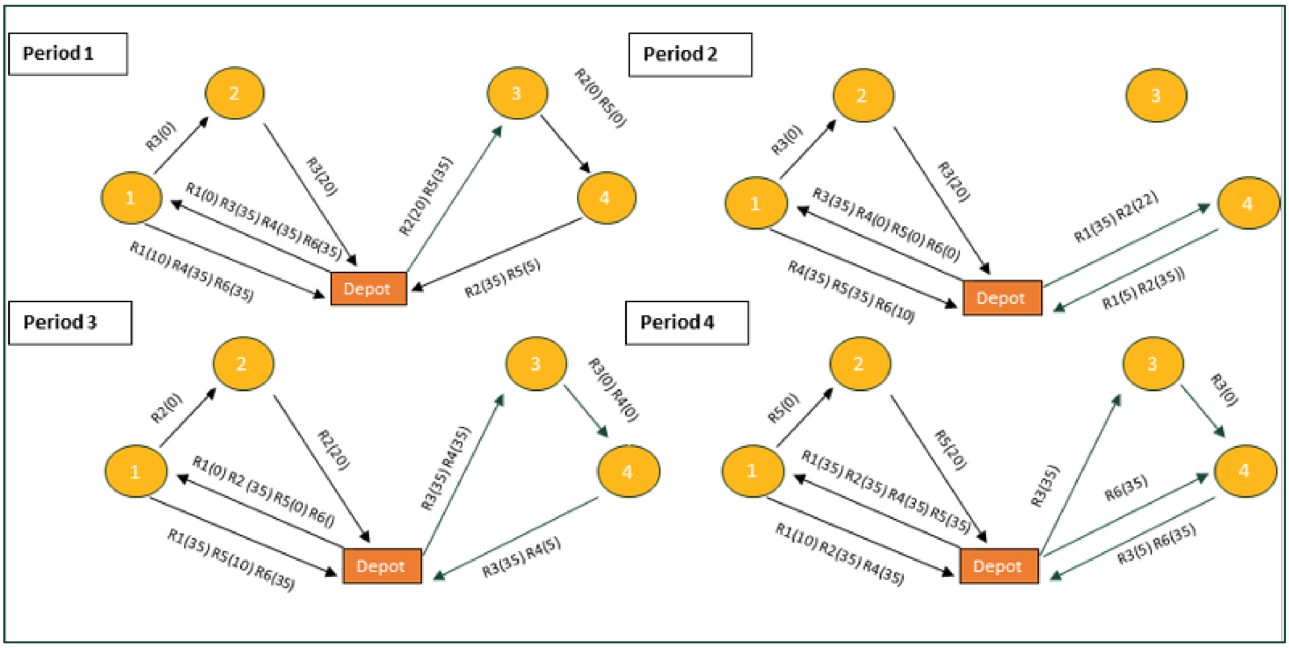

Figure 5 Test results – Vehicle routes and amount linehauled and backhauled each period

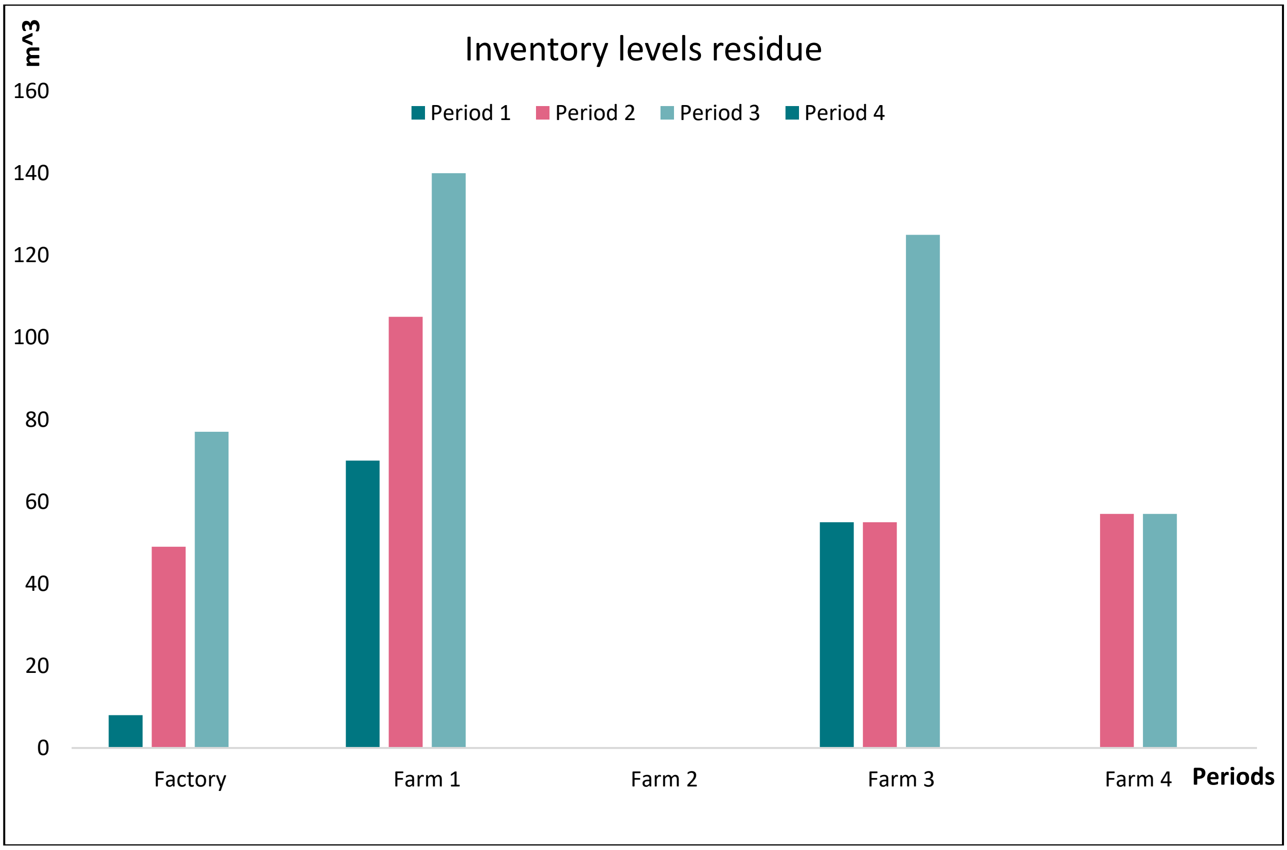

Figure 6 Test results – Inventory levels for each vertex each period

Had all the farms and periods been included in the model the solver would have likely run out of memory before finding an optimal solution. As the model is, it can be used to develop metaheuristics to find solution close to optimal for the more holistic complex problem. Noticeable is that the manure level in *Figure 5* is excluded since at the end of each period all manure is demanded by the factory leaving nothing in the inventory at each vertex.

Biogas Väst estimate that the hourly rate for the vehicles will be about 1500 Swedish crowns (SEK). With the time cost of 27.3 hours and the total amount of 1092 m3 transported, the rate per m3 becomes 37.5 SEK. This means that the annual cost of transportation becomes 26 690 625 SEK. The density of liquid manure is 1000 m3/kg which is used to calculate the cost per tonne kilometre (0.16 SEK) (Agriwise, 2009).

By scaling the total time costs by a factor of 100 and adjusting the time period into days an approximate daily cost for the real case problem could be calculated. With this simplified method the approximate daily time cost is around 49.5 hours meaning that Biogas Väst would need about 3.66 trucks driving 13.5 hour daily. It should be noted that an algorithm including data for the real problem would most likely find a more optimal solution, and thus should this not be seen as an accurate result, while it could be useful as an approximation of the real-case solution.

4.1 Model validation

Model validation is defined as *"the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended use of the model"* (Ling, Mahadevan, 2013). To understand whether the results in this study are reasonable, a comparison was made with trucking companies. The prices of transporting one ton ranging from 0-7 km to 17-19 km is between 40-52 SEK with taxes (Nybrogrus.se, 2023). Considering the study's results of 37.5 SEK average per tonne it is determined that the results are reasonable compared to market prices.

4.2 Sensitivity analysis

There are crucial implications for disease spread between farms when moving residue and manure for biogas generation. To address this worry, a sensitivity analysis was made comparing two scenarios: one in which the truck can make many trips between farms, and another in which the truck may only visit one farm at a time. The effect of altering vehicle capacity and average speed on total time costs was also investigated. The purpose of this analysis is to offer insight on the potential consequences and optimisation opportunities for reducing transportation costs. The results of the sensitivity analysis can be observed in *Table 2*.

It is critical to evaluate the potential dangers connected with disease transmission between farms while optimising the transportation process for residue and manure delivery to biogas plants. A sensitivity study was performed to evaluate the practicality of enabling the vehicle to make several trips, comparing it to a scenario in which the truck can only visit one farm at a time. The analysis provided useful information, showing the influence on total time costs.

Initially, the total time cost was calculated to be 27.3 hours under the assumption that the vehicle may make stops between several farms. However, because of worries about disease transmission, it was necessary to investigate an alternative technique. According to the sensitivity analysis, restricting the vehicle to just visiting one farm each route increased the overall time cost to 32.3 hours, suggesting a 18.5% increase. This finding emphasises the possible consequences of disease spread and the significance of establishing adequate mitigation measures.

The sensitivity analysis was also expanded to investigate the effect of changing the vehicle capacity. A significant change was seen when the maximum truck capacity was increased to 40 cubic metres. The entire time cost was reduced to 19.1 hours, a reduction of 29.7%. This result emphasises the idea that even little changes in vehicle capacity can result in large savings in transportation costs.

Furthermore, real-world conditions must be considered, as the average speed of the vehicle may differ between farms. To account for this variability, the analysis was broadened to include a scenario with a higher average speed of 40 km/h versus the initial speed of 30 km/h. The overall time cost was reduced to 23 hours due to the quicker average pace, representing savings of 15.75% when compared to the initial cost. This conclusion emphasises the importance of considering different average speeds, especially for farms located in remote locations but close to main roadways.

Table 2 Sensitivity analysis, total time cost comparison

	Multiple Stops Scenario	Single Farm Scenario	Increased Vehicle Capacity	Increased Vehicle Speed
Time Costs (hours)	27,3	32,3	19,1	23
Percentage Difference vs. Baseline	-	+18,5%	-29,7%	-15,75%

5. Discussion and analysis

Transporting agricultural waste from farms to biogas facilities is a critical step in the production of biogas process. The efficiency of this process can have a considerable impact on biogas production yield, which in turn affects the biogas plant's overall sustainability and profitability. Numerous elements were studied that can influence the transportation of agricultural waste to Biogas Väst facility, as well as the residue that is transported back to the farm.

The modification of vehicle loads is one of the parameters which was investigated. The optimal amount of manure and residue carried by each truck was calculated to maximise efficiency and reduce transportation expenses. Furthermore, the effect of time periods was explored in the transportation process, focusing on the need of timely placing of manure in the digester to maximise gas output per unit of manure.

Another important issue which was investigated was the different varieties of manure and their differing gas outputs and quality. The limits of dealing with various forms of manure as well as the prioritisation of specific types of manure is discussed. Furthermore, the agricultural waste delivery and pickup schedules, as well as the storage capacity necessary at the farm level for both manure and residue are discussed. The effects of road conditions in the transportation process are also analysed.

Through this study, the aim is to create a comprehensive transportation model to optimise agricultural waste transportation for Biogas Väst. By doing so, it may contribute to the long-term viability and profitability of the biogas production line, as well as providing insights that can be applied to other biogas plants and similar transportation problems.

5.1.1 Adjusting the vehicle load

By the results it can determine that some of the vehicles carry a small or no amount of the maximum vehicle capacity which might not be optimal in practice. This is especially noticeable in the backhauling part since the biogas plant demand the entire supply of manure meaning that however small their inventory is a vehicle will still pick it up to meet the demand. It is hard to say if the additional costs of backhauling a small amount of manure is worth to ensure that the manure is of the highest quality or if some backhauling trips should be scheduled further into the future to save transportation costs while losing some quality in the manure. It is a matter that requires further investigation. One suggestion would be to add a monetary value of the manure which decays over time. This possible solution would however only work if the supply exceeded the demand which is not applicable in our case since all manure produced is demanded by the biogas plant.

5.1.2 Time periods

As the model is as of right now the total time period is two months, it would be interesting to include at least eight months in order to include the winter months where there is no demand of residue for the farms up until the last months in spring where the farms start to demand residue, one possibility is to incorporate the VRP with rolling horizon (Koç and Laporte, 2018). In the real case it would also make sense to set the time period set to a number of days instead of a two-week period. This would imply further challenges on the backhauling constraints of the model. Constraint (14) needs to be adjusted to ensure that the manure produced each day is picked up at the latest in two weeks.

5.1.3 Different types of manure

Initially, the model's design included combining various types of manure, due to their specific biogas-producing capabilities. Furthermore, solid manure was intended to be accounted for as well, the vehicle routing problem with an heterogenus vehicle fleet could be a starting point to include solid manure (Koç and Laporte, 2018, Taillard, E. 1999). Nonetheless, this element was restricted, and solid manure was completely excluded in testing the model due to its small proportion in comparison with liquid manure. Due to Campbell, Clarke, and Savelsbergh's (2002) argument that a model performs optimum when just one product is considered, cow/cattle and pig liquid manure were limited to be handled as a single product. In further development, the model can be turned into a multiproduct problem with a heterogeneous vehicle fleet to account for solid manure.

5.1.4 Deliveries and pickups

As previously stated, the model excludes trucks that transport solid manure and concentrates entirely on trucks that deliver liquid manure. Biogas Väst had predicted that three trucks would be needed to cover supply and demand. However, because the model only comprises four test farms, it cannot estimate an exact number of vehicles required. To obtain an exact response, all actual farms must be incorporated into the model.

Regardless of the number of trucks needed, those who are available will work in two shifts during the week, resulting in visiting farms in the early morning and late evening. It should therefore be mentioned that, if the slurry pit is near the farm's residential area, it may cause annoyance to the residents. However, due to a lack of data, this element was not considered in the model.

5.1.5 Storage capacity

To be able to manage both manure and residue at the farm level, the farms need storage for both. The idea is that the farms have a receival slurry pit for manure which is large enough to hold the produced manure for at least two weeks, this is possible since the biogas facility plans to pick up all manure within two weeks. The original pit for manure is used for storing residue, and this pit needs to meet the demand for residue at the fertilization period since that’s the point in time when it is emptied.

Costs for storage is also a commonality for the IRP (Coelho et al, 2014). In the future Biogas Väst might recognize associated holding costs related to the products in storage. These costs should then be added to the objective function:

(31) $\sum_{i \in V} \sum_{t \in T} \quad h_i I_i^t + \sum_{i \in V} \sum_{t \in T} \quad h_i \, I'^t_i$

Equation (31) represent the holding costs at each vertex for manure and residue.

5.1.6 Road conditions

The varied road conditions throughout the year present a considerable barrier in transporting manure to biogas facilities. Severe snowfall in the winter and heavy vehicle restrictions in the spring can render some roads impassable, causing transportation delays. To overcome this, it may be more beneficial to prioritise and allocate resources to better-connected farms at certain times. Once beneficial road conditions have been restored, compensatory measures might be implemented.

It is worth noting that the existing approach does not account for these problems. As a result, including them would be important in constructing a complete transportation model that accounts for the different factors that may affect manure transportation from farms to biogas facilities.

6. Conclusion and further research

The aim of this thesis was to develop an optimization model that can be used by Biogas Väst in their transport planning as well as contributing to the literature as a case study of the IRPB. The model should be able to calculate the most optimal route for linehaul of residue and backhaul of manure. To reach this aim the following research question was formulated:

- Given a set of locations for linehaul and backhaul customers, what is the optimal route, measured in time?

The research question is supported by the following sub-questions:

- With a given vehicle capacity, how many trucks are required to cover the supply of manure and demand for digestate?
- What is the optimal collection and delivery schedule for manure and residue from and to specific farms?

To address the stated problem, a mathematical model was formulated with the specific purpose in mind. This model was subsequently tested using the solver CPLEX, albeit with a smaller number of farms than what will be present in the Biogas Väst transport logistics. In summary, the model largely fulfils the research questions posed. It determines the most optimal driving distance while also providing a schedule for where the truck should deposit the residue and pick up the manure.

6.1 Further research

The next step in coming closer to solving the real-world problem with scale would be to use the model to incorporate meta heuristics which are to come as close as possible to an optimal solution without solving the algorithm for optimum. Arab et al, (2020) used Nondominated Sorting Genetic Algorithm, version 2 (NSGAII) and Multi Objective Imperialist Competitive Algorithm (MOICA) as the methods to make meta heuristics for their IRPB. This could be a good starting point to create meta heuristics for our problem as well.

Further on, incorporating these elements that is listed below into the model would certainly increase the precision and realism of the outcomes in a real-world setting:

- Prioritising different types of manure depending on their biogas yield: The model can optimise resource allocation by considering the biogas exchange potential of different types of manure. This prioritisation can result in more efficient resource utilisation and higher overall biogas output.

- Accounting for seasonal road accessibility: Acknowledging that not all roads are open all year is critical for proper modelling. This element considers variables such as weather, road maintenance, and seasonal variations that may affect transportation routes. The model may provide more realistic transport schedules and routes by adding this information, guaranteeing that the ideal transport network is picked based on the current season.

- Including a longer time horizon: Extending the model's time horizon provides a more thorough investigation of the system dynamics. The model can account for aspects like as crop rotation cycles, fertiliser application schedules (residue in this case). This aids in capturing the system's interdependencies and feedback loops, allowing for more accurate predictions and decision-making.

By combining these elements into the model, it becomes more resilient and capable of dealing with the complexities and uncertainties that occur in real-world circumstances. As a result, the model's outputs are more reliable and valuable to decision-makers in the agricultural and energy sectors.

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Popular science summary

Getting items from one location to another in the most efficient way possible may be a huge challenge in the world of logistics. This is especially true for vehicle routing problems (VRPs), in which businesses must choose the most efficient routes for their delivery trucks to take. Biogas Väst, which gathers liquid manure from local farms and returns digestate, is one enterprise confronting this difficulty.

The unique challenge faced by Biogas Väst is an inventory routing problem with backhaul (IRPB), which encompasses both linehaul and backhaul operations. In other words, they must collect manure from farms and return the remainder to the farms. This is a complicated problem with several variables, including inventory capacity, travel distance, and timing constraints.

To address this issue, we created a mathematical model based on an IRP version provided by Berg in 2020, while we collaborated closely with Biogas Väst to collect data and ensure that our model was applicable to the company's unique requirements. The model we created was then tested and analysed to determine its effectiveness.

This project aimed to improve Biogas Väst's logistical operations and overall efficiency. They may save time, money, and resources by determining the most efficient routes for their delivery trucks. However, the model became reduced version of the real-world situation, and that more effort was required to develop a realistic solution that satisfied Biogas Väst's specific requirements. The model is a starting point for building a meta heuristic to find the best routing plan.

Overall, our work on an IRP with linehaul and backhaul is an essential step towards assisting Biogas Väst and other companies facing similar issues. Companies can increase their efficiency and lessen their environmental effect by establishing mathematical models and heuristics to optimise delivery routes. This study emphasises the necessity of collaboration between researchers and industry in solving real-world logistics problems and developing more sustainable supply chains.

Acknowledgements

We would like to express our deepest appreciation and gratitude to the individuals who contributed significantly to the completion of this thesis.

First and foremost, we would like to thank our supervisor, Hans Andersson. His advice, knowledge, and constant support were essential in defining our research. His guidance and insightful suggestions have encouraged us to consider new perspectives and improve our ideas.

We also want to thank Axel Trolme and Jacob Landelius for their help in developing our model. Their knowledge and contributions were critical in guaranteeing the accuracy and success of our research. Their willingness to share their experience and offer advice has been beneficial to us.

We are also grateful to the study's participant, Biogas Väst Skaraborg and the CEO Tomas Carlmon, whose participation and collaboration contributed vital insights and data for our research. Their willingness to contribute their time and experiences increased our findings greatly.

Thank you to everyone who helped with this thesis. Your support as well as guidance have been invaluable, and we sincerely appreciate it.

Adam Landelius & William Wejsfelt

Appendix 1 AMPL files

Testmodel.mod

```
param PERIODS >= 0;             # The time periods
set ROUTES;                     # The routes
set VERTEX;                     # All vertexes, depot and farms
set FARMS within VERTEX;        # The farms



param drivetime {i in VERTEX, j in VERTEX: i<>j}>= 0;
# The time it takes to travel between vertex i and j

param vehiclecap >= 0;
# Vehicle capacity

param invcapman {i in VERTEX} >= 0;
# Inventory capacity manure by vertex i

param invcapres {i in VERTEX} >= 0;
# Inventory capacity residue by vertex i

param produceman {i in VERTEX, t in 1..PERIODS} >= 0;
# Manure produced by vertex i on period t

param produceres {i in VERTEX, t in 1..PERIODS} >= 0;
# Residue produced by vertex i on period t

param demandman {i in VERTEX, t in 1..PERIODS} >= 0;  #
Manure demand in vertex i on period t

param demandres {i in VERTEX, t in 1..PERIODS} >= 0;  #
Residue demand in vertex i on period t

param inv0man {i in VERTEX} >= 0;
# Starting level of manure in vertex I

param inv0res {i in VERTEX} >= 0;
# Starting level of residue in vertex i
```

```
var Manlevel {i in VERTEX, t in 0..PERIODS}>= 0;
# Inventory level of manure on vertex i in period t

var Backhaul {i in VERTEX, k in ROUTES, t in 1..PERIODS} >= 0;
# Amount backhauled from vertex i by route k in period t

var Reslevel {i in VERTEX, t in 0..PERIODS}>=0;
# Inventory level at period t on vertex i

var Linehaul { i in VERTEX, k in ROUTES, t in 1..PERIODS} >=0;
# Amount linehauled at vertex i by route k in period t

var Used {i in VERTEX, j in VERTEX, k in ROUTES, t in 1..PERIODS: i<j}integer>=0 <= 2;
# Which roads that are used by route k in period t

var Visited {i in VERTEX,k in ROUTES,t in 1..PERIODS} binary;
# If vertex i is visited on route k in period t

var Hasbackhauled {i in FARMS, k in ROUTES, t in 1..PERIODS} binary;
# If a vehicle backhauls from farm i by route k on period t

var Haslinehauled {i in FARMS, k in ROUTES, t in 1..PERIODS} binary;
# If a vehicle linehauls from farm i by route k on period t

minimize Total_Cost: sum {i in VERTEX, j in VERTEX, k in ROUTES, t in 1..PERIODS: i<j}drivetime[i,j]* Used[i,j,k,t]
+ sum {i in FARMS, k in ROUTES, t in 1..PERIODS} Hasbackhauled [i,k,t] * 0.25 + sum {i in FARMS, k in ROUTES, t
in 1..PERIODS} Haslinehauled[i,k,t] *0.25;
# Minimizes total costs in hours as well as loading and unloading time

subject to Used_farms {i in FARMS, j in FARMS, k in ROUTES, t in 1..PERIODS: i<j}:
Used[i,j,k,t]<= 1;
    # How many times vehicle k travels the arc between farms
subject to manInv_level_depot {t in 1..PERIODS}:
Manlevel[0,t] = Manlevel[0,t-1] + sum{i in FARMS, k in ROUTES} Backhaul[i,k,t] demandman[0,t];
    # Manure inventory constraint for the depot

subject to maninv_level_farms {i in FARMS, t in 1..PERIODS}:
Manlevel[i,t] = Manlevel [i,t-1] + produceman[i,t] - sum {k in ROUTES} Backhaul[i,k,t];
    # Manure inventory constraint for the farms

subject to manInv_lev_start {i in VERTEX}:
Manlevel[i,0]= inv0man[i];
    # Initial manure inventory level for all vertexes

subject to manInv_capacity_dep {i in VERTEX, t in 1..PERIODS}:
Manlevel[i,t]<= invcapman[i];
```

```
    # Ensures that inventory levels does not exeed inventory capacity

subject to ResInv_level_plant {t in 1.. PERIODS}:
Reslevel[0,t] = Reslevel[0,t-1] + produceres[0,t] - sum {i in FARMS, k in ROUTES} Linehaul [i,k,t];
    # Residue inventory level at plant

subject to Resinv_level_farms {i in FARMS, t in 1..PERIODS}:
Reslevel[i,t] = Reslevel [i,t-1] + sum{k in ROUTES} Linehaul[i,k,t] - demandres[i,t];
    # Residue inventory level at farms

subject to resInv_lev_start {i in VERTEX}:
Reslevel[i,0] = inv0res[i];
    # Starting residue level at each vertex

subject to resInv_capacity {i in VERTEX, t in 1.. PERIODS}:
Reslevel[i,t] <= invcapres[i];
    # Inventory capacity of residue at each vertex

subject to Backhaul_max {i in FARMS, t in 1..PERIODS}:
sum {k in ROUTES} Backhaul[i,k,t] <= Manlevel[i,t-1]+ produceman[i,t];
    # Ensures that the amount backhauled does not exeed inventory at period t

subject to Backhaul_visit {i in FARMS, k in ROUTES, t in 1..PERIODS}:
Backhaul[i,k,t] <= invcapman[i]* Visited[i,k,t];
    # Ensures that a vehicle needs to visit the farm in order to backhaul

subject to Linehaul_max {i in FARMS, t in 1.. PERIODS}:
sum {k in ROUTES} Linehaul [i,k,t] <= invcapres[i] - Reslevel[i,t-1];
    # Ensures that the amount linehauled does not exceed inventory at period t

subject to Linehaul_visited {i in FARMS, k in ROUTES, t in 1.. PERIODS}:
Linehaul[i,k,t] <= invcapres[i] * Visited[i,k,t];
    # Ensures that a vehicle needs to visit the farm in order to linehaul

subject to Resvehicle_load {k in ROUTES, t in 1..PERIODS}:
sum {i in VERTEX: i <> 0} Linehaul[i,k,t] <= vehiclecap * Visited[0,k,t];
    # Ensures that the load of the linehaul does not exceed vehiclecapacity

subject to Manvehicle_load {k in ROUTES, t in 1..PERIODS}:
sum {i in FARMS} Backhaul[i,k,t] <= vehiclecap * Visited[0,k,t];
    # Ensures that the load of the backhaul does not exceed vehiclecapacity

subject to Vehicle_balance {i in VERTEX, k in ROUTES, t in 1..PERIODS}:
sum {j in VERTEX: i<j} Used[i,j,k,t]+ sum {j in VERTEX: i>j} Used[j,i,k,t]= 2 * Visited[i,k,t];
    # Ensures that the vehicle comes back to the depot after visiting a farm

subject to PickupallManure {t in 1..PERIODS}:
```

```
sum {i in FARMS, k in ROUTES} Backhaul[i,k,t] = sum{i in FARMS}produceman[i,t];
    # Ensures that all manure is backhauled in period t

subject to Backhaul_consistency {i in FARMS, k in ROUTES, t in 1..PERIODS}:
Backhaul[i,k,t] <= Hasbackhauled[i,k,t]*vehiclecap;
    # Ensures that binary variable Hasbackhauled is connected to backhaul

subject to Backhaul_limit {k in ROUTES, t in 1..PERIODS}:
sum {i in FARMS} Hasbackhauled[i,k,t] <= 1;
    # Ensures that each vehicle can only backhaul from one farm each period
subject to Linehaul_consistency {i in FARMS, k in ROUTES, t in 1..PERIODS}:
Linehaul[i,k,t] <= Haslinehauled[i,k,t]*vehiclecap;

    # Ensures that linehaul is connected to the binary variable Haslinehauled
subject to NoVisitIfNoBackhaulOrLinehaul {i in FARMS, k in ROUTES, t in 1..PERIODS}:
(Hasbackhauled[i,k,t] + Haslinehauled[i,k,t]) >= Visited[i,k,t];
    # Ensures that for a vehicle to backhaul or linehaul it needs to visit a farm
```

.

Testmodel.dat

```
set ROUTES := R1 R2 R3 R4 R5 R6;
set VERTEX := 0 1 2 3 4;
set FARMS := 1 2 3 4;
param PERIODS := 4;

param drivetime: 0     1     2     3     4:=
        0   .      0.166  0.333  0.5    0.666
        1   0.166  .      0.166  0.333  0.5
        2   0.333  0.166  .      0.166  0.333
        3   0.5    0.333  0.166  .      0.166
        4   0.666  0.5    0.333  0.166  .;


param vehiclecap:= 35;
param invcapres:=
0 3200
1 1820
2 720
3 1040
4 1040;



param produceres:
            1     2     3     4:=
0           133   133   133   133
```

```
1            .    .    .    .
2            .    .    .    .
3            .    .    .    .
4            .    .    .    .;


param demandres:    1    2    3    4:=
0            .    .    .    .
1            0    0    0    280
2            0    0    0    0
3            0    0    0    160
4            0    0    0    92;

param inv0res:=
0 0
1 0
2 0
3 0
4 0;

param invcapman :=
0 3000
1 500
2 500
3 500
4 500;

param inv0man:=
0 0
1 0
2 0
3 0
4 0;

param produceman :   1    2    3    4:=
0            .    .    .    .
1            80   80   80   80
2            20   20   20   20
3            0    0    0    0
4            40   40   40   40;



param demandman :    1    2    3    4:=
0            140  140  140  140
1            .    .    .    .
```

```
2                  .     .    .     .
3                  .     .    .     .
4                  .     .    .     .;
```

Testmodel.run

```
model Testmodel.mod;
data Testmodel.dat;
option solver cplexamp;
solve;
display Total_Cost > Testmodel.sol;
display Used, Linehaul, Backhaul, Manlevel, Reslevel, Visited, Hasbackhauled, Haslinehauled   > Testmodel.sol;
```

Testmodel.sol

```
Total_Cost = 27.3

Used [0,1,*,*]
:   1   2   3   4   :=
R1   2   0   2   2
R2   0   0   1   2
R3   1   1   0   0
R4   2   2   0   2
R5   0   2   2   1
R6   2   2   2   0

[0,2,*,*]
:   1   2   3   4   :=
R1   0   0   0   0
R2   0   0   1   0
R3   1   1   0   0
R4   0   0   0   0
R5   0   0   0   1
R6   0   0   0   0

[0,3,*,*]
:   1   2   3   4   :=
R1   0   0   0   0
R2   1   0   0   0
R3   0   0   1   1
R4   0   0   1   0
R5   1   0   0   0
R6   0   0   0   0

[0,4,*,*]
:   1   2   3   4   :=
R1   0   2   0   0
R2   1   2   0   0
```

R3   0   0   1   1
R4   0   0   1   0
R5   1   0   0   0
R6   0   0   0   2

[1,2,*,*]
:   1   2   3   4   :=
R1   0   0   0   0
R2   0   0   1   0
R3   1   1   0   0
R4   0   0   0   0
R5   0   0   0   1
R6   0   0   0   0

[1,3,*,*]
:   1   2   3   4   :=
R1   0   0   0   0
R2   0   0   0   0
R3   0   0   0   0
R4   0   0   0   0
R5   0   0   0   0
R6   0   0   0   0

[1,4,*,*]
:   1   2   3   4   :=
R1   0   0   0   0
R2   0   0   0   0
R3   0   0   0   0
R4   0   0   0   0
R5   0   0   0   0
R6   0   0   0   0

[2,3,*,*]
:   1   2   3   4   :=
R1   0   0   0   0
R2   0   0   0   0
R3   0   0   0   0
R4   0   0   0   0
R5   0   0   0   0
R6   0   0   0   0

[2,4,*,*]
:   1   2   3   4   :=
R1   0   0   0   0
R2   0   0   0   0
R3   0   0   0   0
R4   0   0   0   0

```
R5   0   0   0   0
R6   0   0   0   0

[3,4,*,*]
:    1   2   3   4    :=
R1   0   0   0   0
R2   1   0   0   0
R3   0   0   1   1
R4   0   0   1   0
R5   1   0   0   0
R6   0   0   0   0
;

:      Linehaul Backhaul    :=
0 R1 1      0        0
0 R1 2      0        0
0 R1 3      0        0
0 R1 4      0        0
0 R2 1      0        0
0 R2 2      0        0
0 R2 3      0        0
0 R2 4      0        0
0 R3 1      0        0
0 R3 2      0        0
0 R3 3      0        0
0 R3 4      0        0
0 R4 1      0        0
0 R4 2      0        0
0 R4 3      0        0
0 R4 4      0        0
0 R5 1      0        0
0 R5 2      0        0
0 R5 3      0        0
0 R5 4      0        0
0 R6 1      0        0
0 R6 2      0        0
0 R6 3      0        0
0 R6 4      0        0
1 R1 1      0       10
1 R1 2      0        0
1 R1 3      0       35
1 R1 4     35       10
1 R2 1      0        0
1 R2 2      0        0
1 R2 3     35        0
1 R2 4     35       35
1 R3 1     35        0
```

1	R3 2	35	0
1	R3 3	0	0
1	R3 4	0	0
1	R4 1	0	35
1	R4 2	0	35
1	R4 3	0	0
1	R4 4	35	35
1	R5 1	0	0
1	R5 2	0	35
1	R5 3	0	10
1	R5 4	35	0
1	R6 1	35	35
1	R6 2	0	10
1	R6 3	0	35
1	R6 4	0	0
2	R1 1	0	0
2	R1 2	0	0
2	R1 3	0	0
2	R1 4	0	0
2	R2 1	0	0
2	R2 2	0	0
2	R2 3	0	20
2	R2 4	0	0
2	R3 1	0	20
2	R3 2	0	20
2	R3 3	0	0
2	R3 4	0	0
2	R4 1	0	0
2	R4 2	0	0
2	R4 3	0	0
2	R4 4	0	0
2	R5 1	0	0
2	R5 2	0	0
2	R5 3	0	0
2	R5 4	0	20
2	R6 1	0	0
2	R6 2	0	0
2	R6 3	0	0
2	R6 4	0	0
3	R1 1	0	0
3	R1 2	0	0
3	R1 3	0	0
3	R1 4	0	0
3	R2 1	20	0
3	R2 2	0	0
3	R2 3	0	0
3	R2 4	0	0

3 R3 1 0 0
3 R3 2 0 0
3 R3 3 35 0
3 R3 4 35 0
3 R4 1 0 0
3 R4 2 0 0
3 R4 3 35 0
3 R4 4 0 0
3 R5 1 35 0
3 R5 2 0 0
3 R5 3 0 0
3 R5 4 0 0
3 R6 1 0 0
3 R6 2 0 0
3 R6 3 0 0
3 R6 4 0 0
4 R1 1 0 0
4 R1 2 35 5
4 R1 3 0 0
4 R1 4 0 0
4 R2 1 0 35
4 R2 2 22 35
4 R2 3 0 0
4 R2 4 0 0
4 R3 1 0 0
4 R3 2 0 0
4 R3 3 0 35
4 R3 4 0 5
4 R4 1 0 0
4 R4 2 0 0
4 R4 3 0 5
4 R4 4 0 0
4 R5 1 0 5
4 R5 2 0 0
4 R5 3 0 0
4 R5 4 0 0
4 R6 1 0 0
4 R6 2 0 0
4 R6 3 0 0
4 R6 4 35 35
;

: Manlevel Reslevel :=
0 0 0 0
0 1 0 8
0 2 0 49
0 3 0 77

```
0 4    0      0
1 0    0      0
1 1    0     70
1 2    0    105
1 3    0    140
1 4    0      0
2 0    0      0
2 1    0      0
2 2    0      0
2 3    0      0
2 4    0      0
3 0    0      0
3 1    0     55
3 2    0     55
3 3    0    125
3 4    0      0
4 0    0      0
4 1    0      0
4 2    0     57
4 3    0     57
4 4    0      0
;

:     Visited Hasbackhauled Haslinehauled    :=
0 R1 1    1      .      .
0 R1 2    1      .      .
0 R1 3    1      .      .
0 R1 4    1      .      .
0 R2 1    1      .      .
0 R2 2    1      .      .
0 R2 3    1      .      .
0 R2 4    1      .      .
0 R3 1    1      .      .
0 R3 2    1      .      .
0 R3 3    1      .      .
0 R3 4    1      .      .
0 R4 1    1      .      .
0 R4 2    1      .      .
0 R4 3    1      .      .
0 R4 4    1      .      .
0 R5 1    1      .      .
0 R5 2    1      .      .
0 R5 3    1      .      .
0 R5 4    1      .      .
0 R6 1    1      .      .
0 R6 2    1      .      .
0 R6 3    1      .      .
```

0 R6 4	1	.	.
1 R1 1	1	1	0
1 R1 2	0	0	0
1 R1 3	1	1	0
1 R1 4	1	1	1
1 R2 1	0	0	0
1 R2 2	0	0	0
1 R2 3	1	0	1
1 R2 4	1	1	1
1 R3 1	1	0	1
1 R3 2	1	0	1
1 R3 3	0	0	0
1 R3 4	0	0	0
1 R4 1	1	1	0
1 R4 2	1	1	0
1 R4 3	0	0	0
1 R4 4	1	1	1
1 R5 1	0	0	0
1 R5 2	1	1	0
1 R5 3	1	1	0
1 R5 4	1	0	1
1 R6 1	1	1	1
1 R6 2	1	1	0
1 R6 3	1	1	0
1 R6 4	0	0	0
2 R1 1	0	0	0
2 R1 2	0	0	0
2 R1 3	0	0	0
2 R1 4	0	0	0
2 R2 1	0	0	0
2 R2 2	0	0	0
2 R2 3	1	1	0
2 R2 4	0	0	0
2 R3 1	1	1	0
2 R3 2	1	1	0
2 R3 3	0	0	0
2 R3 4	0	0	0
2 R4 1	0	0	0
2 R4 2	0	0	0
2 R4 3	0	0	0
2 R4 4	0	0	0
2 R5 1	0	0	0
2 R5 2	0	0	0
2 R5 3	0	0	0
2 R5 4	1	1	0
2 R6 1	0	0	0
2 R6 2	0	0	0

2 R6 3	0	0	0
2 R6 4	0	0	0
3 R1 1	0	0	0
3 R1 2	0	0	0
3 R1 3	0	0	0
3 R1 4	0	0	0
3 R2 1	1	0	1
3 R2 2	0	0	0
3 R2 3	0	0	0
3 R2 4	0	0	0
3 R3 1	0	0	0
3 R3 2	0	0	0
3 R3 3	1	0	1
3 R3 4	1	0	1
3 R4 1	0	0	0
3 R4 2	0	0	0
3 R4 3	1	0	1
3 R4 4	0	0	0
3 R5 1	1	0	1
3 R5 2	0	0	0
3 R5 3	0	0	0
3 R5 4	0	0	0
3 R6 1	0	0	0
3 R6 2	0	0	0
3 R6 3	0	0	0
3 R6 4	0	0	0
4 R1 1	0	0	0
4 R1 2	1	1	1
4 R1 3	0	0	0
4 R1 4	0	0	0
4 R2 1	1	1	0
4 R2 2	1	1	1
4 R2 3	0	0	0
4 R2 4	0	0	0
4 R3 1	0	0	0
4 R3 2	0	0	0
4 R3 3	1	1	0
4 R3 4	1	1	0
4 R4 1	0	0	0
4 R4 2	0	0	0
4 R4 3	1	1	0
4 R4 4	0	0	0
4 R5 1	1	1	0
4 R5 2	0	0	0
4 R5 3	0	0	0
4 R5 4	0	0	0
4 R6 1	0	0	0

4 R6 2	0	0	0
4 R6 3	0	0	0
4 R6 4	1	1	1

;

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