Master's degree thesis

LOG950 Logistics

Title

Glass and metal waste collection for Romsdal Interkommunale Renovasjonsselskap

Author

Ning Liu

Number of pages including this page: 75

Molde, 31.08.2020

Molde University College
Specialized University in Logistics

Mandatory statement

Each student is responsible for complying with rules and regulations that relate to examinations and to academic work in general. The purpose of the mandatory statement is to make students aware of their responsibility and the consequences of cheating. Failure to complete the statement does not excuse students from their responsibility.

*Please complete the mandatory statement by placing a mark **in each box** for statements 1-6 below.*		
1.	**I/we hereby declare that my/our paper/assignment is my/our own work, and that I/we have not used other sources or received other help than mentioned in the paper/assignment.**	☒
2.	**I/we hereby declare that this paper** 1. Has not been used in any other exam at another department/university/university college 2. Is not referring to the work of others without acknowledgement 3. Is not referring to my/our previous work without acknowledgement 4. Has acknowledged all sources of literature in the text and in the list of references 5. Is not a copy, duplicate or transcript of other work	Mark each box: 1. ☒ 2. ☒ 3. ☒ 4. ☒ 5. ☒
3.	I am/we are aware **that any breach of the above will be considered as cheating, and may result in annulment of the examination and exclusion from all universities and university colleges in Norway for up to one year, according to the Act relating to Norwegian Universities and University Colleges, section 4-7 and 4-8 and Examination regulations** section 14 and 15.	☒
4.	**I am/we are aware that all papers/assignments may be checked for plagiarism by a software assisted plagiarism check**	☒
5.	**I am/we are aware that Molde University College will handle all cases of suspected cheating according to prevailing guidelines.**	☒
6.	**I/we are aware of the University College's rules and regulation for using sources**	☒

Personal protection

Personal Data Act

Research projects that processes personal data according to Personal Data Act, should be notified to Data Protection Services (NSD) for consideration.

Have the research project been considered by NSD? ☐yes ☒no

- If yes:

Reference number:

- If no:

I/we hereby declare that the thesis does not contain personal data according to Personal Data Act.: ☒

Act on Medical and Health Research

If the research project is effected by the regulations decided in Act on Medical and Health Research (the Health Research Act), it must be approved in advance by the Regional Committee for Medical and Health Research Ethic (REK) in your region.

Has the research project been considered by REK? ☐yes ☒no

- If yes:

Reference number:

Publication agreement

ECTS credits:

Supervisor:

Agreement on electronic publication of master thesis

Author(s) have copyright to the thesis, including the exclusive right to publish the document (The Copyright Act §2).

All theses fulfilling the requirements will be registered and published in Brage HiM, with the approval of the author(s).

Theses with a confidentiality agreement will not be published.

I/we hereby give Molde University College the right to, free of charge, make the thesis available for electronic publication: ☒yes ☐no

Is there an agreement of confidentiality? ☐yes ☒no

(A supplementary confidentiality agreement must be filled in)

- If yes:

Can the thesis be online published when the period of confidentiality is expired? ☐yes ☐no

Date:

Preface

The research topic originally stemmed from the efficiency improvement scheme from a local waste collection service company Romsdalshalvøya Interkommunale Renovasjonsselskap (RIR) AS located in Molde. From its operational experience in the past years, there seems a good chance that the waste collection strategy efficiency could be improved. Thus, the data provided by RIR were analyzed and new improvement strategies were introduced in this thesis. The corona virus in this spring had made some extra challenges in the thesis work such as data collection, on site visiting etc. Therefore, some data correction and estimation methods were applied during data processing and some inaccuracy is expected in the results presented in this thesis.

In truth, I could not have achieved my current level of success without a strong support group. First of all, Professor Arild Hoff, who have impressed and motivated me with his wisdom, professionalism, and rigorous. Those weekly meetings subjected many of my methodology to his critical eyes which helped in correcting my wrong approaches, and it also disperses my morose arise due to the corona virus. He is the lighthouse that helped me through the storm, I greatly appreciate him for his time and assistance. Secondly, RIR transport AS, who had provided the necessary data for this research. Especially, Solrun Fisknes and Geir Simonsen who had facilitated the data retraction for my specific research area. Furthermore, I would also like to express my thanks to my husband, Youhua Fu, who has supported me with love and understanding.

Lastly, may this thesis be useful for readers and researches in the related field.

Summary

Since the past decade, the data collected in MSW management industry has grown extensively, how to process and make improvement according to the data collected recently could make big difference in operational efficiency for the short-term strategy plans. This thesis has investigated the latest data collected in a waste collection company in Norway in 2019 and provided a few strategies to improve its operational efficiency. A newly introduced dynamic route routine scheduler algorithm was introduced in the thesis which can be used for solving the complicated routine scheduling problem and spare resource scheduling problem through a local search heuristic algorithm.

Contents

List of figures

List of tables

1 Introduction

As global population increases, human activities inevitably went up and the amount of waste generated start piling up. According to research by Hoornweg and Bhada-Tata (2012), at least 1.3 billion tons of Municipal solid waste (MSW) has been generated in 2012 and expected to reach 2.2 billion tons by 2025 in the cities across the globe. After the environment issues surfaced one after another: heavy metals pollution, smog, microplastics pollution, global warming etc., most countries have realized that environment is the most vulnerable and foremost aspect during its economy development, recent measures of ban waste importing tells the world that environment awareness become a universal consensus. MSW may cause pollution especially when they are unsorted and directly send to landfill, on the other hand, collecting and recycling the MSW brings considerable advantages to the environment.

MSW is the waste generated in a municipality, typically consisting of household waste, construction waste, industrial waste, service industry waste etc. According to Statistics Norway (SSB, 2020): 11.82 million tons of MSW was generated in 2018 in Norway, and the household waste consists of 2.42 million tons which holds roughly 20% of the MSW. Such waste includes biodegradable organic waste, recyclable waste (paper, plastic, glass, metal), remaining household waste, and each resident generates around 421 kg of house hold waste in the same year. These household wastes are usually disposed adjacent to inhabitants' house. Some of the wastes such as food and residual waste that cannot be kept for long time as it is prone to rot and release unpleasant odors. Thus, in order to create a hygiene dwelling environment, these wastes must be collected and transported for disposal as soon as possible.

MSW management as a part of the waste life cycle management is mainly about collection, sorting, and disposal, however, prevention of MSW could potentially bring many environmental benefits such us reduces landfill, Green House Gas (GHG) and hazardous material pollution. As suggested by Gentil et al. (2011) and Papargyropoulou et al. (2014) that prevention of food waste has great environmental impact save and a sustainable resolution of the food waste issue is to adopt a sustainable production and consumption approach and tackle food surplus and waste throughout the entirety food supply chain. Generally, there are three aspects for MSW prevention: prevention of MSW on the producer side, prevention of MSW from been generated on consumer side, prevention of MSW through policy instruments guidance. Ekvall (2008) has given many constructive strategies for MSW prevention, such as: increase material-efficient (design by using less material on producer side), increase products service life, expand service life (by repairing, second hand trade on consumer side), increase product use efficiency (leasing or co-ownership), change focus of consumption on consumer side (promote choose material efficient product), impose policy instruments (taxes and fees on natural resources, raw materials, energy and emissions on government side).

EU waste legislation has introduce a five step waste management hierarchy as shown in Figure 1 (EU, 2008b) for its member states. Its member states' legislation and policy follow such reverse pyramid structure, which means the rules and regulation made shall have the most priority on prevention of the waste from been generated and disposal is the least favorable phase regarding to the waste handling.

Figure 1 Waste management hierarchy

1.1 MSW challenges

Norway together with European Union (EU) countries have spent lots of effort on implanting waste sorting and waste processing system development in the past decades. The latest data from Eurostat (2020) indicate that 40.7% household waste (also includes similar wastes generated by small businesses and public institutions) from Norway had been recycled by 2018, back in 1995 the recycling rate was only 13.7%. The average recycling rate for the 28 EU countries also gradually increased to 47% from 17.4% in the same period. EU have a strategic plan of reduce its MSW for a long time. It has set a target of increase household waste recycling rate since 2008, especially for those recyclable wastes such as plastic, glass and metal, and the recycling rate shall be increased to a minimum of 50% when account all type of wastes by 2020 (EU, 2008a). Latest statistical figures indicate the target can be achieved by the end of 2020. However, there are still many possibilities on the horizon, especially when we look at the best performing country in Europe - Germany where over 67% recycling rate has been achieved in 2018.

MSW collection approach differs between household waste and industrial waste in Norway. Household waste in garbage bins are usually located in front of houses and distributed around the street. However, industrial waste in container style waste tank are usually randomly spread around the service area in the form of nodes. For household waste it requires the waste collection company to drive through required streets to empty garbage bins, sometimes also refer to curbside collection waste collection. Since the trucks are driving through streets, capacitated arc routing problem (CARP) mathematic models and its algorithms are commonly used for solving household waste collection problem. As the waste collection vehicles has capacity limit, the predefined streets (arcs) that have scheduled waste pickup service must be traversed during the operation process. On the other hand, commercial or industrial customers are scattered around the service area and each location are provided with large containers. In order to maximize pickup efficiency, the waste truck need to plan pickups at different nodes before return to depot, this process refers to vehicle routing problems (VRP). The routes are driven by different vehicles start from the depot and visit customers that located at various nodes in the service area and then return. The number of customers can be serviced at one departure is limited when compared with household customers. Thus, commercial customers route planning usually requires different strategies (Toth and Vigo, 2002). VRP targets problems where vehicles need to visit nodes, unlike the arc routing problem (ARP) where vehicles need to visit arcs (in this case is the roads the vehicles need to drive) such as the household waste collection problems. However, both problems aim to reduce the total cost of routing while meeting the capacity constraints.

Collecting recyclable material from waste, as an effective way of reuse resources, contribute both to the environment and resources. The more recyclable wastes, especially hazardous and poor biodegradability wastes, being picked out, the lower burden environment will bear and less natural resource extraction is needed for human activities. Waste sorting is an essential procedure in waste recycling. After sorting, the materials that cannot be recycled such as combustible wastes may be delivered to incineration and become district heating. The waste that contain hazardous substances, will be treated properly so that they will not lead to more pollution than necessary. Maximizing the collection of recyclable waste, to some extent, means more fuel consumption and higher operation cost for waste collection company. And higher service level leads to higher picking up frequency more complex routing, which might contribute to more fuel consumption as well as labor cost. Finding out a relatively good balance is one of the goals for waste collection companies, thus, this is one of the purposes of writing this thesis.

Waste collection typically involves the waste collection direct from houses and transport it to the disposal sites. Waste management on the other hand includes all activities and actions that is required to manage the waste from initial points to its final disposal sites. It mainly consists of collecting process, transportation, treatment and dispose waste. Waste collection and disposal usually have high expenses such as operation cost (i.e. staff payment, fuel cost, vehicle maintenance, ferry and toll fee etc.) and investments (i.e. fleet of vehicles, waste processing equipment etc.) (Tirkolaee et al., 2016). According to Tavares et al. (2009), more than 70 percent of solid waste management cost is related to the waste collection. Golden et al. (2002) have estimated that between 75 and 80 percent of cost may relate to the waste collection and transportation process. Thus, small improvements in such cost elements leads to huge saving for the company. Therefore, optimization of household waste system plays a crucial role in reducing cost of solid waste service provided by local waste collection companies or communities. Meanwhile, local governmental regulations are the basic requirements and key points that the company have to follow up and consider while doing the operations. Whereas, service level, as an important indicator to reflect the service degree of satisfaction provided by the waste collection company, is another factor that the waste collection company needs to take into account. This thesis will look into the data provided by a waste collection service company and try to improve the efficiency of curbside waste collection.

1.2 Research target and objectives

This research is carried out for a waste collection company called RIR (Romsdalshalvøya Interkommunale Renovasjonsselskap) located in Molde in Norway. The company is responsible for household waste collection in the Norwegian municipalities of Molde, Midsund, Fræna, Eide, Gjemnes, Aukra and Rauma. The service region has 70 679 inhabitants by the 2019 (SSB, 2020).

There are two subsidiaries under RIR: RIR Nutrition AS and RIR Transport AS. While RIR Nutrition offers waste collection services to the commercial sector, RIR transport provide household waste collection service for the inhabitants in the aforementioned municipalities. Figure 2 *(Wikipedia, 2020)* below shows the municipalities' location.

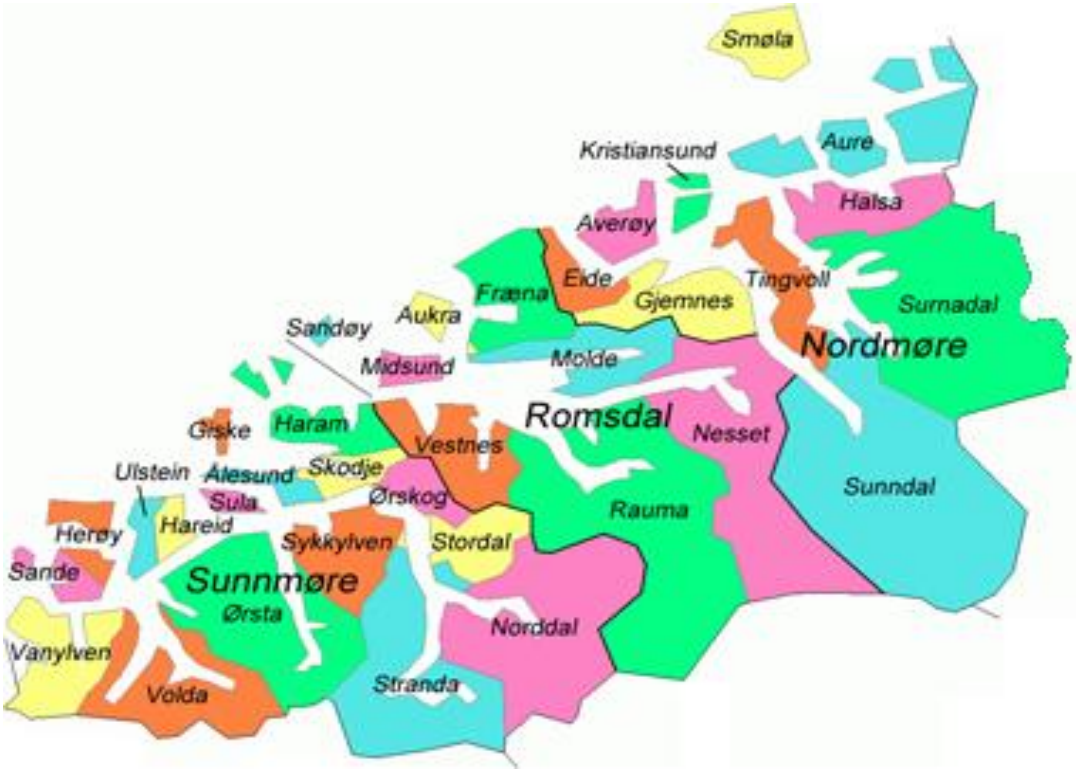

Figure 2 Municipalities locations

Due to municipalities merge in Norway 01.01.2020, the zoning in Figure 2 has two changes, although they do not affect the total RIR service area:

- Molde now includes Nesset and Midsund (which previously were independent regions)
- Hustadvika (merging of the previous regions of Fræna and Eide)

Each waste collection vehicle at RIR transport drive a predefined route and return with the collected household waste to the recycling station at the end of the day. When returning to the base, a weighting process is performed for each vehicle. The weight is logged before the wastes are dumped to the dedicated waste processing system on the site. The recycling station works mainly as a transshipment point (RIR, 2020), however, a small portion of carefully selected wastes such as non-combustible waste from commercial activities can be dumped at the landfill on site. Combustible residual wastes are crushed and packed into balls after the wastes are delivered to the station and then be transported to combustion plant at another location. Nowadays, almost all collected waste that enters to the plant will be transported out again. The plant also plays an intermediate storage role before the wastes are transported to the final waste processing plants, thus, achieve higher logistics efficiency.

Figure 3 shows an example of the combustible wastes being packed in white “grass hay” style and waiting to be transported.

Figure 3 RIR plant in Årødalen

Waste collection frequency are typically varying between different waste types, take RIR Transport's service strategy as an example: food waste is usually collected every two weeks, paper waste is usually collected every four weeks, glass and metal waste are usually collected every eight weeks. Reduction of the frequency of the collection service may cause hygiene problems such as food waste start rotting and smelling, trash bin overflow etc. On the other hand, increasing the frequency leads to higher operation cost and also reduces collecting efficiency as the trash bin could be under filled. The weights between operational cost and client satisfaction defines the service degree. A higher service degree demands a more frequent waste pickup service, vice versa.

Based on the previous years' experiences, glass and metal collection vehicles on a majority of the routes are usually under filled while some routes are commonly close to the capacity which will be discussed in section 3.2. Besides, the glass and metal trash bin also commonly found under filled, these are the indications that the routes might not be very efficient and the planned collection frequency might be too conservative, Therefore, reducing the frequency of the glass and metal waste collection could be viable a solution to reduce the operational cost.

2 Literature review

2.1 MSW collection VRP

MSW typically consist of various waste types and the pickup points are scattered in a wide area, and as D'Onza et al. (2016) has concluded, more than 70% of the MSW management cost are related to waste collection process. Therefore, how to efficiently collect and relocate the waste for further processing could create enormous economic and environmental benefits and gained a lot of popularities in the research of MSW waste management. Waste collection generally involves the process of waste sorting and pickup route planning. Since the waste sorting is mainly carried out by the households in Norway in this case study, this thesis will focus on the waste collection problem in the waste management system.

MSW waste collection problem, according to description by Corberán and Laporte (2015), is basically a routing problems with four main constraints: how to design routes that can traverse all household problem, route visiting frequency constraint, vehicle capacity constraint, time window constraint. As descripted by Corberán and Laporte (2015), it consists of designing a set of routes that

- Every route starts at a depot with an empty vehicle and ends with an empty vehicle at the same depot, basically collected all waste along the route and relocate them to intermediate storage site, final treatment site or landfill;
- Every bin needs to be emptied before it is full, thus minimum frequency has to be met depends on the waste type;
- On every route the total amount of waste collected before visiting intermediate storage site, final treatment site or landfill must not exceed the vehicle capacity;
- The duration of any route does not exceed a maximum shift length based on local rules and regulations.

It is not difficult to notice that the visiting frequency constraint can be estimated based on the waste creation speed and the trash bin size. However, the main challenge is how to design the routes so that it traverses each node which also met the capacity and time window constraints. Such routing problem is usually categorized as two sub categories: Node routing and Arc routing (Corberán and Laporte, 2015), which are differentiated by the collection continuality and the overall number of pickup nodes. When the collection points are located relatively far away from each other and number of nodes are relatively small, such routing problems needs to plan the route between exact nodes and they are treated like vehicle routing problem (VRP). On the other hand, when the collection points are located in a way that can be modelled as arcs in a network, typically, like a vehicle driving on the streets are the problems that can be treated as arc routing problem.

The VRP or ARP research history is considered been originated from graph theory research which can be traced all the way back to 1741 when Euler introduces the famous Seven Bridges of Königsberg problem and laid the foundations of graph theory (Euler, 1736), there are a few other researches continued between the 19th and early 20th century in path searching on graph with different constraints such as Kirkman, Hamilton and Menger as described in (Laporte, 2006). However, it is not until digital computational availabilities from 1960s before the VRP research is taking off. According the data in a research (Eksioglu et al., 2009), the number of published VRP articles grows almost exponentially from 1956.

VRP is known as NP-hard (Lenstra and Kan, 1981). Take the basic one vehicle VRP variants - traveling salesman problem (TSP) as an example, which is finding the optimal route for visiting N cities and returning to the point of origin where inter-node distances are given. The most obvious approach is to try all permutations of (N-1) factorial possible solutions until finding the optimal. However, as Karp (1972) has proved TSP is NP-hard, and the permutation approach are almost impossible for scenarios where nodes usually count up to hundreds or even thousands. The computation time grows exponentially (Little et al., 1963) and could not be completed in realistic timespan even for computer as of today. VRP are even more complex than the TSP, since the vehicle capacity needs to be added to the already complicated constraints. Therefore, optimal solution can be found only for small instances, for larger instances, approximation algorithms such as classical heuristics and metaheuristics needs to be used for solving such VRP.

Classical heuristics for VRP is a group of algorithms that are widely discussed from the beginning of VRP research until recent years. Due to its easy to implement properties, it is also widely adopted in many commercial vehicle routing software. It generally includes three categories: constructive heuristics, two phase heuristics, improvement heuristics (Toth and Vigo, 2002). The constructive heuristics approach for solving VRP is constructing a possible solution from scratch and ends when the solution is complete, for example, by merging existing routes through saving criterion, then gradually assigning nodes to routes through insertion cost model. The two-phase heuristics approach for solving VRP like it laterally means, separate the heuristics approach into two distinctive processes: clustering (of nodes) and route forming (from a pre-defined cluster of nodes). Depending on algorithm sequence, it could be clustering first then route forming or the opposite way. Improvement heuristics for VRP is a type approach that used on complete solution with known routes, for example created by constructive heuristics. It is targeting to take a route or multiple routes at a time and try to improve it gradually.

Metaheuristics for VRP is a modern approach in solving VRP, it is a group of algorithms that are evolved during the classical heuristics research. It provides better solution quality when compared with classical heuristics. Classical heuristics which is based on simple construction and local descent improvement sometimes leads to limited room for better results. Metaheuristics on the other hand allows deterioration and even infeasible intermediary solutions in the algorithm. Therefore, it is able to better explore the full search space and identify better solution than classical heuristics. Such improvement is of course leading to longer computational time for metaheuristics algorithms. There are many types metaheuristics such as: Simulated Annealing (SA), Deterministic Annealing (DA), Tabu Search (TS), Genetic Algorithms (GA), Ant Systems (AS), and Neural Networks (NN) as described by Toth and Vigo (2002). More recent research tends to focus on combinations of heuristics, and even combining heuristics with exact methods. Such methods are called 'Matheuristics' and they could for example solve smaller parts of the problem (like the single routes) to optimality, while the search for a complete solution is managed by a heuristic.

It is commonly known that waste collection problem consists of routing problem, clustering (into single routes) problem, deciding collecting frequency etc. Routing problem usually can be treated as undirected capacitated arc routing problem (UCARP), this has been described through a mathematical formulation by Golden and Wong (1981):

Objective function: Minimize $\sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{p=1}^{K} c_{ij} x_{ij}^{p}$

Where n = the number of nodes; K= the number of available vehicles; c_{ij}= the length of arc (i, j); x_{ij}^{p} = 1, if arc (i, j) is traversed by vehicle p, 0 otherwise. And the minimization process is subject to constraints:

1) $\sum_{k=1}^{n} x_{ki}^{p} - \sum_{k=1}^{K} x_{ik}^{p} = 0$ for i = 1, …, n and p = 1, …, K

2) $\sum_{p=1}^{K} (l_{ij}^{p} + l_{ji}^{p}) = \left\lceil \frac{q_{ij}}{W} \right\rceil$ for (i,j) ∈ E

3) $x_{ij}^{p} \geq l_{ji}^{p}$ for (i,j) ∈ E and p = 1, …, K

4) $\sum_{i=1}^{n} \sum_{j=1}^{n} l_{ij}^{p} q_{ij} \leq W$ for p = 1, …, K,

5) $$\begin{cases} \sum_{k=1}^{n} f_{ik}^{p} - \sum_{k=1}^{n} f_{ki}^{p} = \sum_{j=1}^{n} l_{ij}^{p} & \text{for } i = 2, \dots, n \text{ and } p = 1, \dots, K, \\ f_{ki}^{p} \leq n^{2} x_{ij}^{p} & \text{for } (i, j) \in E \text{ and } p = 1, \dots, K, \\ f_{ij}^{p} \geq 0 & \text{for } (i, j) \in E \text{ and } p = 1, \dots, K, \end{cases}$$

6) $$\begin{cases} y_{1\tilde{q}}^{p} + y_{2\tilde{q}}^{p} \leq 1;\ y_{1\tilde{q}}^{p}, y_{2\tilde{q}}^{p} \in \{0,1\} & \text{for } p = 1, \dots, K \text{ and } \tilde{q} = 1, \dots, 2^{n-1} - 1 \\ x_{ij}^{p}, l_{ji}^{p} \in \{0,1\} & \text{and every nonempty subset } \tilde{Q} \text{ of } \{2,3, \dots, n\} \end{cases}$$

Assume network G(N, E, C) (N is the set of all nodes, E the set of all arcs, and C the matrix of costs) W is the vehicle capacity (W ≥ max q_{ij}); l_{ij}^{p} = 1 if vehicle p services arc (i, j), 0 otherwise; q_{ij}=the demand on arc(i, j); f_{ij}^{p} is a flow variable which can take on positive values only if x_{ij}^{p} = 1. Q is the subset of nodes $Q \subseteq N$ which covered by the arc, each index $\tilde{q}$ corresponds to a set $\tilde{Q}$. According to Golden and Wong (1981), constraint 1) ensure route continuity, 2) states each arc with positive demand is serviced exactly once, 3) guarantee that arc(i,j) can be serviced by vehicle p only if it covers arc(i,j). 4) ensures that the vehicle capacity is not violated. 5) prohibit the formation of illegal subtours, 6) ensures the integrality restrictions.

There are many existing algorithms developed for solving UCARP, Corberán and Laporte (2015) has summarized these algorithms, this includes: 1) constructive heuristics such as: construct strike, path-scanning, augment-merge, Ulusoy's route-first cluster-second method, Wohlk's heuristics, Improvements to augment-merge and path-scanning, Improved tour splitting heuristics, 2) metaheuristics such as: Simulated annealing, Tabu search, Variable neighborhood search, Greedy Randomized Adaptive Search Procedure (GRASP) algorithms, Guided local search, Memetic algorithms, Scatter search, Ant colony optimization.

In order to tackle the real world UCARP, realistic route information such as route length and the actual geographical relation between each route must be digitalized. Geographic information system (GIS) data structure as one the most common way of representing such geographic data typically store the geographic information into multiple layers and commonly separate into two groups: vector representation and raster representation. Vector representation typically includes layer of points, lines, and polygons, point for example can be households, buildings etc., lines are usually used to represent the routes. Raster representation can be the layer of altitudes, satellite images etc. A full review of the GIS history can be found in research by Mark et al. (1997) and Goodchild (2003). With the completion of accurate and sophisticated GIS database under the support from government projects and non-commercial projects, GIS is now able to provide many research possibilities such as vehicle routing (Sarkar, 2007), (Wang et al., 2008), (Tavares et al., 2009). A case study by Tavares et al. (2008) has achieved 52% less fuel consumption after implementing GIS 3D route modelling for the collection route planning for service the same clients.

2.2 Route planning and scheduling improvement

Collection strategy should be continuously evaluated due to the changes in premises such as demand, capacity, road infrastructure and so on, this is both with respect to the division of region for each tour, and for the exact routing on the tours. Prosser and Shaw (1996) have provided an interesting approach where a steepest descent search engine is implemented by using multiple improvement heuristics for solving VRP. Alternatively, split delivery vehicle routing problem (SDVRP) algorithm can also be used for further improving the route planning. Casazza et al. (2018) had introduced an exact algorithm finding the optimal solution based on branch-and-price algorithm which decompose a part of the existing routes to substructures, and mitigating the combinatorial explosion of feasible solutions; Silva et al. (2015) introduced a iterated local search (ILS) and randomized variable neighborhood descent (RVND) based heuristic that includes a novel perturbation mechanism, provides fast and improved solution for the problem.

The waste collection vehicle fleets typically travel at a fixed plan; however, this does not guarantee the best efficiency as not all clients on the route has the same demands. There are many researches that suggests the dynamically scheduling could potentially increase the efficiency (Johansson, 2006), (Elia et al., 2018). In the research by Zsigraiova et al. (2013), it has shown an example of provide dynamic scheduling of the vehicles depends on its fill-up rate.

2.3 Smart trash bin system

The smart trash bin is a type of internet connected trash bin information collection system which is target to provide live information to the cloud, therefore enables decision makers get updated information to be used in the detailed schedule and route planning. Such system is widely discussed in recent years such as (Hrabec et al., 2019) (Sharma et al., 2015), (Al Mamun et al., 2015), (Kristanto et al., 2016), (Navghane et al., 2016) (Murugaanandam et al., 2018), and this research field is expected to become more popular with the advancing radio technology such LTE-M, NB-IoT and sensing technologies such as 3d surface sensing (Morinaga et al., 2019). This is due to the low power consumption of the radio communication and sensors allows smart bin can run longer without maintenance of the batteries therefore became less expensive.

Based on the previous studies, the filling level sensor could be combined with 5th Generation mobile network (5G) and Internet of Things (IoT) technology to offer tailored service to individual households. This is a system that each households trash bin in the service area are connected to the cellular networks, once the trash bin has exceeded household's defined pickup level or the household have manually requesting a pickup service of the trash bin. Such information can be immediately sent to the waste collection company together with its geolocation info. The waste collection company will then plan the routes accordingly e.g. pick up the requested trash bin within a given number of working days.

In such waste collection system, the trash bins need to be served, its location and waste weight or volume are provided before each collection attempt. Therefore, it could bring some economic and environmental benefits. Besides, due to the high level of client information, the system could provide the optimal routes, time estimation and the exact clients need to be served before each departure. Therefore, the optimal vehicle operational plan can be achieved, and could potentially gain the initiative when compared with the conventional passive plans (due to the uncertainty of clients demands). Furthermore, since the vehicles will focus on the clients who need the service, the pickup efficiency can be improved and capacity overflow risk can be eliminated, thus, travelling distance and pickup duration can be optimized. It is also beneficial that after the system becomes fully operational, the unnecessary pickups can be avoided, therefore less collection activity is needed. Furthermore, the system can also be changed so that the clients are charged based on the waste generation or the number of trash bin pickup services. This would help guide the citizens to generate less MSW than needed.

Traditionally, the smart trash bin level sensors include load sensor (Sohail et al., 2019), ultrasonic sensor (Samann, 2017), and infrared sensor. Load sensor usually require complex installation and the accuracy could be an issue which prevent it from been used for light weight wastes. Ultrasonic and infrared sensors are contact less which are very easy to be mounted on trash bins, however, they are still not problem free. Ultrasonic sensor works by emitting the sound waves and check the time difference from its received sound waves then convert it to the distance between sensor and garbage, and in some cases, the trash bin wall could also reflect the waves which might cause wrong level readings. The infrared sensor measures the level by checking the ToF (time of fly) of the light emitted from the infrared light source until the light received at an image sensor then convert it to the distance between sensor and garbage. In recent years 3d surface sensing as discussed in (Morinaga et al., 2019) has become popular in IoT industries due to its wide usage in the smart phone industry. Such sensor is basically projecting tens of thousands of randomly scattered dotted lights the image sensor collects the pattern of the dots and compared with its previously calibrated pattern then generates the 3D (3 dimension) contours, therefore, could be used to avoid the error that could happen when using ultrasonic and infrared sensor. Both infrared and 3d surface sensors requires clean working environment for image sensors and light focus lens which means they might not be very suitable to work alone in the trash bins where dirty and dusty are not uncommon. Thus, many of these sensors are combined in level sensing to achieve the most accurate measurement.

There are also many researches about implementing of such smart bin systems, Sharifyazdi and Flygansvær (2015) discussed a case in Oslo which compares the differences in service level and haulage distance between the conventional static routing (fixed schedule pickup strategy) and the dynamic routing. The dynamic routing is made possible with the help of such smart bin system where live level and its geolocation information is available. Then the dynamic routes are generated everyday based on the status of the smart bins. The study has made a benchmark comparison of the static and dynamic routing strategy, it turns out the dynamic routing has outperformed static strategy in most of the aspects. The dynamic routing also achieves shorter working hours and haulage distance, less capacity of the vehicles, and better customer service level. On the other hand, in order to achieve better results after the implementation of the smart bin system, route needs to be carefully planned every day. As discussed by Ramos et al. (2018), three different operational management approaches (and dynamic routing strategies) were analyzed for a waste collection company in Portugal. It also suggests that dynamic routing strategy could perform better in key performance indicators (when compared with the static strategy), of course, this requires a smart collection approach that involves various methods to find the better dynamic routing strategy.

3 Case description

3.1 General

3.1.1 Waste sorting

According to the municipal regulations, inhabitants in RIR transport service area has the obligation to sort the household waste before dumping to the dedicated trash categories as shown below (sortere.no, 2020):

Type	Description
Bio waste	Food waste, napkins, candles and small potted plants.
Paper	All paper, cardboard, paperboard and drinking cartons.
Plastic	Cleaned soft plastic and plastic packaging.
Glass and metal	Bottles and cans.
Residual waste	Residual wastes (excluding all recyclables)
Hazards wastes	Electronic waste, oil-products, paint, batteries

Table 1 Recyclable household waste sorting scheme

Hazards waste has to be transported to the collection areas by the customer itself. It is also worth to mention that, the aforementioned waste sorting is crucial for maximizing the recycling rate. However, in some communities in Norway where the population density is higher, such as Stavanger, some of the waste disposal is only available at centralized waste tanks (glass and metal) or been mixed to other categories (plastic), thus, causing inconveniences for inhabitants and reducing the waste recycling rate.

The trash bins provided to the customers (households) have five different sizes, they are 140 liters (140L), 240 liters (240L), 360 liters (360L), 660 liters (660L), and 1000 liters (1000L). Therefore, based on the fixed frequency pickup service, customers can choose the desired trash bin size to meet their demands. Furthermore, different trash bin uses dedicated color for its suitable type of waste or at least distinguished by the color of the trash bin lid.

3.1.2 Collection zoning

This thesis will focus on glass and metal (G&M) collection zoning and its collection strategy. As of 2019, a total of 14569 nodes (trash bins) should be serviced within the service area. RIR have given their vehicles a number-id, and the id of the glass and metal vehicle is 10. Each zone contains a route name that made of four digits. It consists of two parts: the vehicle id (two digits) and the route number (two digits). Take route name 1001 as an example: it represents the route number 1 that vehicle number 10 covers.

Figure 4 and Figure 5 provide the collection zoning strategy for paper/plastic waste in 2019 (G&M collection follows the same routes as the paper/plastic collection, but on different frequencies). The regions highlighted with green polygons are the service area covered by RIR transport. Each of the polygons represents a service zone with a route name on the region. According to the graphs, a total of 45 zones were divided in the service area and served with three vehicles (vehicle number 3, 6 and 7). The multipurpose vehicle (vehicle 7) serve five remote zones: 0704, 0707, 0708, 0715, 0716 as shown in the graphs. It collects glass and metal wastes together with other types of wastes in the zones, therefore, these areas are not discussed in this thesis. The other 40 zones' glass and metal waste collection are served with only one vehicle (vehicle number 10) and each zone is visited in every eight weeks. This thesis will only focus on the area covered by these routes.

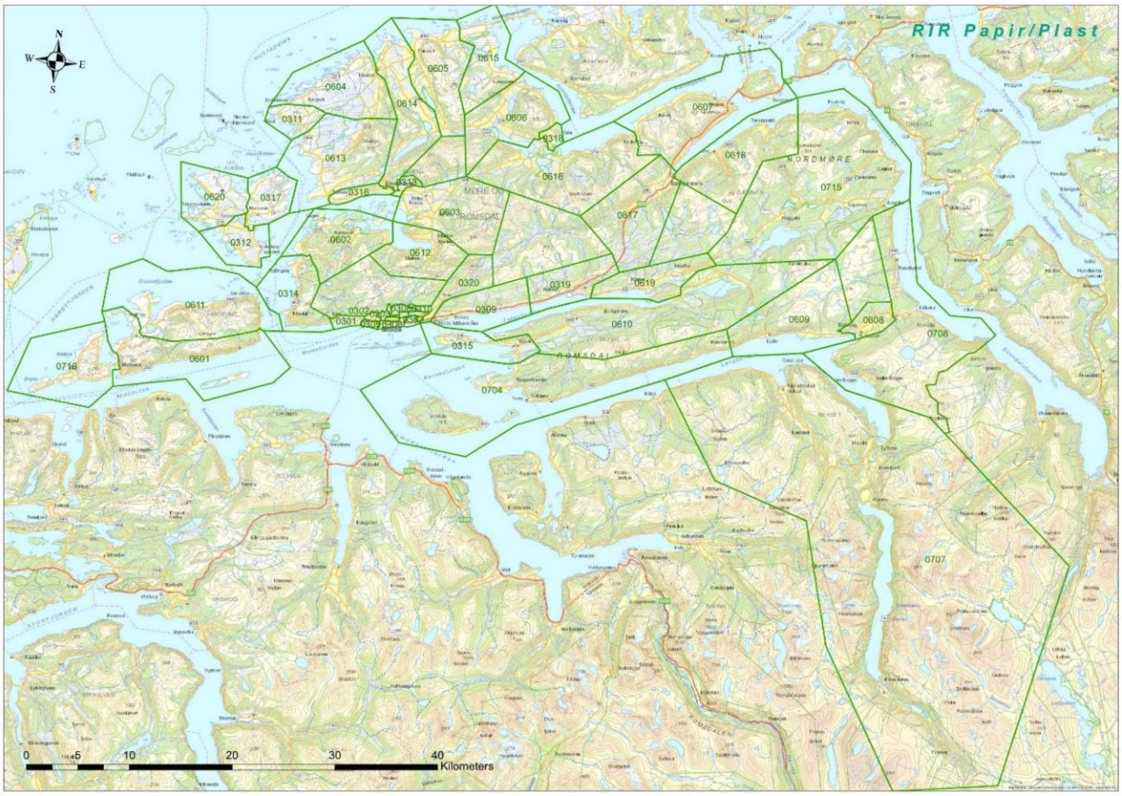

Figure 4 RIR transport zones outside of Molde

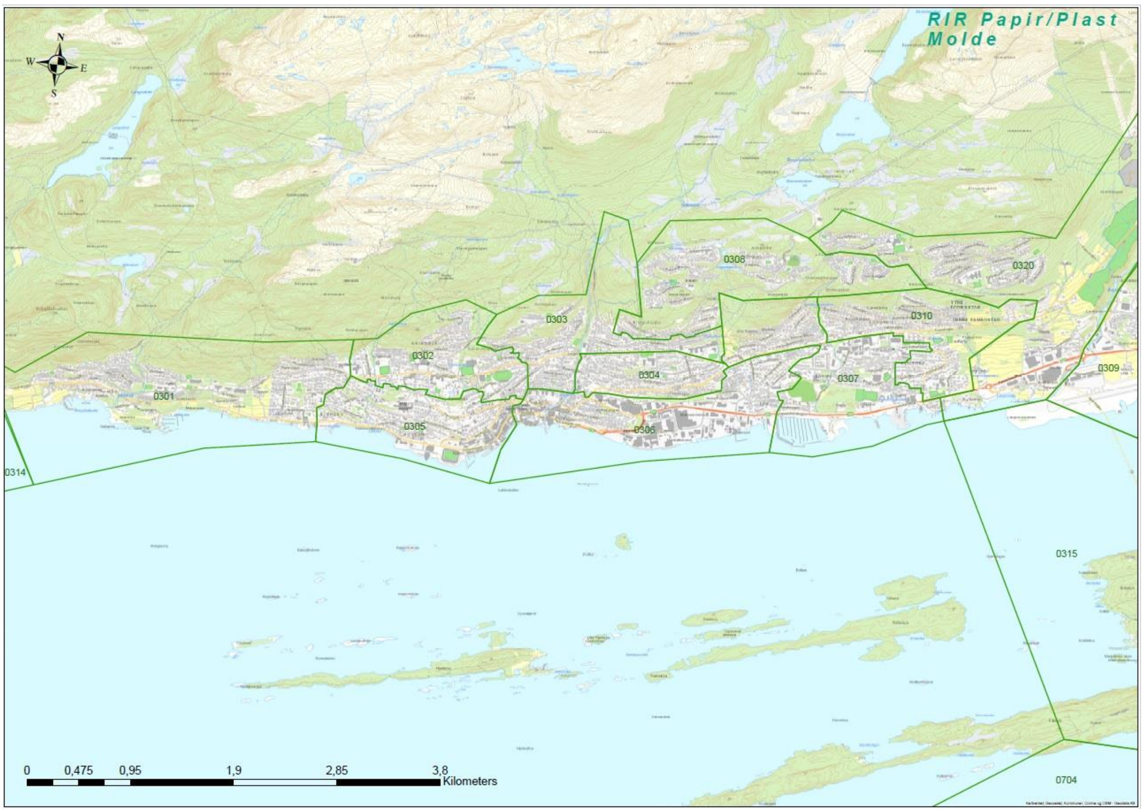

Figure 5 RIR transport zones in Molde

G&M waste collection routes	Corresponding paper waste collection routes	G&M waste collection routes	Corresponding paper waste collection routes
1001	0301	1021	0601
1002	0302	1022	0602
1003	0303	1023	0603
1004	0304	1024	0604
1005	0305	1025	0605
1006	0306	1026	0606
1007	0307	1027	0607
1008	0308	1028	0608
1009	0309	1029	0609
1010	0310	1030	0610
1011	0311	1031	0611
1012	0312	1032	0612
1013	0313	1033	0613
1014	0314	1034	0614
1015	0315	1035	0615
1016	0316	1036	0616
1017	0317	1037	0617
1018	0318	1038	0618
1019	0319	1039	0619
1020	0320	1040	0620

Table 2 Route 1001-1040 and its corresponding routes (with the same service area)

Table 2 shows the G&M waste collection routes and its corresponding paper waste collection routes. Therefore, the geolocation of the G&M waste routes can be referenced in Figure 4 and Figure 5.

The service regions are quite complex when considering transportation between the depot and the service zones. This includes high density city areas where garbage bins are very close to each other, and many rural areas where residential buildings are relatively far from each other, furthermore, it also includes five zones on two islands that require ferry transportation.

3.1.3 Collection strategy

As of today, RIR is using zoning proposed by an external logistics consultancy company serval years ago. Waste collection vehicles drive predefined routes to collect pre-sorted waste with different picking up frequency to the designated areas.

The waste collection zones are the same for bio-waste, plastic and paper, glass and metal, residual waste (Restavfall), however, picking up frequencies varies depends on waste type as described in section 1. There are four vehicles dedicated for residual waste collection, two vehicles for plastic and paper waste collection, one vehicle for glass and metal collection. The service frequencies for the residences are every second, fourth and eight weeks for the corresponding waste types.

3.1.4 RIR data in 2019

To reduce research complexity, this thesis will only look at the data of metal and glass waste collection. The following data was provided:

- Route pick schedule
- Route map
- Route length
- Weight of collected waste for each trip in the period
- Time used for each trip in the period

This research will mainly use the data collected during 2019 regarding to the relationship of the operation time, driving distance, collected waste etc.

3.2 Data visualization

In order to provide an overview of the collected data, the raw data from RIR in 2019 has been grouped, summarized, sorted, and then plotted in this section. The raw data grouped in tables has also been attached in Appendix 1.

3.2.1 Waste collection routes

As of today, the glass and metal collection vehicle under discussion covers 40 service regions, thus, 40 routes are planned for the vehicle. Each of the routes take up to one working day to cover, and it takes 40 working days to cover the whole service area. The pickup schedule is a repeating strategy, which means the routes are repeated exactly after 40 working days.

The lengths of each route are shown in Figure 6 (Route length in the figure are approximations, this is due to the limited data available for these routes). The total route length of each service zone includes service region internal route length and the trip back and forth between the service zone and depot are shown in different colors. The average route length is 111 km for the 40 service regions. Details can be found in Appendix 1.

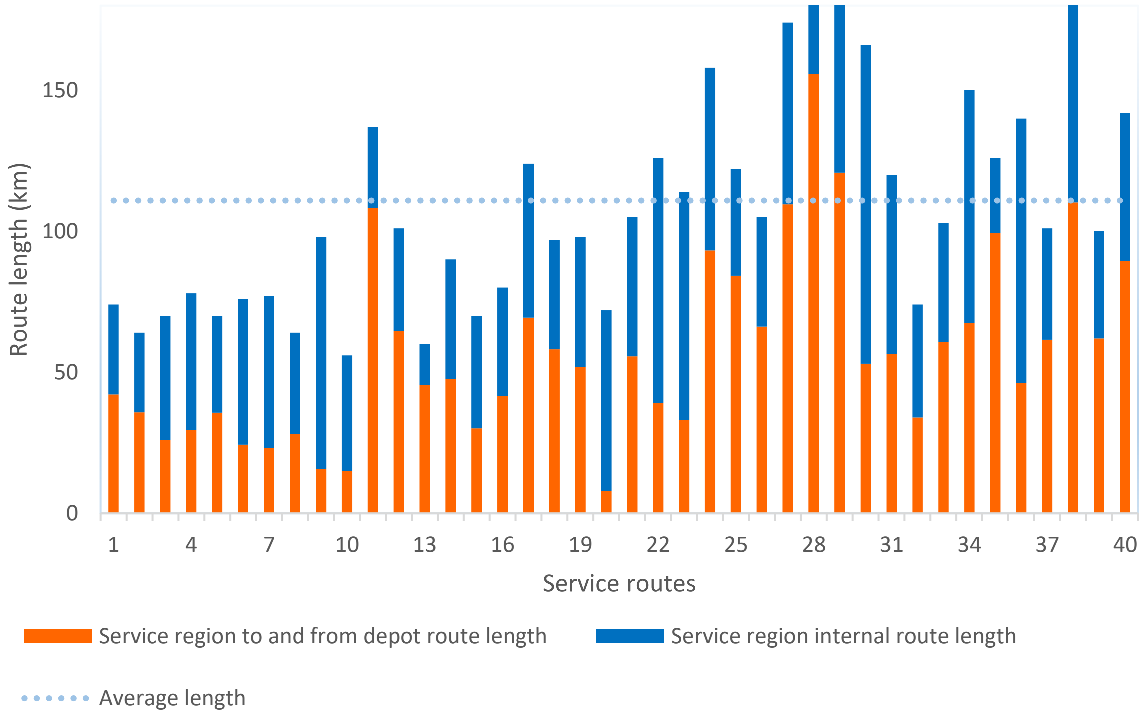

Figure 6 Glass and metal collection route length

3.2.2 Drive duration

According to Norwegian work regulation, the daily working hours is typically 7.5 hours or 450 minutes. During this time, the vehicle is driven and operated by the driver (sometime with extra operator dedicated for bring the trash bins to truck and return them after emptying). Therefore, if more time is needed to complete the work, it is expected that operator(s) has to work overtime with additional compensation scheme from the employer. Thus, driver working hours is one of the constraints of this waste collection problem in RIR. Since the drive duration directly reflects the working hours of the driver and the waste collection operation time, the drive duration data of each service region is considered as the waste collection operation time in each route. The data from 2019 indicates that each route was driven around 6 times. Due to uncertain factors like traffic congestion, difference in amount and so on, the duration was not exactly the same in these six occasions. Therefore, the standard deviations were also been calculated. Figure 7 presents the drive duration statistical average of drive duration on each route and its standard deviation, the ferry time (include back and forth) for each route is also included in the figure.

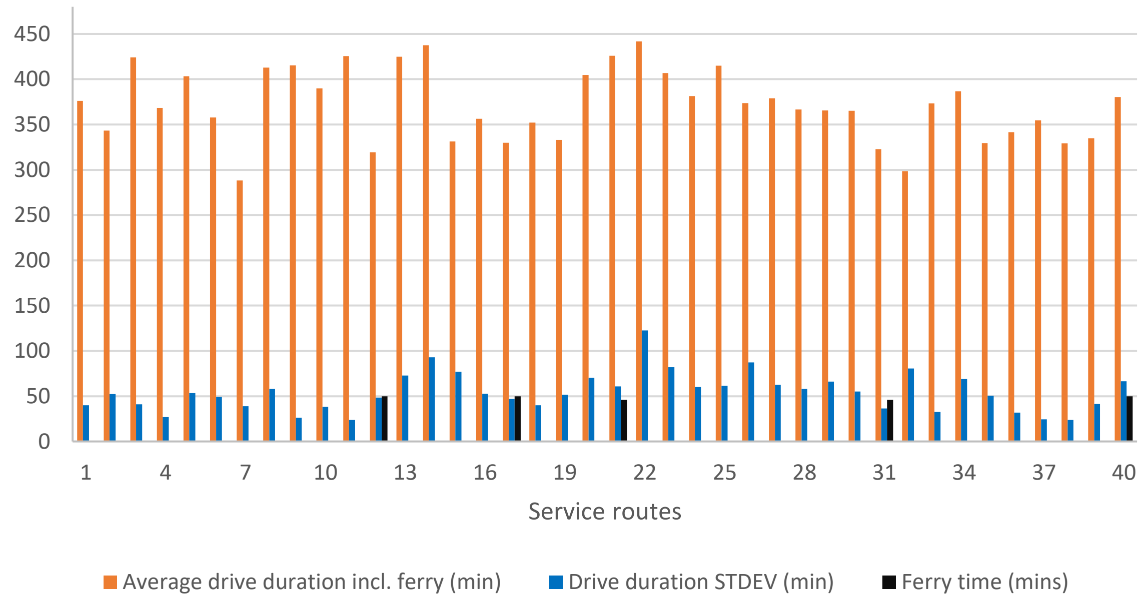

Figure 7 Drive duration, standard deviation and ferry time

3.2.3 Collected wastes

The vehicle capacity among with the drive duration are the two key constraints for this waste collection problem in RIR. Vehicle capacity determines the total collected waste weight can be retrieved, and this collected waste weight reflects the demands of the customers in each route. Figure 8 includes the regions' collected waste average weight together its standard deviation in each route.

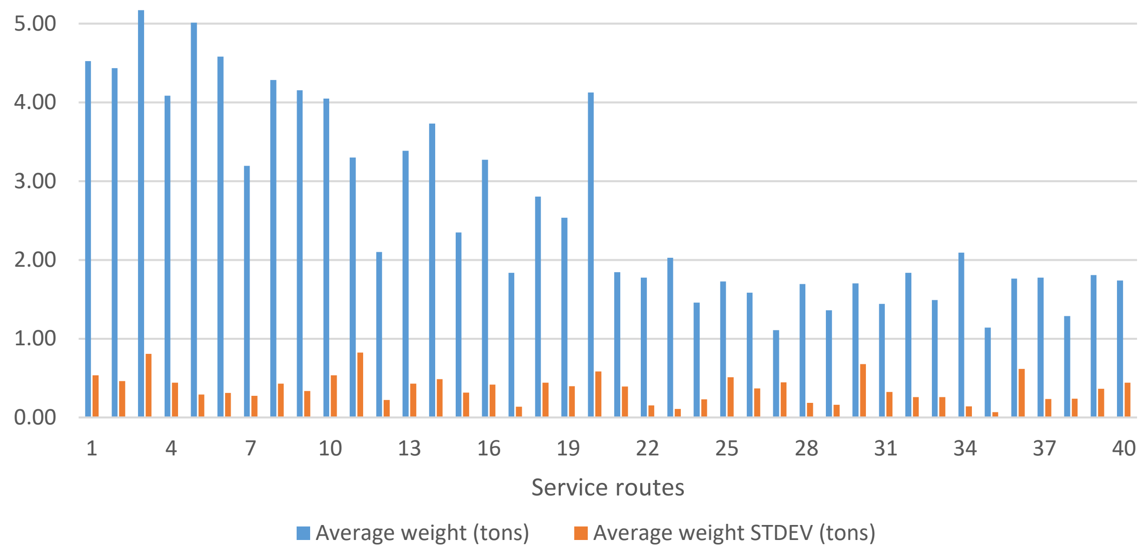

Figure 8 Weight of collected waste (statistical data in 2019)

Due to high service level requirement from the community, all routes need to be served on schedule, which means the waste collection schedule are strictly followed. If the collected waste on a route exceeds the vehicle capacity, an early return to depot for unloading wastes and return to the service region for completion the rest of service is required, such violation of capacity constraints cause considerably more driving distance and overtime.

3.2.4 Customer demands

The collected waste weight is closely related to customer's demands which can be reflected by size of its trash bin been chosen. Therefore, total volume of the trash bins in each service route are a main factor of the customer demands in its service region. The total volume of the trash bins in a service region consists of different types trash bin volumes, these trash bins are selected by customers as described in section 3.1.1. Figure 9 shows total volumes of the trash bins on each route. Larger (volume) trash bin on customers side usually reflect larger demands, therefore, the total volumes are used to reflect customer demands.

Figure 9 Trash bin total volumes

3.3 Existing problems

According to the data provided, a few known problems can be found in the glass and metal collection routes. This includes low filling rate, frequent capacity overflow etc. These problems eventually cause higher operational cost and reduces customer satisfaction.

3.3.1 Low filling rate

Glass and metal waste collection vehicle has a weight capacity of 4 tons, however, a big portion of the routes (25 out of 40) has less than 70% of that capacity being filled. This means the number of households being serviced or its demands are too small in those routes. It is worth to mention that the route 1001 to 1010 are the Molde urban region and which is closer to the vehicle depot, and route 1011 to route 1040 are zones located further away (rural areas). The zones in rural areas normally located further away, although a few of the rural routes are close to the depot as well. This is particularly the case for route 20 which has high filling rate as shown in Figure 8. Furthermore, the increased order of statistical average waste collected (demands) on each route has been presented in Figure 10. As shown in the figure, route 12, 15, 17, 18, 19 and all routes between 21 and 40 have a relatively low filling rate even if the weight deviation is considered.

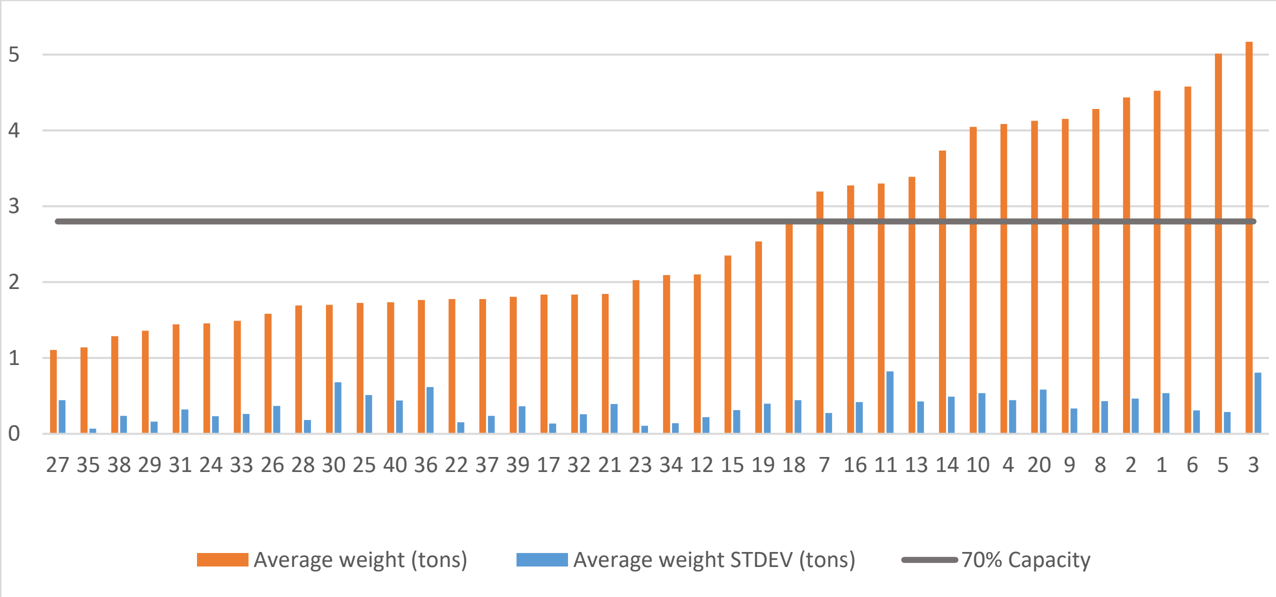

Figure 10 Collected waste weight in increased order

As mentioned in section 3.2.3, the waste collection vehicle may return to depot multiple times if needed. On some of the urban routes, multiple returned appeared, according to the data described in section 3.3.3. Some routes are frequently overfilled, and others have a very low filling degree, which is an indication that there could be room for improvement of the collection strategy. Therefore, increase the filling rate on those low demanding regions is very interesting, even if the consequences of exceeding the capacity on routes far away are higher than the routes closer to the depot.

3.3.2 Long working hours

According to the operation time log, the waste collection vehicle has been operated by the operator overtime for 29 days among the 251 pickups in 2019, which accounts for 11.55% of the overall pick up routine. Various reasons may have caused the overtime works, such as longer routes have higher chances that can expose traffic congestions, ferry waiting time etc. and shorter routes that may need to have multiple returns to depot due to higher capacity overflow risks. Each route has around 6 samples which are grouped together and plotted from left to right according to route sequence, therefore, the first 60 samples are the Molde urban routes (route 1001 to 1010) and the rest are the rural area routes (route 1011 to 1040). As seen in Figure 11, most of the overtime appeared on rural routes, this could be the rural routes are longer i.e. vehicle is exposed longer in traffic, therefore, have a higher chance to encounter delays caused by traffic congestion, road work, missed ferries etc.

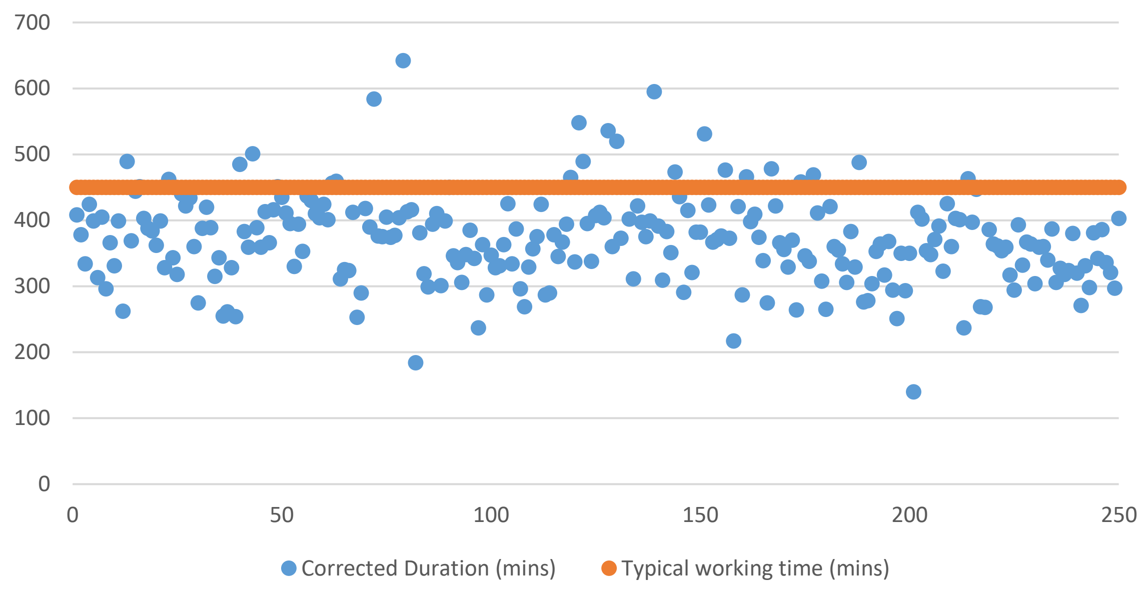

Figure 11 Waste collection vehicle operational time and the typical working time for operators

3.3.3 Capacity overflow

Currently, there are many routes often having overflow issues, according to the statistics 2.4% of the total 251 pickups in 2019 require one extra return to depot. Additionally, 25% of the average weight among the 40 routes exceed the four tons theoretical weight capacity (the real capacity is the volume of the truck dump box), hence, there are high possibilities that those regions need multiple return to depot in current route design and its collecting strategy. In order to compare the relationship among the statistical weight and capacity overflow scenarios, Figure 12 has included both the statistical weight and number of capacity overflow on each route. Due to current system limitation, the exact weight of the waste loaded on the vehicle is not accurately shown to the operator before weighted at depot. Therefore, some of the routes (such as route 1001, 1002, 1004, 1005, 1008, and route 1010) did not return depot even though it has the weight exceeded the vehicle theoretical load capacity. According to Figure 12, routes 1003, 1004, 1009, and 1020 had extra returns to depot, and the first three routes are the urban route, while the last route is in the rural area closest to depot.

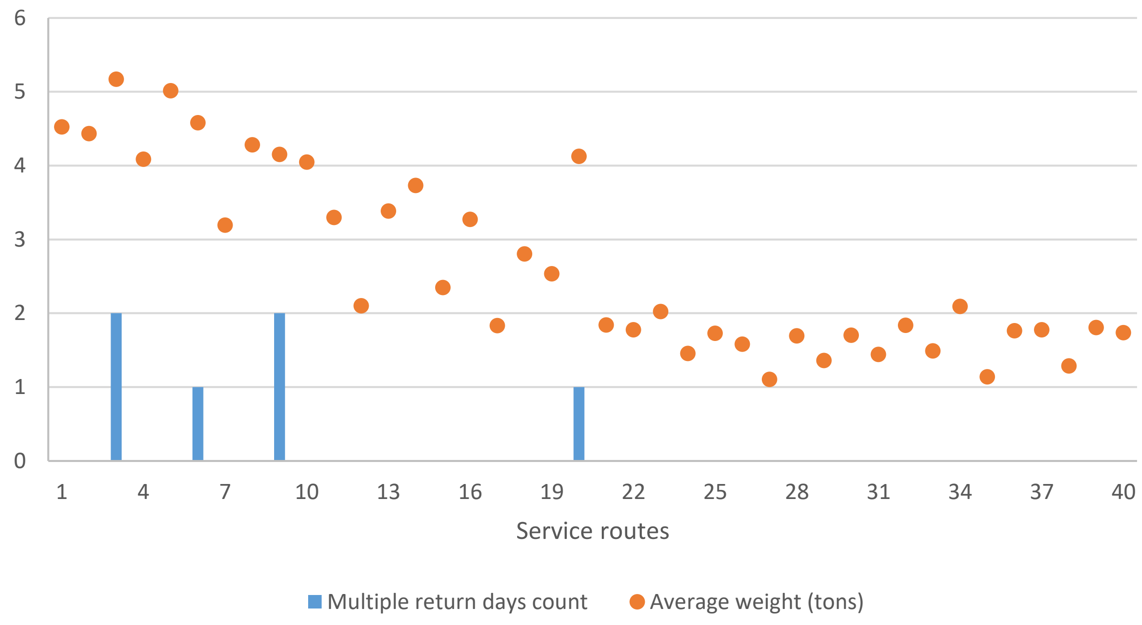

Figure 12 Capacity overflow statistics and average weight of all routes

3.4 Research problem

The goal of the research is analyzing and suggesting possible improvements of the current collecting strategy for glass and metal waste. This research question includes several subproblems such as:

- Should the company change the collection frequency on the routes?
- Are the current collection zones appropriate?
- Is the suggested service degree, defined as frequency, acceptable for the customers?
- What other consequences will appear if changing the strategy.

4 Operational cost and constrain estimation

4.1 Cost estimation for the current collection strategy

The operational cost typical consists of waste collection labor cost; operation management cost, fuel cost, vehicle maintenance cost etc. In order of simplify the cost model, we assume the following criteria in this thesis:

- the waste collection operation manpower cost can be considered as a fixed cost, since the drivers work on a fixed salary. Therefore, it is exempted from the operation cost estimation;
- the vehicle maintenance cost is linear (factor b') to the vehicle drive distances y, and the same for fuel cost (factor b'');

Thus, the vehicle operation cost C is:

$$C = b \cdot y$$

Where:

Vehicle operation cost rate: $b = b' + b''$

Vehicle drive distances y:

$$y = \sum_{i=1}^{251} d_i + \sum_{i=1}^{251} Td_i$$

d_i is the total distance required to complete service of route i, Td_i is the traveling distance between the depot and the service region when day i had extra return to the depot, otherwise $Td_i = 0$.

According to the data in 2019 and above calculation we have:

- The vehicle fuel consumption in 2019 is estimated around 0.86 Liters per kilometer (calculated by dividing 24443.66 liters of fuel consumption and 28427.4 driven kilometers on the vehicle, data in 2019 from RIR). The fuel price in 2019 was roughly 15 NOK per liter. Furthermore, the vehicle maintenance cost is approximately around 10 000 NOK per 10 000 kilometers. Therefore, the vehicle operation cost rate **b** is approximately 14 NOK per kilometer.
- According to the travelling log in Appendix 2, $y = 28427.4$ kilometers (including 115.4 kilometers transportation distance due to required early return to depot), detailed travelling distance log can be found in appendix 2.

Thus, the vehicle operation cost C is estimated to

$$C = 14 \times 28427.4 = 397\,983\ NOK$$

Note that this cost calculation is an approximation, there are many factors may cause small deviations such as the fuel price fluctuation, road work, detours and other unforeseen happenings. Therefore, the result shall mainly be treated as the benchmark for the cost of using the current strategy when comparing to suggested strategy adjustments. Furthermore, the costs are proportional with the driven distance, and hence, it is sufficient to compare the distance when comparing strategies.

4.2 Time and demand estimation

In order to provide new waste collection strategies and its cost estimation, the drive duration (available services) and vehicle capacity (customer demands) and its fundamental cost components are investigated in this section.

4.2.1 Drive duration estimation and its drive components

As discussed earlier in section 3.2.2, drive duration depends on many factors but route length and number of trash bins (i.e. number of stops for pickup) are the two main contributors and they are highly dependent on the region road condition (speed limit) and density of the trash bins. Drive duration can be separated into two parts, the time spent on the transportation back and forth from the collection area and time spent on the pickup (including the travelling between each pickup).

4.2.1.1 Waste transportation

In order to simplify the scenario, average speed between the depot and service region is set to 60 km/h (this is a realistic number as the speed limit might be higher in rural area or highway, but cross road and congestion make it difficult to achieve a higher speed). Since the travel distance between depot and service region are given, the time spent on the transportation T_r is listed in Table 3:

Route	Transport time (mins)	Route	Transport time (mins)	Route	Transport time (mins)	Route	Transport time (mins)
1001	42	1011	108	1021	102	1031	102
1002	36	1012	115	1022	39	1032	34
1003	26	1013	46	1023	33	1033	61
1004	30	1014	48	1024	93	1034	68
1005	36	1015	30	1025	84	1035	100
1006	24	1016	42	1026	66	1036	46
1007	23	1017	119	1027	110	1037	62
1008	28	1018	58	1028	156	1038	110
1009	16	1019	52	1029	121	1039	62

1010	15	1020	8	1030	53	1040	140

Table 3 Transportation time between depot and service region

4.2.1.2 Waste collection

Waste collection time includes the time spent from the waste collection vehicle enters service region until it exits the zone. Household density or density of the trash bins varies between regions, therefore, if the household are evenly distributed among each service region, the time spent in the region can be calculated by pick up speed multiplies the number of houses. Thus, the average pickup speed can be calculated in each region based on total drive duration, transportation time, and number of trash bins in the region. Table 4 listed the pickup speed (average time per pickup) P_r.

Route	Average pickup (Seconds)	Route	Average pickup (Seconds)	Route	Average pickup (Seconds)	Route	Average pickup (Seconds)
1001	46	1011	60	1021	89	1031	93
1002	47	1012	61	1022	93	1032	58
1003	46	1013	51	1023	77	1033	95
1004	46	1014	50	1024	81	1034	70
1005	56	1015	51	1025	98	1035	84
1006	50	1016	45	1026	79	1036	73
1007	43	1017	52	1027	100	1037	80
1008	52	1018	41	1028	76	1038	92
1009	43	1019	51	1029	93	1039	67
1010	48	1020	46	1030	99	1040	84

Table 4 Average time per pickup in each route

The primary focus of this thesis is collecting frequency, however, if merging of zones would be considered. The distance could be calculated this way: if route 32 and 35 are two neighboring region and region 35 are decided to be merged to 32, the estimated new duration D_{32}^{e} could be calculated as:

$$D_{32}^{e} = D_{32} + D_{35} - Max(T_{32}, T_{35})$$

Where D_{32} and D_{35} is the current service duration for region 32 and 35, and we assume that the adjacent routes 32 and 35 can be driven in a way starting and ending at the same point as the route closest to the depot.

4.2.2 Demand estimation

Typically, the waste expected to be collected (or demands by households) in a region is linear to its trash bin total volume. RIR provides 5 different type of glass and metal trash bins to the public, Figure 13 shows the composition of the different size of trash bin that distributed in its service area. Theoretically, the demand estimation is more accurate to look at the volume of trash bins when compared with using trash bin count, this is due to the volume of trash bin size are not one size. However, since the majority of the trash bins are 140L version (accounts for 92.76% of the overall volume), to simplify the calculation, this thesis will use 140L trash bins count (household count) for the demand estimation. Thus, since the trash bins are considered as one-size and each household generates the same amount of the waste, the expected waste per household R_r^e can be calculated as shown below:

$$R_r^e = \frac{W_r}{N_r}$$

Where W_r is the average waste collected in route r. N_r is the number of trash bin (household) in route r. R_r^e on each route is shown in Table 5 below.

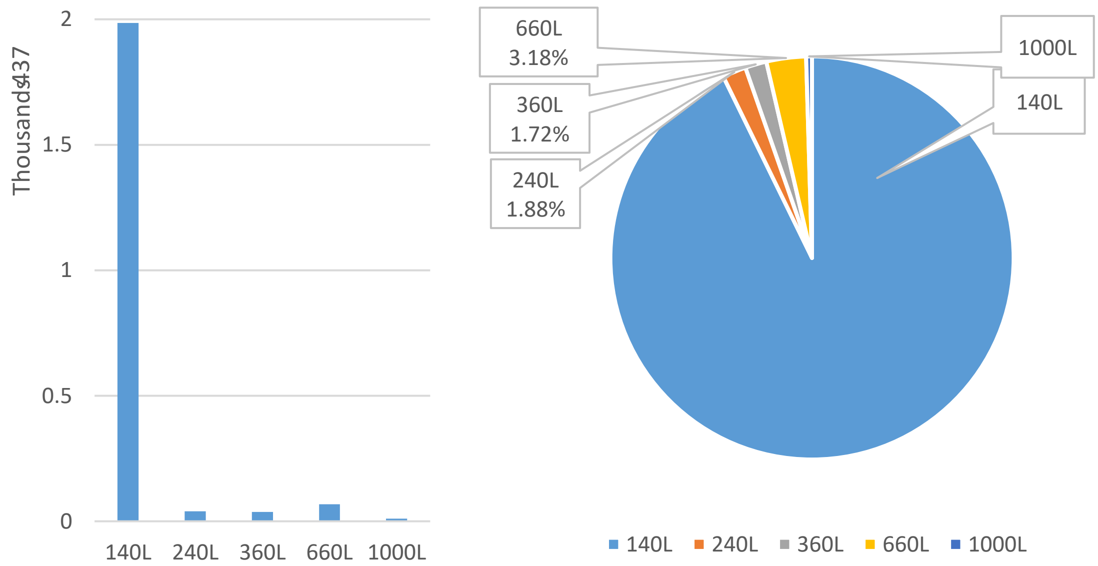

Figure 13 Trash bin types and volumes in RIR service area

Route	Average waste (kg/house)	Route	Average waste (kg/house)	Route	Average waste (kg/house)	Route	Average waste (kg/house)
1001	9.28	1011	7.75	1021	6.41	1031	6.92
1002	10.14	1012	7.32	1022	6.54	1032	5.92
1003	9.68	1013	7.09	1023	6.74	1033	6.29
1004	8.54	1014	8.26	1024	5.16	1034	6.30
1005	11.68	1015	6.04	1025	6.81	1035	4.85
1006	10.73	1016	6.93	1026	5.94	1036	6.24
1007	7.92	1017	4.80	1027	5.61	1037	6.69
1008	8.99	1018	5.38	1028	5.83	1038	6.00
1009	7.12	1019	6.68	1029	5.79	1039	6.01
1010	8.25	1020	7.76	1030	7.66	1040	6.37

Table 5 Average waste per household in each route

5 Optimization approach

In order to tackle the problems described in section 3.3, this thesis will discuss two possible approaches:

- Reduce the waste pickup frequency (of low filling rate zones)
- Re-arrange pickup frequency of all routes based on statistical demands

5.1 Reduce pickup frequency

As described earlier in section 3.2.3 and 3.3.1, many routes (12, 15, 17, 18, 19 and all routes between 21 and 40) utilize less than 70% of the vehicle capacity. These routes can be serviced with less frequency (longer interval) to increase the filling rate (pick up efficiency), therefore, operation cost may be reduced. In this section, a new reduce visiting frequency strategy will be introduced to these routes and cost saving estimation will be provided.

In order to find the new strategy's operation cost, we assume the original strategy's resource requirement for a complete service cycle (service all 40 zones exactly once) is 1 resource unit R, R is the resources used during a 40 days period. Therefore, every route requires 1/40 unit of resources R to complete the service, this is due to each route require similar amount of time (a complete working day) to complete the service.

Thus, for any new frequency F reduction strategy (note: $F = \frac{1}{\mathrm{I}}$ where I is the pickup interval for each zone), we have the following formula for the resource requirement R' for service a time period T that consume one unit of the original resource R exactly once, in this case, the new resource usage R' in the period T can be described as:

$$R' = \sum_{i=1}^{40} F_i$$

Take an example of reduce the frequency to 50 days for the route 12, 15, 17, 18, 19 and all routes between 21 and 40. The maximum capacity which can be expected for these routes are $70\% \times \frac{50}{40} = 87.5\%$ (there are some variations, but the uncertainty should still be within an acceptable level. Most of the routes have a lower utilization degree than 70%, making it even more unlikely with an overflow.). Therefore, the collection vehicle is still able to collect the waste without extra return to depot. Furthermore, the new resource requirement $R' = \frac{1}{40} + \frac{1}{40} + \cdots + \frac{1}{50} + \frac{1}{50} = 0.875$, a R' value below 1 means the new strategy can be achieved without additional resources vice versa. Theoretically, approximately 12.5% $(1 - R')$ of the working days could be reduced for glass and metal operation, i.e. the operators which were assign to glass and metal waste collection operation in the current strategy could have 12.5% of its working hours (and this also corresponds to the vehicle being idle every 8th day) for other tasks.

Furthermore, the total traveling distance

$$y' = \sum_{i=1}^{40} d_i \cdot N \cdot F_i$$

where d_i is the total distance required to complete service of route i, F_i is the new route frequency, N is 251 which is the number of days glass and metal had carried out pickup service in 2019. Here we assume all the routes are strictly serviced according to its frequency, however, in the real world this is not the case due to the number of visits can only be integers. It's worth to mention that all cost calculations in this chapter are theoretical approximation, this is due to the fact that in a specific time window the actual pickup interval of a route is not always guaranteed matching with its frequency that used in the cost calculations.

$$y' = 74 \times 251 \times \frac{1}{40} + 64 \times 251 \times \frac{1}{40} + \cdots + 142 \times 251 \times \frac{1}{50} = 23732\ km$$

$$C' = b \cdot \sum_{i=1}^{40} d_i \cdot N \cdot F_i = 14 \times 23732 = 332\ 249\ NOK$$

The current strategy's (theoretical corresponding) traveling distance can also be calculated in the similar way:

$$C' = 74 \times 251 \times \frac{1}{40} + 64 + \cdots + 142 \times 251 \times \frac{1}{40} = 27\ 836\ km$$

Therefore, vehicle operation cost could be reduced by:

$$\left(1 - \frac{23732}{27836}\right) \times 100\% = 14.8\%$$

Thus, the new strategy could save around 15% of the vehicle operation cost (i.e. fuel, vehicle maintenance costs etc.), furthermore, if the operator could be assigned to other tasks (other than the glass and metal collection), the overall work load and labor cost could be reduced especially for other overloaded tasks in RIR.

The aforementioned cost estimation is benchmarking comparison of the original strategy. The calculation is based on the assumption that the new strategy has been implemented in 2019. As there are minor route frequency and working days variances in different years.

5.2 Strategy change caused route scheduling issues

5.2.1 Pickup routine scheduling problem

It is easy to schedule the pickup routine if all routes have the same pickup frequency or interval, where the pickups can be a simple recurring routine that each route was visited exactly at the same sequence in each recurring cycle. However, since the example mentioned above does not have the same frequency, the pickup routine has to be planned so that routes has higher frequency requirements been visited more often (or the pickup interval for such routes needs to be shorter) than others. Therefore, a heuristic search method is introduced in this section to provide a viable scheduling solution.

First of all, like many other heuristic search algorithms, the scheduling problem for a period can be decomposed to (a successor states which is) a schedule problem on a certain day. If, for example, a N days vehicle schedule is needed. The heuristic search can separate to N times successor states.

Secondly, among each of its successor states we may use greedy algorithm approach, which, in this case is to find the most suitable route to be served. In order to find out this suitable route to be served, a test condition: **awaiting days before it has to be served** is introduced on all the routes every day (each successor states). For example, if we assume the test conditions for day n is 1, 2, 3, …, 39, 40 from route 1001 to 1040 and the service interval I_r is 40 for all route. It is obvious that the route with the least amount of awaiting days to be served, is the most suitable route to be serviced. In this case, route 1001 is selected as it is just one day before it has to be serviced. Meanwhile, since there are no other routes has same or higher priority in this specific example, service route 1001 is the local optimal solution for day n.

Furthermore, before moving to the next successor state's scheduling problem (schedule for day n+1), the test condition for this state (day n+1) needs to be updated. i.e. when route 1001 is selected and to be the schedule of day n, its test condition for the following day has to be updated to $\boldsymbol{40}$, 1, 2, …, 38, 39. This is due to the new service requirement of route 1001 is updated to the service interval $I_r = 40$, since it has just been serviced, and do not expect another service until 40 days later. Besides, since the other routes has not been services, their awaiting days to be serviced have deducted by 1, to reflect the awaiting days has been one day less than it was on day n.

Lastly, recurring the same approach until day N.

Hereby, the aforementioned approach can be described by the **Algorithm 1** shown below:

```
Define Ir_Array[40]        //Preferred service interval
Define daysAwaitToBeServed_Array[40],
Define Schedule_Array[totalDaysToBeScheduled];
FUNCTION Main()
FOR i FROM 1 TO numberOfDaysToBeScheduled DO
        minValueIndex = findMinValueIndex(daysAwaitToBeServed_Array);
        Schedule_Array[i] = minValueIndex;
        daysAwaitToBeServed_Array[minValueIndex]= Ir_Array[minValueIndex]
        FOR j FROM 1 TO 40 DO
                IF j <> minValueIndex THEN
                        daysAwaitToBeServed_Array[j]=daysAwaitToBeServed_Array[j] – 1;
                ENDIF
        NEXT j
NEXT i
FUNCTION_END
```

In the aforementioned Algorithm 1, *daysAwaitToBeServed* is the test condition and needs to be initialized with the desired values. Take the original pickup strategy 40 days service interval (for the 40 routes) as an example: at any given date, this array always consists of 40 members which ranges from 1 to 40. If route 40 has just been serviced before the scheduling day started, the initial test condition would become [1, 2, 3, …, 38, 39, 40] and this is the initial array *daysAwaitToBeServed* used in the algorithm.

It is easy to tell, the route schedule from the day n to day n+40 is 1001, 1002, … 1039, 1040. And its test condition for day n+41 become exactly the same as day n, hence, the schedule is recurring pattern. However, if the $I_r$is not a fixed number this becomes interesting.

If we assume day n test condition is still 1, 2, 3, …, 39, 40 from route 1001 to 1040, but the service interval I_r is 40 for r between 1 to 20 and I_r is 60 when r is between 21 to 40. It is easy to tell from day n to day n+40, the schedule is 1001, 1002, … 1039, 1040 but the test condition on day n+40 has now been updated to 1, 2, … , 19, 20 between route 1001 and 1020 and 41, 42, … , 59, 60 for route between 1021 and 1040. Therefore, the scheduling from day n+60 became the turning point, where both route 1 to 20 and route 21 to 40 has the same test conditions (21, 22, … , 39, 40, 21, 22, … , 39, 40), according to the Algorithm 1, both route 1 and 21 will have their next planned visit 21 days ahead, but since no other routes have an earlier planned visit, they are selected for a visit in day n+61 and n+62, similarly, route 1002 and 1022 will be visited in day n+63 and n+64. As seen from this pattern, the test conditions are gradually starts diverting the route with different frequencies and eventually provides a pickup frequency (pickup interval) that is close to what has been requested. Hence, the scheduling of the pickup routes with different frequency can be made with the help of the aforementioned method.

In order to verify the scheduling result from the aforementioned algorithm 1, an Excel VBA project is made, and the source code is also attached to Appendix 3. Figure 14 provides a possible scheduling quality result when using the example case as discussed earlier in this section. The quality result is checked by looking at the minimum awaiting days after find the schedule on each day, i.e. the smallest number in the test condition row. This quality indicator covers all 750 days been scheduled after day n (in x-axis) and the y axis is showing the remaining days before a route is been serviced. Therefore, the y axis shows how good is the schedule quality, i.e. the closer to x-axis (from a value in y axis), the better the scheduling result. This is due to the y axis represents the days before a route is been serviced, a positive value means a route is served number of days ahead of required service interval, which is not good for the pickup efficiency. On the other hand, a negative value means a route has not been serviced in time according to the scheduling plan.

From the schedule quality result, it indicates there are basically two phases: settling phase (before day 200), and stable phase (after day 200). As shown in Figure 14, there are some difficulties to meet the request interval at the given initial condition especially in the in the settling phase. However, the schedule quality is relatively consistent after entering stable phase between day 300 and day 750. As figure shows, such schedule plan is expecting an 8 or 9 working days ahead of the required service interval, i.e. if a route request 60 days service interval, the actual service interval been scheduled (by this algorithm) is around 51 or 52 days, and the route request 40 days, will ended up in 31 or 32 days. Please be aware that each dot plot has only one unique y axis value, however, due to the low resolution in the figure, the dots plotted on y axis has overlapped to the adjacent dots which make them looks like two parallel lines.

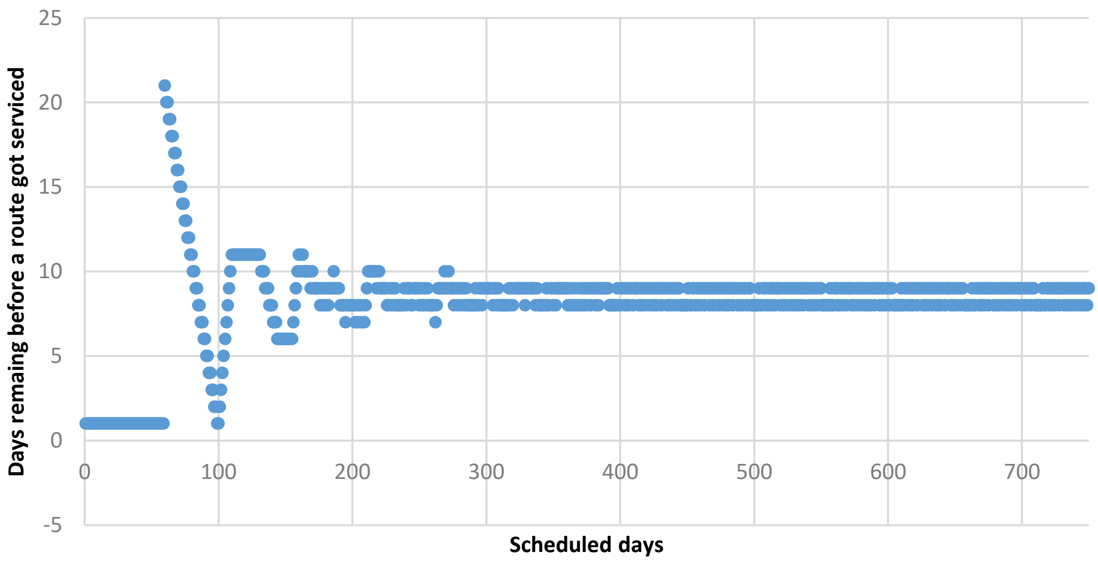

Figure 14 Scheduling quality from a possible data input (using algorithm 1)

Similarly, the strategy discussed in section 5.1 may also use such algorithm to solve route scheduling problem. Therefore, the solver can be initialized with the following setup: 1) service interval; 2) initial test conditions (day of the first visit). Where:

1) 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 50, 40, 40, 50, 40, 50, 50, 50, 40, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50
2) 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40

Therefore, the result for the scheduling quality for strategy mentioned in section 5.1 is shown in Figure 15. Where all of the routes will be ended up being serviced 6 or 7 days ahead of the scheduled interval (after entering the stable phase).

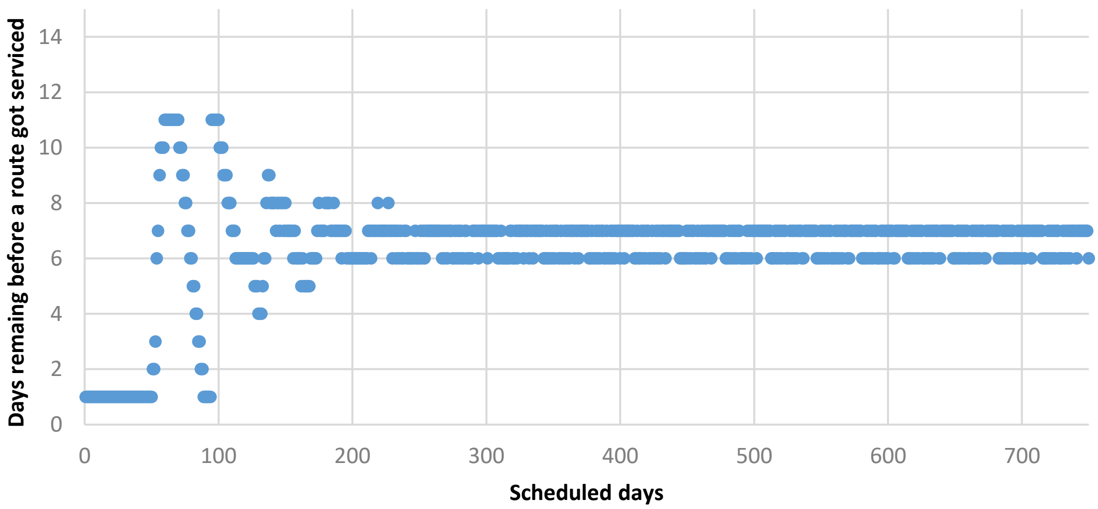

Figure 15 Scheduling quality for reduce frequency strategy (using algorithm 1)

5.2.2 Excessive resources

It is easy to notice that, in Figure 15, the route scheduling has visited the routes more often than necessary (around 6 and 7 days ahead of schedule in average). This is due to the frequency reduction caused resource redundancy on the service provider side. According to discussion in section 5.1, the expected spared resources is 12.5% ($(1 - 0.875) \times 100\% = 12.5\%$) for a 40 days period, however, such spare resource has already been utilized by servicing regions more frequently (shorter service intervals than necessary) in section 5.2.1. In order to avoid waste on resources, spare resources have to be planned (to be used for other tasks), otherwise, the strategy may reduce its effect on the cost saving. This is because the time used for the pickup will not be changed due to the daily tasks are fully booked, additionally, the total actual travelling distance $y'' = N \cdot \sum_{i=1}^{40} d_i \cdot F_i^t$, where F_i^t is the actual (true) frequency, since F_i^t is always larger or equals to F_i (theoretical frequency) if schedule is created based on Algorithm 1 in section 5.2.1. Therefore, the vehicle operation cost could be reduced further with spare resource planning.

In order to achieve the cost saving discussed in section 5.1, the following addition is included to the Algorithm 1 in section 5.2.1:

- a new route (for reserving the spare resources. And when this route, 1041, is chosen, in fact the vehicle is parked for that day) is added to existing routes with the following set up
    - the new route will take all the spare resources ($R_s = 1 - R'$, where $R' = \sum_{i=1}^{40} F_i = 0.875$, thus, $R_s = 0.125$) that remains after the service frequency change
    - the spare route service interval $I_s = round\left(\frac{1}{R_s}\right) = 8$
    - the spare route test condition for day n is initialized with 40 (the largest among the first 40 routes)

Therefore, the strategy discussed in section 5.1 may also use the same algorithm to solve the route scheduling problem. i.e. the solver can be initialized with the following setup: 1) service interval; 2) initial test conditions. Where:

1) 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 50, 40, 40, 50, 40, 50, 50, 50, 40, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, **8**
2) 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, **40**

Thus, the improved scheduling quality for strategy mentioned in section 5.1 is shown in Figure 16 (an improvement for the given example represented in Figure 15), where the same scheduling of 750 days are planned but for a total of 41 routes instead of 40. From the figure we can see after day 200, the schedule can always ensure the service accuracy is within 3 days of the planned pickup interval, i.e. the unnecessary early visit is avoided. After day 200, the frequency will be stabilized (routing days entered stable phase). Besides, the improved solution also means the planned spare resource can be reserved for other tasks once in every 8 days, and such resources could be assigned to other tasks in RIR if needed.

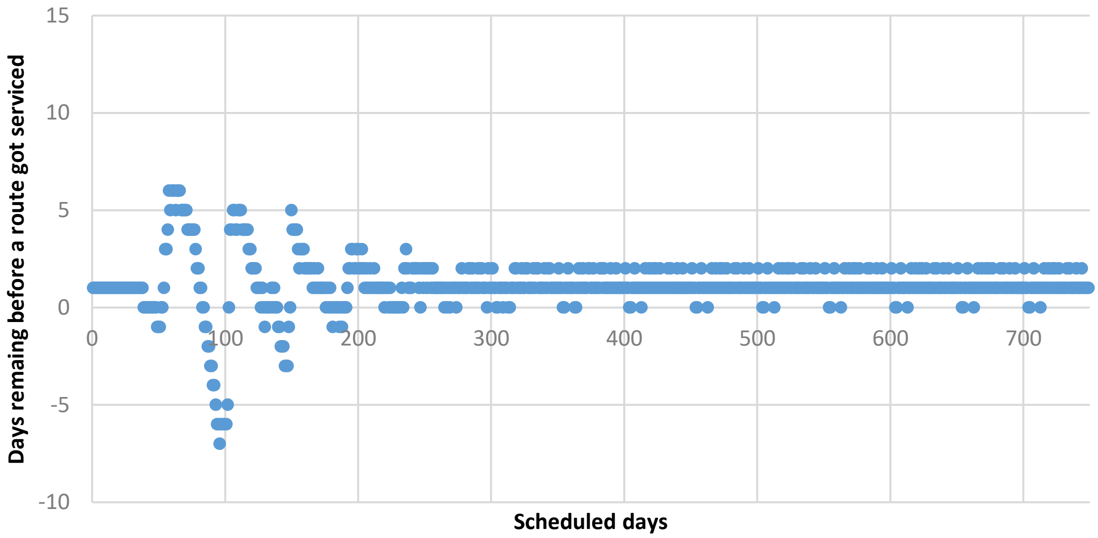

Figure 16 Scheduling quality for reduce frequency strategy (using improved algorithm 1)

Similarly, given example (service interval I_r is 40 for r between 1 to 20 and I_r is 60 when r is between 21 to 40) scheduling quality indicator in Figure 14 can be reduced from maximum 9 days down to maximum 2 days ahead of schedule through aforementioned spare resource planning. Therefore, the solver can be initialized with the following setup: 1) service interval; 2) initial test conditions. Where:

1) 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, **6**
2) 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, **40**

The improved scheduling quality result (an improvement for Figure 14) is shown in Figure 17.

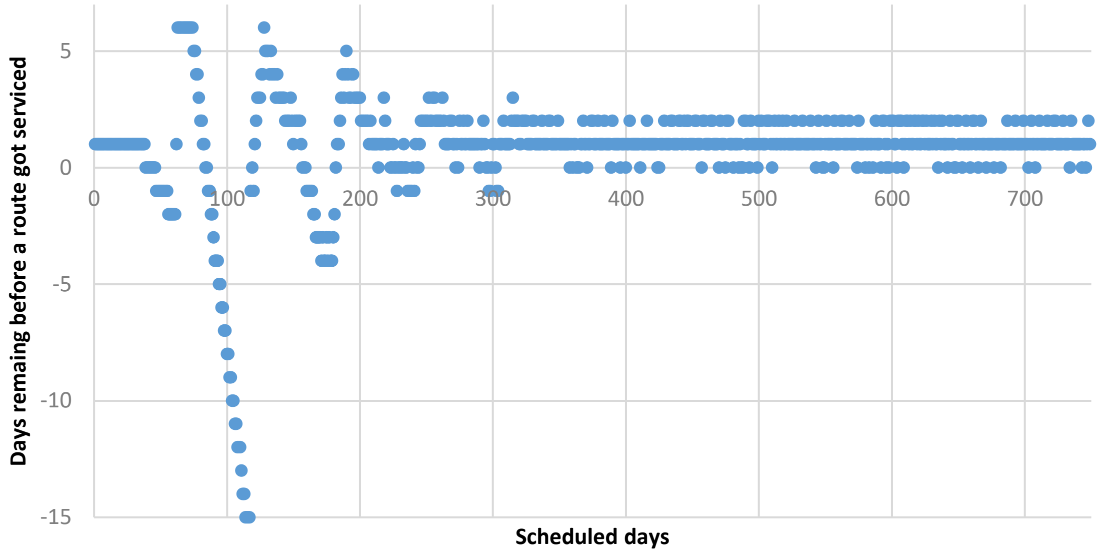

Figure 17 Scheduling quality from a possible data input (using improved algorithm 1)

5.2.3 Settling phase

It is noticeable that in Figure 17 there are a few serious **service schedule violations** (at around day 100) where some routes encountered up to 15 days of delay after the planned pickup dates. This is caused by the limited resources available during the **settling phase** (before a stable resources is available, in this case, between day 1 to day 156 according to Figure 14), thus, the spare resource route 41 may be put low precedence during the period. Such approach can be achieved by postponing the start of planning spare routes during this phase, i.e. the route 41 can be postponed for 156 days on purpose. Therefore, the spare route test condition for starting day is extended from 40 to 156 days to avoid the spare route from been planned in the settling phase. Therefore, the solver can be initialized with the following setup: 1) service interval; 2) initial test conditions. Where:

1) 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, **6**
2) 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, **156**

The further improved schedule result is achieved as shown in Figure 18. The violation is now reduced to a maximum of 2 days instead of 15 days from the original spare route planning strategy discussed in section 5.2.2. The scheduler Excel setup can be found in Appendix 4.

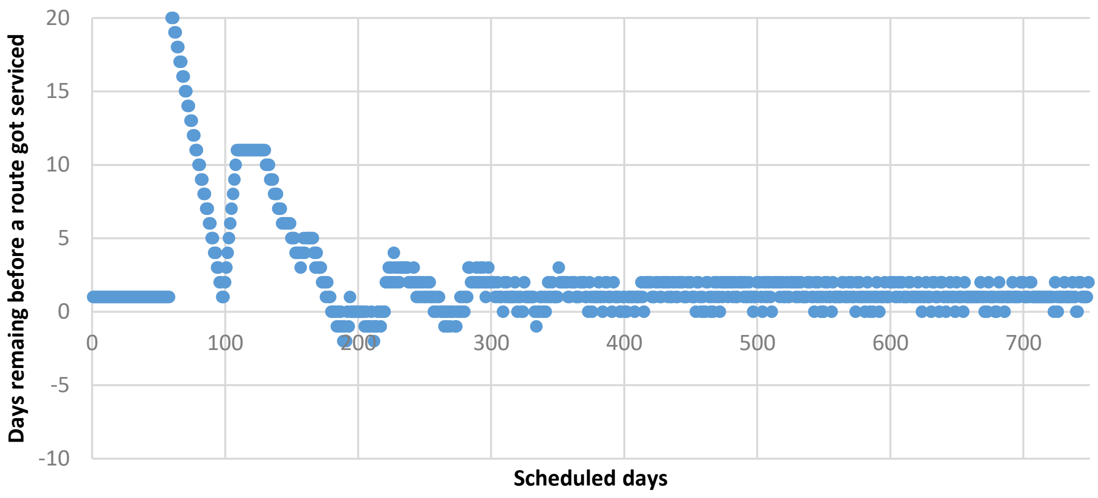

Figure 18 Scheduling quality from a possible data input (postpone 156 days before implement spare route)

Similarly, the postponing of spare route may also be introduced to the strategy discussed in section 5.1. Therefore, the solver can be initialized with the following setup: 1) service interval; 2) initial test conditions. Where:

1) 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 50, 40, 40, 50, 40, 50, 50, 50, 40, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, 50, **8**
2) 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, **160**

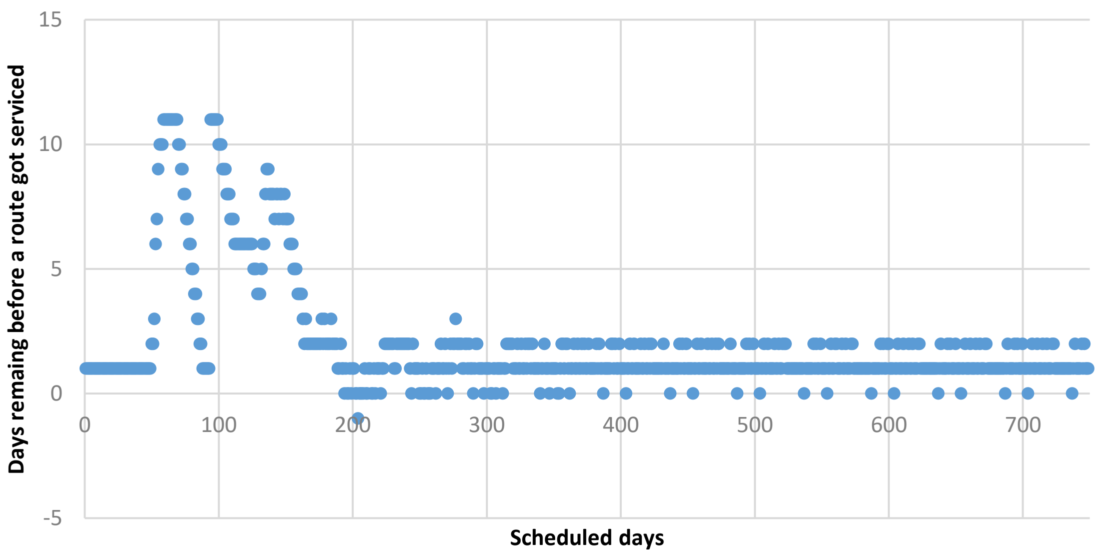

Figure 19 Scheduling quality reduce frequency strategy (postpone 160 days before implement spare route)

As shown in Figure 19, the maximum violation days is reduced from 7 days to 1 day. According to aforementioned discussions, it’s also noticeable that all cost calculations in this chapter will be influenced due to the actual pickup intervals are shorter than planned even in stabilized phase (most of the routes have a few days ahead of scheduled pickup time) i.e. the actual spare resource will be less than calculation, thus, the actual savings is expected to be less than the theoretical calculation in this chapter.

5.3 Dynamic pickup frequencies

Some of the regions have small number of clients, but the garbage collection vehicles still need to cover such routes where small amount of waste is expected. If we may reduce the service frequency on those regions, i.e. increase service interval awaiting more waste being accumulated (provide bigger garbage bins for those clients if needed), the collection strategy could be more efficient. Hereby, we can introduce the following new service interval I_r' which is the amount of days needed to expect 4000 kg of wastes on each route r. If we assume the waste accumulation speed Acc_S will not be changed after the service interval update, I_r' will have the following relationship:

$$\frac{N_r \times R_r^e}{40} = Acc_S = \frac{4000}{I_r'}$$

Where N_r is the number of trash bin (household) in route r, R_r^e is the expected waste per household after 40 days, i.e. $N_r \times R_r^e$ is the expected total waste for route r when pickup is happening after 40 days.

Therefore, the new service interval I_r' can be expressed as shown below:

$$I_r' = \frac{40 \times 4000}{N_r \times R_r^e}$$

It is easy to noticed that the above I_r' calculation may contain decimals. Therefore, we need to convert I_r' to integer. Meanwhile, we also need to ensure the route are serviced before the trash bin is full, i.e. the we need have shorter interval if possible (results in less expected total waste), thus the final I_r' calculation could be described as shown below:

$$I_r' = rounddown\left(\frac{40 \times 4000}{N_r \times R_r^e}\right)$$

The number of trash bins N_r can be find in Table 8 under column *Total Pickups per route*, the average waste weight per house R_r^e is available in Table 5. Thus, I_r' is calculated and shown in Table 6 below.

Route	New pickup Interval (days)	Route	New pickup Interval (days)	Route	New pickup Interval (days)	Route	New pickup Interval (days)
1001	35	1011	48	1021	86	1031	110
1002	36	1012	76	1022	90	1032	87
1003	30	1013	47	1023	78	1033	107
1004	39	1014	42	1024	109	1034	76
1005	31	1015	68	1025	92	1035	140
1006	34	1016	48	1026	101	1036	90
1007	50	1017	87	1027	144	1037	90
1008	37	1018	57	1028	94	1038	124
1009	38	1019	63	1029	117	1039	88
1010	39	1020	38	1030	93	1040	92

Table 6 New pickup interval

As shown in Table 6, a big portion of the service interval have exceeded 60 working days (over 3 months) and some over 120 working days (over 5 months). While customers are expecting a collection interval no more than 12 weeks (60 working days). It is also not very practical to wait too long between each pick up and it would require each household to acquire a very big trash bin to preserve waste in such long period. Therefore, all pickup interval I_r' which exceeded 60 will be replaced with 60 in later calculations.

Furthermore, there are also some routes been planned to be serviced sooner than the original 40 days service interval, this is to overcome the risk of overflow. According to statistics these routes often has higher than 4000 kg of load been measured without having registered a return trip to the depot.

$$R' = \sum_{i=1}^{40} F_i = \frac{1}{35} + \frac{1}{36} + \cdots + \frac{1}{60} + \frac{1}{60} = 0.80659$$

Therefore, according to section 5.2.2, $R_s = 1 - R' = 0.193$, i.e. $I_r' = 5$

$$y' = \sum_{i=1}^{40} d_i \cdot N \cdot F_i = \left(74 \times 251 \times \frac{1}{35} + \cdots + 142 \times 251 \times \frac{1}{60}\right) = 21190.28\ km$$

$$C' = b \cdot \sum_{i=1}^{40} d_i \cdot N \cdot F_i = 14 \times 21190.28 = 296\ 663\ NOK$$

The current strategy's theoretical traveling distance is 27836 as calculated in section 5.1, therefore, vehicle operation cost could be reduced by:

$$\left(1 - \frac{21190.28}{27836}\right) \times 100\% = 23.9\%$$

Which is 23.9% of vehicle operation cost savings, if all spared resources can be utilized.

Since the routes 1 to 41 requested frequency is in 1), and we assume the route initial test condition is 2). Similarly, we can also implement completely region independent pickup frequencies by using the scheduling algorithm discussed between section 5.1 and 5.2.2.

1) 35, 36, 30, 39, 31, 34, 50, 37, 38, 39, 48, 60, 47, 42, 60, 48, 60, 57, 60, 38, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, **5**

2) 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, **40**

Figure 20 shows how the scheduling quality for the aforementioned set up.

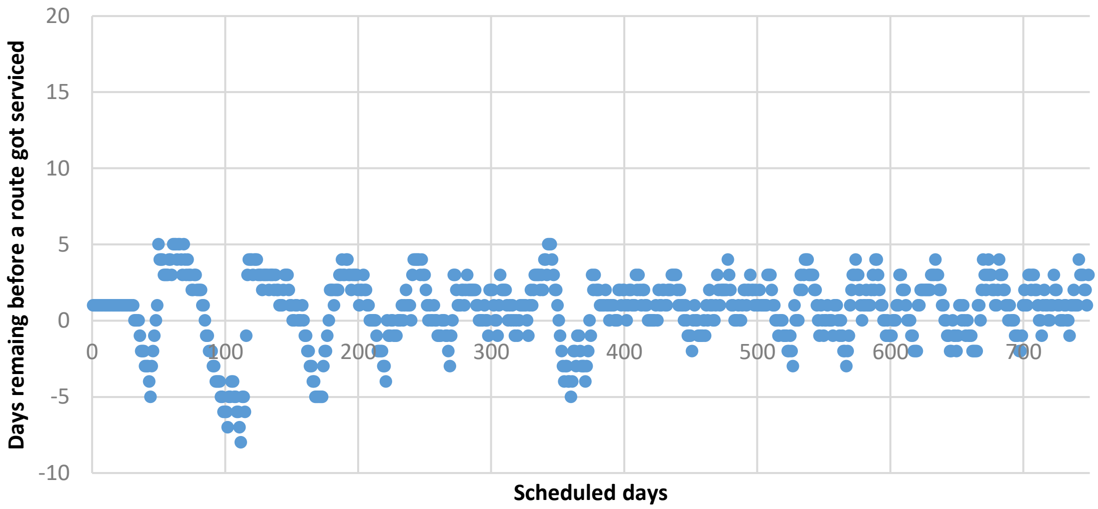

Figure 20 Scheduling quality of dynamic scheduler

Table 7 provides the results of the actual frequency of the route been scheduled by using the algorithm implemented in VBA project. The full schedule result can also be found in Appendix 5.

Route	Scheduled Count	Average Interval	Requested Interval	Route	Scheduled Count	Average Interval	Requested Interval
1001	22	34	35	1021	13	58	60
1002	21	36	36	1022	13	58	60
1003	25	30	30	1023	13	58	60
1004	20	38	39	1024	13	58	60
1005	25	30	31	1025	13	58	60
1006	22	34	34	1026	13	58	60
1007	15	50	50	1027	13	58	60
1008	20	38	37	1028	12	63	60
1009	20	38	38	1029	12	63	60
1010	20	38	39	1030	12	63	60
1011	16	47	48	1031	12	63	60
1012	13	58	60	1032	12	63	60

1013	16	47	47	1033	12	63	60
1014	18	42	42	1034	12	63	60
1015	13	58	60	1035	12	63	60
1016	15	50	48	1036	12	63	60
1017	13	58	60	1037	12	63	60
1018	13	58	57	1038	12	63	60
1019	13	58	60	1039	12	63	60
1020	19	39	38	1040	12	63	60
				1041	**144**	**5**	**5**

Table 7 Schedule algorithm actual result

Alternatively, a settling phase delay as discussed in section 5.2.3 could also be used to reduce the maximum days of violation, the starting of the spare route planning is postponed by 97 days, therefore, the routes requested frequency 1) and route initial test condition 2) are updated to:

1) 35, 36, 30, 39, 31, 34, 50, 37, 38, 39, 48, 60, 47, 42, 60, 48, 60, 57, 60, 38, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, **5**

2) 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, **97**

The new result is shown in Figure 21, we may notice that the improvement was not very big (from maximum 8 days behind schedule to maximum 5 days behind schedule).

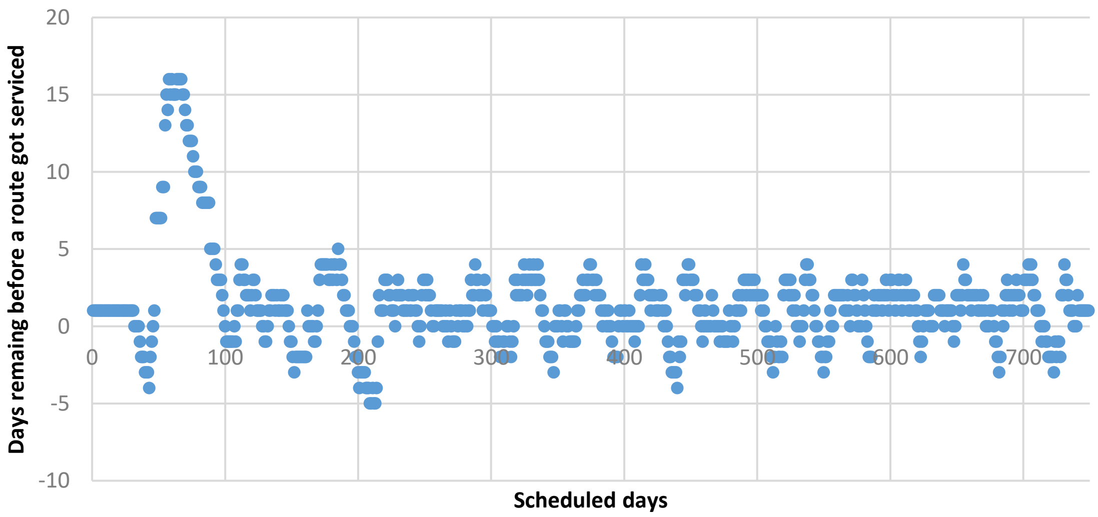

Figure 21 Scheduling quality dynamic scheduler (postpone 97 days before implement spare route)

Another alternative can be reducing the spare resource usage. I.e increase spare resource route service interval I_r' to a bigger value until satisfying scheduling quality is achieved. The routes requested frequency 1) and route initial test condition 2) can be updated to:

1) 35, 36, 30, 39, 31, 34, 50, 37, 38, 39, 48, 60, 47, 42, 60, 48, 60, 57, 60, 38, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, 60, **7**
2) 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 97

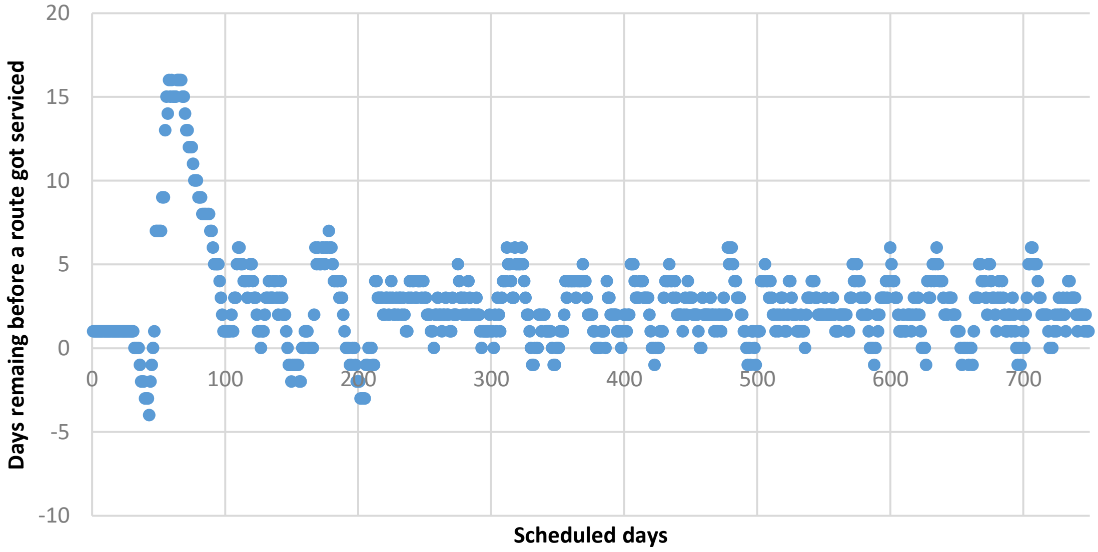

Figure 22 Scheduling quality dynamic scheduler (increase spare route service interval)

As result has shown in Figure 22, the schedule can be further improved (reduced to maximum 1 day behind schedule in stabilized phase) with such adjustment. However, this would result in less resource been spared. Furthermore, as discussed in the end of section 5.2.3, there are many routes been serviced early in this example as well (average 2.5 days ahead of schedule). Therefore, the cost reduction for this strategy will be less than 23.9% as previously estimated.

6 Other solution strategies

6.1 Zone change

According to service duration from statistics, we can conclude that the time spent on each route do not vary a lot, and the same is the case with the deviation of waste collected in the same region. This means that change of time and vehicle capacity usage can be estimated by transferring some part of the service area from one route to another.

6.1.1 Cut overloaded zones to smaller sector for drop by service

Rural zones usually having much available capacity, while some of the urban zones have a relatively big chance of encountering capacity overflow. There are possibilities to combine two such regions. Therefore, this can be achieved through drop by in the urban zones when returning from a rural zone (or any other zone which usually) with extra capacity.

6.1.2 Fine tune the number of pickups in remote areas

From the data in section 3.2.2 and 3.2.3, it is easy to notice that the number of pickups and the overall weight collected from some remote regions are small. About 75% of the regions service time have more than 50 mins or more available on the day. If these times may be used for providing service on the other remote regions nearby, it potentially can increase the waste collection efficiency of remote zones.

6.2 Miscellaneous other approaches

6.2.1 Increase capacity of vehicle

According to the data in 2019, the average overall waste collected in each route are under 5.5 tons, if the capacity of the waste collection vehicle can increase from 4 tons to 5.5 tons, this would eliminate all capacity overflow happened in 2019. Furthermore, the extension of capacity means more clients can be serviced, i.e. the routes can be extended since the capacity constraints will be relaxed when the time constraint is still valid. In order to release such time constraints, measures such as increase pickup speed (e.g. add additional operator) could also be implemented together with such vehicle capacity increase.

6.2.2 Set up remote storage location

It is also a common practice that centralized glass and metal collection point could increase efficiency for waste collection. Introducing such centralized collection point to the remote regions or islands could bring down the cost of collection on those regions.

7 Conclusion and further studies

7.1 Conclusion

The thesis mainly considers the real-world waste collection case from RIR. It started with the reviewing of MSW management situation, and its challenges that Norway and EU are facing today, and then various MSW management and VRP algorithms were discussed in the literature review section. After that, the thesis has reviewed a set of waste collection operation data provided by RIR, including the glass and metal collection routes' data in 2019. The data is then been interpreted and visualized by various chart and tables presented in the thesis. The operational challenges that RIR were facing has also been summarized from the data analysis. In addition, the thesis has introduced a cost model that can estimate the operational cost for the glass and metal waste collection operation, and such model has also been used for benchmarking the new strategies cost saving performances. According to the waste collecting frequency adjustment strategies discussed in the thesis, significant savings on its vehicle operational cost can be achieved, in addition, the operator working time can also been reduced in the new strategies, therefore, the total waste collection operation cost can be reduced. Furthermore, a dynamic pickup frequency route routine scheduler algorithm was introduced after the side effect of the frequency change strategies were introduced. The algorithm has also been implemented in Visual Basic in an excel sheet and may also be used (or inspire to be used) in other real-world scenarios where client demands are non-universal or the operator has spare resource to be scheduled while original operation needs to be kept intact. Moreover, some other operation improvement strategies and technologies were discussed in the last few chapters in the thesis.

7.2 Dynamic frequency scheduler improvement

7.2.1 Optimal scheduler

Generally speaking, an optimal scheduler means tasks are planned as it has been requested. In the route scheduling discussed in the thesis, this means the service interval shall be as close to the planned interval as possible. However, as discussed earlier, the scheduling algorithm introduced in this thesis does not guarantee the optimal solution, this is because during the search there might be better strategy than only look for the lowest number in the test conditions. For example, if many of the routes have similar test conditions i.e. expected next collection due date, these routes might be ended up demanding service at a limited time window. A better strategy might be start identified such scenarios in the early stages to prevent it from happening. This is a case that can be found: in Appendix 5 day 62 to day 67, we may find spare resource route 1041 has been continuously visited and this contributes the later stages service could not be carried out in time. Therefore, there are room for further improving the scheduler.

7.2.2 Settling time reduction

Besides, due to the natural property when changing the frequency of a scheduled tasks, there are always some settling time before the schedule could actually reaching a new zone where the service frequency is aligning with the pre-defined frequency. How to reduce settling time is also an interesting research topic as the current method is a constructive heuristic approach. The algorithm quality indicator introduced in this thesis is very close to a control theory graph as shown below, where the initial start position is far away from the preferred service frequency and gradually enters the region where service time inaccuracy reduced to an acceptable level.

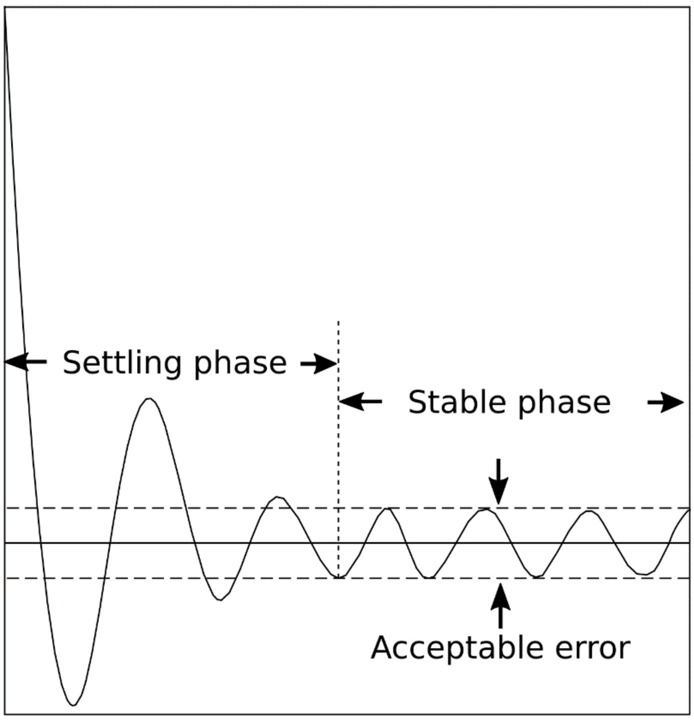

Figure 23 Scheduling quality stabilization phases

7.2.3 Minimize stable phase service quality indicator fluctuation

Furthermore, how to reduce such service time inaccuracy could also be an interesting topic when comparing the Figure 18 and Figure 20, where one scheduling only has 2 different pickup frequencies and the other has 15 different pickup frequencies. The scheduling result quality of such two scenarios have big difference as shown in the two figures mentioned above. These behaviors seem related to the total number of variances in pickup intervals, however, further study is needed to proof if the quality indicator can actually achieve a straight line for any given time of a certain route interval combination, i.e. if the planned routine can meet the routes' required service interval of a given route interval combination.

7.3 Dynamic pickup scheduling for smart trash pin system

Dynamic pickup scheduler is even more interesting for the case where smart trash bin system has been implemented in the service area. Since the waste level, waste weight, location information, days awaiting to be serviced will be dynamically updated for each trash bin, the operation scheduling also requires dynamic planning. Therefore, dynamic planned service points can be introduced same as the routes in Algorithm 1.

Such scheduling algorithm could be used for dynamic scheduling of the vehicle pickup multiple trash bins for the smart trash bin system (discussed in section 2.3). In order to increase efficiency, when servicing a trash bin, adjacent trash bins close to servicing date could also be served in one go. The concept of 'must serve' and 'can serve' may fit well for this case, Therefore, an evolved algorithm could be developed sorting the nodes closest to servicing date, and get the nodes serviced if they are close to the node that is planned to be served. I.e. if a bin is critically filled up, it must be served immediately. Then, adjacent bins filled up to a certain level (can serve), could be visited on the same trip if there is excess capacity. Furthermore, the smart trash bin system requires all households' support to be able to make the collection system efficient, therefore, introduction of smart bins should be done consistently across the service region to be efficient.

Basically, the minimum requirement of the dynamic scheduler requires generating a route that capable of servicing the trash bins requested service, while not exceeding the vehicle capacity and operational time limitation. In order to achieve this, various VRP heuristic methods can be used to find such a route. However, due to the stochastic nature of trash bin filling rate and its location, the planned route might result in vehicle travelling a very long route (just like the 'limited approach' discussed by Ramos et al. (2018)) to be able to meet all customer’s demand in one day. Therefore, an ‘expected delay of service’ can be introduced to the scheduler so that the trash bins demands service can be further separated into groups based on their geolocation. For example, request pickup level can be set to less than 100% (for example 95%) and the pickup can be set to guaranteed pickup within three working days. Then each trash bin requested service could have two chance to be postponed to avoid too long route. Hereby, the travelling distance of a route can be reduced. Furthermore, since the time and capacity usage can be forecasted before operation, it could give routing algorithm flexibility to include ‘can serve’ trash bins, the trash bins (which are closing to request pickup waste level and) adjacent to the ‘must serve’ trash bins can be considered in the route planning. Thus, such dynamic scheduler could help waste collection operator become more efficient and have more confidence of the workload estimation when comparing with the conventional static scheduling pickup strategies.

8 Reference

AL MAMUN, M. A., HANNAN, M. A., HUSSAIN, A. & BASRI, H. 2015. Integrated sensing systems and algorithms for solid waste bin state management automation. *IEEE Sensors Journal,* 15**,** 561-567.

CASAZZA, M., CESELLI, A. & CALVO, R. W. 2018. A branch and price approach for the Split Pickup and Split Delivery VRP. *Electronic Notes in Discrete Mathematics,* 69**,** 189-196.

CORBERÁN, Á. & LAPORTE, G. 2015. *Arc routing: problems, methods, and applications*, SIAM.

D'ONZA, G., GRECO, G. & ALLEGRINI, M. 2016. Full cost accounting in the analysis of separated waste collection efficiency: A methodological proposal. *Journal of Environmental Management,* 167**,** 59-65.

EKSIOGLU, B., VURAL, A. V. & REISMAN, A. 2009. The vehicle routing problem: A taxonomic review. *Computers & Industrial Engineering,* 57**,** 1472-1483.

EKVALL, T. Waste prevention: Environmental effects and policy instruments. Nordic Workshop–Waste Resource Management and Climate Actions, Fredrikstad, Norway, 2008.

ELIA, V., GNONI, M. G. & TORNESE, F. 2018. Improving logistic efficiency of WEEE collection through dynamic scheduling using simulation modeling. *Waste Management,* 72**,** 78-86.

EU. 2008a. *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives* [Online]. Official Journal of the European Union. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN [Accessed 30th of April 2020].

EU. 2008b. *Directive 2008/98/ec of the European Parliament and of the council on waste and repealing certain directives* [Online]. Official Journal of the European Union. Available: https://ec.europa.eu/environment/waste/framework/ [Accessed 30th of April 2020].

EULER, L. 1736. The seven bridges of Königsberg. *In "The world of mathematics" (1956, ed. J.R.Newman) Simon and Schuster, New York, (1), pp. 573-580.,* 1**,** 573-580.

EUROSTAT. 2020. *Waste Main Table* [Online]. Available: https://ec.europa.eu/eurostat/web/waste/data/main-tables [Accessed 3rd of May 2020].

GENTIL, E. C., GALLO, D. & CHRISTENSEN, T. H. 2011. Environmental evaluation of municipal waste prevention. *Waste Management,* 31**,** 2371-2379.

GOLDEN, B. L., ASSAD, A. A. & WASIL, E. A. 2002. Routing Vehicles in the Real World: Applications in the Solid Waste, Beverage, Food, Dairy, and Newspaper Industries. *The Vehicle Routing Problem.* SIAM Monographs on Discrete Mathematics and Applications: Philadelphia, pp. 245-286.

GOLDEN, B. L. & WONG, R. T. 1981. Capacitated arc routing problems. *Networks,* 11**,** 305-315.

GOODCHILD, M. 2003. *Geographic information system (GIS),* John Wiley and Sons Ltd.

HOORNWEG, D. & BHADA-TATA, P. 2012. What a waste: a global review of solid waste management. *Urban development series; knowledge papers no. 15.,* World Bank, Washington.

HRABEC, D., SENLAND, P., NEVRLÝ, V., POPELA, P., HOFF, A., ŠOMPLÁK, R. & PAVLAS, M. 2019. Quantity-predictive vehicle routing problem for smart waste collection. *Chemical Engineering Transactions,* 76**,** 1249-1254.

JOHANSSON, O. M. 2006. The effect of dynamic scheduling and routing in a solid waste management system. *Waste Management,* 26**,** 875-885.

KARP, R. M. 1972. Reducibility among combinatorial problems. *Complexity of computer computations.* Springer.

KRISTANTO, S., YASHIRO, T., KOSHIZUKA, N. & SAKAMURA, K. Dynamic polling algorithm for low energy garbage level measurement in smart trash bin. Proceedings of the Second International Conference on IoT in Urban Space, 2016. 92-94.

LAPORTE, G. 2006. A short history of the traveling salesman problem. *Canada Research Chair in Distribution Management, Centre for Research on Transportation (CRT) and GERAD HEC Montréal, Canada*.

LENSTRA, J. K. & KAN, A. R. 1981. Complexity of vehicle routing and scheduling problems. *Networks,* 11**,** 221-227.

LITTLE, J. D., MURTY, K. G., SWEENEY, D. W. & KAREL, C. 1963. An algorithm for the traveling salesman problem. *Operations research,* 11**,** 972-989.

MARK, D. M., CHRISMAN, N., FRANK, A. U., MCHAFFIE, P. H. & PICKLES, J. 1997. The GIS history project. *UCGIS Summer Assembly***,** 15-21.

MORINAGA, M., GU, X., SHIMURA, K., MATSUTANI, A. & KOYAMA, F. Compact dot projector based on folded path VCSEL amplifier for structured light sensing. 2019 Conference on Lasers and Electro-Optics (CLEO), 2019. IEEE, 1-2.

MURUGAANANDAM, S., GANAPATHY, V. & BALAJI, R. Efficient iot based smart bin for clean environment. 2018 International Conference on Communication and Signal Processing (ICCSP), 2018. IEEE, 0715-0720.

NAVGHANE, S., KILLEDAR, M. & ROHOKALE, V. 2016. IoT based smart garbage and waste collection bin. *International Journal of Advanced Research in Electronics and Communication Engineering (IJARECE),* 5**,** 1576-1578.

PAPARGYROPOULOU, E., LOZANO, R., K. STEINBERGER, J., WRIGHT, N. & UJANG, Z. B. 2014. The food waste hierarchy as a framework for the management of food surplus and food waste. *Journal of Cleaner Production,* 76**,** 106-115.

PROSSER, P. & SHAW, P. 1996. Study of greedy search with multiple improvement heuristics for vehicle routing problems.

RAMOS, T. R. P., DE MORAIS, C. S. & BARBOSA-PÓVOA, A. P. 2018. The smart waste collection routing problem: Alternative operational management approaches. *Expert Systems with Applications,* 103**,** 146-158.

RIR. 2020. *RIR Anlegget* [Online]. Romsdalshalvøya Interkommunale Renovasjonsselskap. Available: https://www.rir.no/om-rir/anlegget [Accessed 8th of May 2020].

SAMANN, F. E. 2017. The design and implementation of smart trash bin. *Academic Journal of Nawroz University,* 6**,** 141-148.

SARKAR, A. 2007. GIS applications in logistics: A literature review. *School of Business, University of Redlands,* 1200.

SHARIFYAZDI, M. & FLYGANSVÆR, B. M. 2015. DYNAMIC ROUTING IN REVERSE LOGISTICS: The effect of sensors in waste containers on uncertainty. *In Jæger, B. (2015). NOFOMA 2015: Post Conference Proceedings, Molde, 3-5 June 2015, Nordic Logistics Research Network.*

SHARMA, N., SINGHA, N. & DUTTA, T. 2015. Smart bin implementation for smart cities. *International Journal of Scientific & Engineering Research,* 6**,** 787-791.

SILVA, M. M., SUBRAMANIAN, A. & OCHI, L. S. 2015. An iterated local search heuristic for the split delivery vehicle routing problem. *Computers & Operations Research,* 53**,** 234-249.
SOHAIL, H., ULLAH, S., KHAN, A., SAMIN, O. B. & OMAR, M. Intelligent Trash Bin (ITB) with Trash Collection Efficiency Optimization using IoT Sensing. 2019 8th International Conference on Information and Communication Technologies (ICICT), 2019. IEEE, 48-53.
SORTERE.NO. 2020. Available: https://sortere.no [Accessed 23rd of April 2020].
SSB. 2020. *Statistics Norway* [Online]. Statistisk sentralbyrå. Available: https://www.ssb.no/en/natur-og-miljo [Accessed 3rd of May 2020].
TAVARES, G., ZSIGRAIOVA, Z., SEMIAO, V. & CARVALHO, M. D. G. 2008. A case study of fuel savings through optimisation of MSW transportation routes. *Management of Environmental Quality: An International Journal,* 19**,** 444-454.
TAVARES, G., ZSIGRAIOVA, Z., SEMIAO, V. & CARVALHO, M. G. 2009. Optimisation of MSW collection routes for minimum fuel consumption using 3D GIS modelling. *Waste Management,* 29**,** 1176-1185.
TIRKOLAEE, E. B., ALINAGHIAN, M., SASI, M. B. & ESFAHANI, M. M. S. 2016. Solving a robust capacitated arc routing problem using a hybrid simulated annealing algorithm: A waste collection application. *Journal of Industrial Engineering and Management Studies* 3**,** 61 - 76.
TOTH, P. & VIGO, D. 2002. *The vehicle routing problem,* SIAM Monographs on Discrete Mathematics and Applications, Philadelphia.
WANG, Y., HO, O. K., HUANG, G. Q. & LI, D. 2008. Study on vehicle management in logistics based on RFID, GPS and GIS. *International Journal of Internet Manufacturing and Services,* 1**,** 294-304.
WIKIPEDIA. 2020. *Møre og Romsdal* [Online]. no.wikipedia.org. Available: https://no.wikipedia.org/wiki/M%C3%B8re_og_Romsdal [Accessed 23rd of April 2020].
ZSIGRAIOVA, Z., SEMIAO, V. & BEIJOCO, F. 2013. Operation costs and pollutant emissions reduction by definition of new collection scheduling and optimization of MSW collection routes using GIS. The case study of Barreiro, Portugal. *Waste Management,* 33**,** 793-806.

Appendix 1 – Glass and metal route information

Table 8 Glass and metal route info

Route	Route total length	Distance from depot	Region route length	Ferry time	Average Drive Duration (min)	Total Pickups per route	Total Volume m3	Average weight (tons)
1001	74	42.2	31.8	-	376	487	72.52	4.52
1002	64	35.8	28.2	-	343	437	65.22	4.43
1003	70	25.9	44.1	-	424	559	85.04	5.17
1004	78	29.6	48.4	-	368	479	68.76	4.09
1005	70	35.7	34.3	-	403	429	65.02	5.01
1006	76	24.3	51.7	-	358	427	69.68	4.58
1007	77	23.1	53.9	-	288	404	58.84	3.20
1008	64	28.2	35.8	-	413	477	69.14	4.28
1009	98	15.7	82.3	-	415	583	84.24	4.15
1010	56	15.1	40.9	-	390	491	74.9	4.05
1011	137	108.2	28.8	-	426	426	62.48	3.30
1012	101	64.6	36.4	50	319	313	45.48	2.10
1013	60	45.6	14.4	-	425	501	71.94	3.39
1014	90	47.7	42.3	-	438	529	74.82	3.73
1015	70	30.1	39.9	-	331	389	55.8	2.35
1016	80	41.6	38.4	-	356	472	69.5	3.27
1017	124	69.4	54.6	50	330	381	54.08	1.83
1018	97	58.2	38.8	-	352	520	74.28	2.80
1019	98	51.9	46.1	-	333	389	55.9	2.53
1020	72	7.9	64.1	-	405	532	80.84	4.13
1021	105	55.7	49.3	46	426	287	44.76	1.84
1022	126	39.1	86.9	-	442	286	40.24	1.78
1023	114	33.1	80.9	-	407	316	44.44	2.03
1024	158	93.2	64.8	-	381	283	40.48	1.46
1025	122	84.2	37.8	-	415	254	36.6	1.73
1026	105	66.2	38.8	-	374	283	41.92	1.58
1027	174	109.6	64.4	-	379	228	32.78	1.11
1028	236	155.8	80.2	-	366	290	41.02	1.69
1029	228	120.8	107.2	-	365	235	33.44	1.36
1030	166	53.1	112.9	-	365	222	34.62	1.70
1031	120	56.4	63.6	46	323	208	31.3	1.44
1032	74	34.0	40.0	-	299	311	43.74	1.84
1033	103	60.8	42.2	-	373	237	34.26	1.49
1034	150	67.5	82.5	-	387	332	51.12	2.09
1035	126	99.5	26.5	-	330	235	33.1	1.14
1036	140	46.2	93.8	-	342	282	42.52	1.76
1037	101	61.6	39.4	-	354	266	39.78	1.78
1038	190	110.2	79.8	-	329	215	30.32	1.29
1039	100	62.0	38.0	-	335	301	43.7	1.81
1040	142	89.5	52.5	50	380	273	42.38	1.74

Appendix 2 – Glass and metal route cost related logs

Table 9 Glass and metal cost related info

Date	Scheduled Route	Drive duration (mins)	Working time (mins)	Overtime yes/no	Drive distance (km)	Additional Trans. Dis. (km)
04.02.2019	1001	408	450	-	74	-
01.04.2019	1001	378	450	-	74	-
27.05.2019	1001	334	450	-	74	-
22.07.2019	1001	424	450	-	74	-
16.09.2019	1001	399	450	-	74	-
11.11.2019	1001	313	450	-	74	-
05.02.2019	1002	405	450	-	64	-
02.04.2019	1002	296	450	-	64	-
28.05.2019	1002	366	450	-	64	-
23.07.2019	1002	331	450	-	64	-
17.09.2019	1002	399	450	-	64	-
12.11.2019	1002	262	450	-	64	-
06.02.2019	1003	489	489	1	70	25.9
03.04.2019	1003	369	450	-	70	-
29.05.2019	1003	444	450	-	70	25.9
24.07.2019	1003	451	451	1	70	-
18.09.2019	1003	403	450	-	70	-
13.11.2019	1003	388	450	-	70	-
07.02.2019	1004	384	450	-	78	-
31.05.2019	1004	362	450	-	78	-
25.07.2019	1004	399	450	-	78	-
14.11.2019	1004	328	450	-	78	-
08.02.2019	1005	462	462	1	70	-
05.04.2019	1005	343	450	-	70	-
01.06.2019	1005	318	450	-	70	-
26.07.2019	1005	440	450	-	70	-
20.09.2019	1005	422	450	-	70	-
15.11.2019	1005	434	450	-	70	-
11.02.2019	1006	360	450	-	76	-
08.04.2019	1006	275	450	-	76	-
03.06.2019	1006	388	450	-	76	24.3
29.07.2019	1006	420	450	-	76	-
23.09.2019	1006	389	450	-	76	-
18.11.2019	1006	315	450	-	76	-
12.02.2019	1007	343	450	-	77	-
09.04.2019	1007	255	450	-	77	-
04.06.2019	1007	261	450	-	77	-
30.07.2019	1007	328	450	-	77	-
19.11.2019	1007	254	450	-	77	-
13.02.2019	1008	485	485	1	64	-
10.04.2019	1008	383	450	-	64	-
05.06.2019	1008	359	450	-	64	-
31.07.2019	1008	501	501	1	64	-
25.09.2019	1008	389	450	-	64	-

20.11.2019	1008	359	450	-	64	-
14.02.2019	1009	413	450	-	98	15.7
11.04.2019	1009	366	450	-	98	-
06.06.2019	1009	416	450	-	98	15.7
01.08.2019	1009	451	451	1	98	-
26.09.2019	1009	435	450	-	98	-
21.11.2019	1009	411	450	-	98	-
15.02.2019	1010	395	450	-	56	-
12.04.2019	1010	330	450	-	56	-
07.06.2019	1010	394	450	-	56	-
02.08.2019	1010	353	450	-	56	-
27.09.2019	1010	437	450	-	56	-
22.11.2019	1010	430	450	-	56	-
18.02.2019	1011	410	450	-	137	-
13.04.2019	1011	404	450	-	137	-
11.06.2019	1011	424	450	-	137	-
05.08.2019	1011	401	450	-	137	-
30.09.2019	1011	456	456	1	137	-
25.11.2019	1011	459	459	1	137	-
19.02.2019	1012	311	450	-	101	-
15.04.2019	1012	325	450	-	101	-
12.06.2019	1012	324	450	-	101	-
06.08.2019	1012	412	450	-	101	-
01.10.2019	1012	253	450	-	101	-
26.11.2019	1012	290	450	-	101	-
20.02.2019	1013	418	450	-	60	-
13.06.2019	1013	584	584	1	60	-
07.08.2019	1013	376	450	-	60	-
02.10.2019	1013	375	450	-	60	-
27.11.2019	1013	405	450	-	60	-
16.04.2019	1013/1014	390	450	-	150	-
21.02.2019	1014	374	450	-	90	-
14.06.2019	1014	404	450	-	90	-
08.08.2019	1014	642	642	1	90	-
03.10.2019	1014	413	450	-	90	-
28.11.2019	1014	416	450	-	90	-
22.02.2019	1015	184	450	-	70	-
17.04.2019	1015	381	450	-	70	-
15.06.2019	1015	319	450	-	70	-
09.08.2019	1015	299	450	-	70	-
04.10.2019	1015	394	450	-	70	-
29.11.2019	1015	410	450	-	70	-
25.02.2019	1016	301	450	-	80	-
23.04.2019	1016	399	450	-	80	-
17.06.2019	1016	450	450	1	80	-
12.08.2019	1016	346	450	-	80	-
07.10.2019	1016	336	450	-	80	-
02.12.2019	1016	306	450	-	80	-
02.01.2019	1017	348	450	-	124	-
26.02.2019	1017	385	450	-	124	-

24.04.2019	1017	342	450	-	124	-
18.06.2019	1017	237	450	-	124	-
13.08.2019	1017	363	450	-	124	-
08.10.2019	1017	287	450	-	124	-
03.12.2019	1017	347	450	-	124	-
03.01.2019	1018	328	450	-	97	-
27.02.2019	1018	331	450	-	97	-
25.04.2019	1018	363	450	-	97	-
19.06.2019	1018	425	450	-	97	-
14.08.2019	1018	334	450	-	97	-
09.10.2019	1018	387	450	-	97	-
04.12.2019	1018	296	450	-	97	-
04.01.2019	1019	269	450	-	98	-
28.02.2019	1019	329	450	-	98	-
26.04.2019	1019	357	450	-	98	-
20.06.2019	1019	375	450	-	98	-
15.08.2019	1019	424	450	-	98	-
10.10.2019	1019	287	450	-	98	-
05.12.2019	1019	290	450	-	98	-
05.01.2019	1020	378	450	-	72	-
01.03.2019	1020	345	450	-	72	-
27.04.2019	1020	367	450	-	72	-
21.06.2019	1020	394	450	-	72	-
16.08.2019	1020	465	465	1	72	7.9
11.10.2019	1020	337	450	-	72	-
06.12.2019	1020	548	548	1	72	-
07.01.2019	1021	489	489	1	105	-
04.03.2019	1021	395	450	-	105	-
29.04.2019	1021	338	450	-	105	-
24.06.2019	1021	407	450	-	105	-
19.08.2019	1021	412	450	-	105	-
14.10.2019	1021	404	450	-	105	-
09.12.2019	1021	536	536	1	105	-
08.01.2019	1022	360	450	-	126	-
05.03.2019	1022	520	520	1	126	-
30.04.2019	1022	373	450	-	126	-
25.06.2019	1022	704	704	1	126	-
20.08.2019	1022	402	450	-	126	-
15.10.2019	1022	311	450	-	126	-
10.12.2019	1022	422	450	-	126	-
09.01.2019	1023	397	450	-	114	-
06.03.2019	1023	375	450	-	114	-
02.05.2019	1023	399	450	-	114	-
26.06.2019	1023	595	595	1	114	-
21.08.2019	1023	391	450	-	114	-
16.10.2019	1023	309	450	-	114	-
11.12.2019	1023	383	450	-	114	-
10.01.2019	1024	351	450	-	158	-
07.03.2019	1024	473	473	1	158	-
03.05.2019	1024	436	450	-	158	-

27.06.2019	1024	291	450	-	158	-
22.08.2019	1024	415	450	-	158	-
17.10.2019	1024	321	450	-	158	-
12.12.2019	1024	382	450	-	158	-
11.01.2019	1025	382	450	-	122	-
08.03.2019	1025	531	531	1	122	-
23.08.2019	1025	423	450	-	122	-
18.10.2019	1025	367	450	-	122	-
13.12.2019	1025	371	450	-	122	-
14.01.2019	1026	376	450	-	105	-
11.03.2019	1026	476	476	1	105	-
06.05.2019	1026	373	450	-	105	-
01.07.2019	1026	217	450	-	105	-
26.08.2019	1026	421	450	-	105	-
21.10.2019	1026	287	450	-	105	-
16.12.2019	1026	466	466	1	105	-
12.03.2019	1027	398	450	-	174	-
07.05.2019	1027	409	450	-	174	-
02.07.2019	1027	374	450	-	174	-
27.08.2019	1027	339	450	-	174	-
22.10.2019	1027	275	450	-	174	-
17.12.2019	1027	478	478	1	174	-
16.01.2019	1028	422	450	-	236	-
13.03.2019	1028	366	450	-	236	-
08.05.2019	1028	356	450	-	236	-
03.07.2019	1028	329	450	-	236	-
28.08.2019	1028	370	450	-	236	-
23.10.2019	1028	264	450	-	236	-
18.12.2019	1028	458	458	1	236	-
17.01.2019	1029	346	450	-	228	-
14.03.2019	1029	338	450	-	228	-
09.05.2019	1029	469	469	1	228	-
04.07.2019	1029	411	450	-	228	-
29.08.2019	1029	308	450	-	228	-
24.10.2019	1029	265	450	-	228	-
19.12.2019	1029	421	450	-	228	-
18.01.2019	1030	360	450	-	166	-
15.03.2019	1030	355	450	-	166	-
10.05.2019	1030	334	450	-	166	-
05.07.2019	1030	306	450	-	166	-
30.08.2019	1030	383	450	-	166	-
25.10.2019	1030	329	450	-	166	-
20.12.2019	1030	488	488	1	166	-
21.01.2019	1031	276	450	-	120	-
18.03.2019	1031	278	450	-	120	-
13.05.2019	1031	304	450	-	120	-
08.07.2019	1031	353	450	-	120	-
02.09.2019	1031	364	450	-	120	-
28.10.2019	1031	317	450	-	120	-
21.12.2019	1031	368	450	-	120	-

22.01.2019	1032	294	450	-	74	-
19.03.2019	1032	251	450	-	74	-
14.05.2019	1032	350	450	-	74	-
09.07.2019	1032	293	450	-	74	-
03.09.2019	1032	350	450	-	74	-
29.10.2019	1032	140	450	-	74	-
23.12.2019	1032	412	450	-	74	-
23.01.2019	1033	402	450	-	103	-
20.03.2019	1033	354	450	-	103	-
15.05.2019	1033	348	450	-	103	-
10.07.2019	1033	371	450	-	103	-
04.09.2019	1033	391	450	-	103	-
30.10.2019	1033	323	450	-	103	-
24.12.2019	1033	425	450	-	103	-
24.01.2019	1034	360	450	-	150	-
21.03.2019	1034	403	450	-	150	-
16.05.2019	1034	401	450	-	150	-
11.07.2019	1034	237	450	-	150	-
05.09.2019	1034	463	463	1	150	-
31.10.2019	1034	397	450	-	150	-
27.12.2019	1034	447	450	-	150	-
22.03.2019	1035	269	450	-	126	-
12.07.2019	1035	268	450	-	126	-
06.09.2019	1035	386	450	-	126	-
01.11.2019	1035	364	450	-	126	-
28.12.2019	1035	361	450	-	126	-
28.01.2019	1036	354	450	-	140	-
25.03.2019	1036	359	450	-	140	-
20.05.2019	1036	317	450	-	140	-
15.07.2019	1036	294	450	-	140	-
09.09.2019	1036	393	450	-	140	-
04.11.2019	1036	332	450	-	140	-
29.01.2019	1037	367	450	-	101	-
26.03.2019	1037	364	450	-	101	-
21.05.2019	1037	304	450	-	101	-
16.07.2019	1037	359	450	-	101	-
10.09.2019	1037	360	450	-	101	-
05.11.2019	1037	340	450	-	101	-
31.12.2019	1037	387	450	-	101	-
30.01.2019	1038	306	450	-	190	-
27.03.2019	1038	327	450	-	190	-
22.05.2019	1038	318	450	-	190	-
17.07.2019	1038	324	450	-	190	-
11.09.2019	1038	380	450	-	190	-
06.11.2019	1038	320	450	-	190	-
31.01.2019	1039	271	450	-	100	-
28.03.2019	1039	331	450	-	100	-
23.05.2019	1039	298	450	-	100	-
18.07.2019	1039	381	450	-	100	-
12.09.2019	1039	342	450	-	100	-

07.11.2019	1039	386	450	-	100	-
01.02.2019	1040	336	450	-	142	-
29.03.2019	1040	321	450	-	142	-
24.05.2019	1040	297	450	-	142	-
19.07.2019	1040	403	450	-	142	-
13.09.2019	1040	465	465	1	142	-
08.11.2019	1040	460	460	1	142	-

Appendix 3 – Vba source code

'The dynamic frequency scheduler Excel VBA code

```
'Generate the route schedule
Private Sub GenerateSchedule_Click()
Call SpareRouteEnable_Click
Dim Solution As Variant
Dim RowBuffer As Variant
Dim scheduleBuffer As Variant
Dim routeBuffer As Variant
Dim iniBuffer As Variant
ReDim workingBuffer(1 To ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 1) As Integer
Dim i As Integer, j As Integer, k As Integer, minDem As Integer
routeBuffer = Range(ActiveSheet.Cells(4, 2), ActiveSheet.Cells(4, ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 1)).Value
scheduleBuffer = Range(ActiveSheet.Cells(5, 2), ActiveSheet.Cells(5, ActiveSheet.Range("B1") + ActiveSheet.Range("G1") +
1)).Value
iniBuffer = Range(ActiveSheet.Cells(6, 2), ActiveSheet.Cells(6, ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 1)).Value
RowBuffer = Range(ActiveSheet.Cells(6, 2), ActiveSheet.Cells(6, ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 3)).Value
Solution = Range(ActiveSheet.Cells(9, 1), ActiveSheet.Cells(ActiveSheet.Range("B2") + 8, ActiveSheet.Range("B1") +
ActiveSheet.Range("G1") + 2)).Value
workingBuffer(1) = 32674 'Set a relatively large value
For i = 1 To ActiveSheet.Range("B1") + ActiveSheet.Range("G1")
 If iniBuffer(1, i) <= 0 Then
  ActiveSheet.Cells(6, i + 1) = "Err!"
  ActiveSheet.Cells(6, i + 1).Font.Color = vbRed
  Exit Sub
 End If
 workingBuffer(i + 1) = iniBuffer(1, i)
Next i

For i = 1 To ActiveSheet.Range("B2")
  k = findMin(workingBuffer) - 1 'Find local optimal route
  If routeBuffer(1, k) = "" Then
    ActiveSheet.Cells(4, k + 1) = "Err!"
    ActiveSheet.Cells(4, k + 1).Font.Color = vbRed
    Exit Sub
  End If
  Solution(i, 1) = routeBuffer(1, k)
  If Solution(i, 1) = ActiveSheet.Cells(4, ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 1) And ActiveSheet.Range("G1") =
1 Then
    ActiveSheet.Cells(i + 8, 1).Font.Color = vbBlue
  End If
  minDem = 32674 'Set a relatively large value
 For j = 1 To ActiveSheet.Range("B1") + ActiveSheet.Range("G1")
  If j <> k Then  'Update test conditions for all routes not been serviced
    workingBuffer(j + 1) = workingBuffer(j + 1) - 1
    If minDem > workingBuffer(j + 1) Then
     minDem = workingBuffer(j + 1)
     End If
  Else          'Pass in defined interval to the route just been serviced
    If scheduleBuffer(1, k) <= 0 Then
     ActiveSheet.Cells(5, k + 1) = "Err!"
     ActiveSheet.Cells(5, k + 1).Font.Color = vbRed
     Exit Sub
    End If
    workingBuffer(k + 1) = scheduleBuffer(1, k)
    If minDem > workingBuffer(k + 1) Then
     minDem = workingBuffer(k + 1)
     End If
  End If
  Solution(i, j + 1) = workingBuffer(j + 1)
 Next j
 'save minimum days before been serviced for schedular quality indicator
 Solution(i, ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 2) = minDem
Next i
'save solution to excel sheet
ActiveSheet.Range(ActiveSheet.Cells(9, 1), ActiveSheet.Cells(i + 8, ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 2)) =
Solution
'Save the last day's test condition from the current solution, in case the schedule needs to be planned after the current solution.
'By copy the "End Wait" row data can be copied to "Init. Wait" row, the schedule can be continued after the previous result
For i = 2 To ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 1
  RowBuffer(1, i - 1) = Solution(ActiveSheet.Range("B2"), i)
Next i
ActiveSheet.Range(ActiveSheet.Cells(7, 2), ActiveSheet.Cells(7, ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 1)) =
RowBuffer
End Sub

'Find the min value index of an array
Public Function findMin(ByRef arrayInput() As Integer) As Integer ', ByVal value As Integer
Dim i As Integer, min As Integer, temp As Integer
```

```
min = arrayInput(LBound(arrayInput))
temp = 1
For i = LBound(arrayInput) + 1 To UBound(arrayInput)
   If arrayInput(i) < min Then
     min = arrayInput(i)
     temp = i
   End If
Next i
findMin = temp
End Function

'Clean results and reset "include spare route scheduling" calculation checkbox
Private Sub Reset_Click()
  ActiveSheet.Range("A1:AZ1010").Font.Color = vbBlack
  ActiveSheet.Range(ActiveSheet.Cells(9, 1), ActiveSheet.Cells(ActiveSheet.Range("B2") + 8, ActiveSheet.Range("B1") +
ActiveSheet.Range("G1") + 2)).ClearContents
  SpareRouteEnable.Value = False
  AdjustSpareRouteInitialCondition.Value = False
  Call SpareRouteEnable_Click
  ActiveSheet.Range(ActiveSheet.Cells(7, 2), ActiveSheet.Cells(7, ActiveSheet.Range("B1") + ActiveSheet.Range("G1") +
2)).ClearContents
  ActiveSheet.Range(ActiveSheet.Cells(5, ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 2), ActiveSheet.Cells(6,
ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 2)).ClearContents
  ActiveSheet.Range("G1:G2").ClearContents
End Sub

'Checkbox to include spare routes in the schedular
'Read the checkbox to see if spare route needs to be included in the scheduling process
'if Checkbox is checked, a spare route will be included in the scheduling process
Private Sub SpareRouteEnable_Click()
Dim i As Integer
Dim sum As Single, resSum As Single
If SpareRouteEnable.Value = True Then
   refSum = 0
   For i = 1 To ActiveSheet.Range("B1")
     If ActiveSheet.Cells(3, i + 1) <> 0 Then
       resSum = resSum + 1 / ActiveSheet.Cells(3, i + 1)
       End If
   Next i
   sum = 0
   For i = 1 To ActiveSheet.Range("B1")
     If ActiveSheet.Cells(5, i + 1) <> 0 Then
       sum = sum + 1 / ActiveSheet.Cells(5, i + 1)
     End If
   Next i
   If sum >= 1 Then
       ActiveSheet.Range("D1:G2").Font.Color = vRed
   End If
   ActiveSheet.Range("G1") = 1
   ActiveSheet.Range("G2") = resSum - sum
   ActiveSheet.Range("D1:D2").Font.Color = vbBlack
   ActiveSheet.Cells(4, ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 1).Font.Color = vbBlue
   If AdjustSpareRouteInitialCondition.Value = False Or ActiveSheet.Cells(5, ActiveSheet.Range("B1") + ActiveSheet.Range("G1")
+ 1) = "" Then
       ActiveSheet.Cells(5, ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 1) = WorksheetFunction.Round(1 /
ActiveSheet.Range("G2"), 0)
       ActiveSheet.Cells(6, ActiveSheet.Range("B1") + ActiveSheet.Range("G1") + 1) =
WorksheetFunction.max(Range(ActiveSheet.Cells(6, 2), ActiveSheet.Cells(6, ActiveSheet.Range("G1") + ActiveSheet.Range("B1")
+ 1)))
   End If
Else 'if unchecked, remove unrelated contents
   ActiveSheet.Range("G1:G2").ClearContents
   ActiveSheet.Range("D1:D2").Font.ColorIndex = 15
   ActiveSheet.Range(ActiveSheet.Cells(5, ActiveSheet.Range("B1") + 2), ActiveSheet.Cells(6, ActiveSheet.Range("B1") +
2)).ClearContents
End If
End Sub

'Checkbox to allow manual adjust the spare route initial conditions, such as postpone spare route etc.
Private Sub AdjustSpareRouteInitialCondition_Click()
If AdjustSpareRouteInitialCondition.Value = False Then
   Call SpareRouteEnable_Click
End If
End Sub
```

Appendix 4 - Glass and metal pickup scheduler setup

Route	40	Spare Route	1
Plan Day	750	Spare resource	0.167

☑ Include Spare Route Sche.

☑ Manual adj. spare route Settings

Sche. Old	40	40	40	40	40	40	40	40	40	40	40	40	40
Route	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013
Sch. Day	40	40	40	40	40	40	40	40	40	40	40	40	40
Init. Wait	1	2	3	4	5	6	7	8	9	10	11	12	13
End Wait	26	27	29	32	33	35	38	39	0	3	5	6	9
Viol. Cnt	3	3	2	4	4	5	3	4	4	4	6	4	4

40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028
40	40	40	40	40	40	40	60	60	60	60	60	60	60	60
14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
11	12	15	17	20	21	22	24	28	30	34	36	38	43	44
2	4	1	2	2	1	1	0	0	1	0	0	0	2	1

40	40	40	40	40	40	40	40	40	40	40	40	
1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041
60	60	60	60	60	60	60	60	60	60	60	60	**6**
29	30	31	32	33	34	35	36	37	38	39	40	**156**
48	50	54	56	60	4	5	8	11	14	17	22	3
0	1	2	3	3	7	7	7	7	9	9	9	29

Appendix 5 - Glass and metal pickup schedule strategy 2

Route	**40**	**Spare Route**	1
Plan Day	**750**	**Spare resource**	0.193

Include Spare Route Sche.

Sche. Old	40	40	40	40	40	40	40	40	40	40	40	40	40
Route	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013
Sch. Day	35	36	30	39	31	34	50	37	38	39	48	60	47
Init. Wait	1	2	3	4	5	6	7	8	9	10	11	12	13
End Wait	10	6	7	23	28	15	10	4	26	35	33	38	37
Viol. Cnt	9	15	12	6	15	17	12	9	9	13	13	5	19

40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028
42	60	48	60	57	60	38	60	60	60	60	60	60	60	60
14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
13	39	10	42	10	43	3	46	49	51	53	54	58	59	3
11	5	22	5	6	4	15	3	3	3	2	1	3	7	6

40	40	40	40	40	40	40	40	40	40	40	40	
1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041
60	60	60	60	60	60	60	60	60	60	60	60	5
29	30	31	32	33	34	35	36	37	38	39	40	40
7	11	12	15	16	17	21	23	26	32	33	36	5
11	11	12	12	14	15	17	21	21	22	24	25	80

Table 10 Glass and metal route schedule strategy 2

Day	Route	Day	Route	Day	Route	Day	Route	Day	Route	Day	Route
1	1001	41	1002	81	1041	121	1003	161	1011	201	1009
2	1002	42	1038	82	1023	122	1004	162	1013	202	1024
3	1003	43	1039	83	1024	123	1041	163	1004	203	1041
4	1004	44	1006	84	1008	124	1009	164	1033	204	1025
5	1005	45	1040	85	1025	125	1041	165	1009	205	1026
6	1006	46	1041	86	1004	126	1012	166	1034	206	1027
7	1007	47	1004	87	1026	127	1018	167	1005	207	1041
8	1008	48	1008	88	1041	128	1041	168	1016	208	1011
9	1009	49	1009	89	1009	129	1010	169	1035	209	1013
10	1010	50	1010	90	1027	130	1015	170	1041	210	1003
11	1011	51	1041	91	1028	131	1041	171	1036	211	1007
12	1012	52	1014	92	1010	132	1005	172	1037	212	1028
13	1013	53	1041	93	1029	133	1017	173	1038	213	1041
14	1014	54	1007	94	1003	134	1020	174	1010	214	1010
15	1015	55	1020	95	1030	135	1041	175	1039	215	1001
16	1016	56	1041	96	1031	136	1019	176	1020	216	1020
17	1017	57	1011	97	1032	137	1021	177	1040	217	1029
18	1018	58	1013	98	1020	138	1022	178	1041	218	1030
19	1019	59	1041	99	1041	139	1041	179	1001	219	1016
20	1020	60	1003	100	1014	140	1014	180	1003	220	1006
21	1021	61	1016	101	1033	141	1023	181	1014	221	1031
22	1022	62	1041	102	1034	142	1001	182	1041	222	1032
23	1023	63	1041	103	1005	143	1024	183	1006	223	1041
24	1024	64	1041	104	1035	144	1041	184	1018	224	1002
25	1025	65	1005	105	1036	145	1025	185	1012	225	1014
26	1026	66	1041	106	1037	146	1026	186	1041	226	1033
27	1027	67	1041	107	1038	147	1041	187	1002	227	1034
28	1028	68	1001	108	1001	148	1027	188	1015	228	1005
29	1029	69	1012	109	1039	149	1003	189	1041	229	1008
30	1030	70	1041	110	1007	150	1006	190	1008	230	1041
31	1031	71	1015	111	1041	151	1028	191	1017	231	1035
32	1032	72	1018	112	1011	152	1002	192	1041	232	1036
33	1003	73	1041	113	1013	153	1041	193	1019	233	1037
34	1033	74	1002	114	1040	154	1029	194	1021	234	1038
35	1034	75	1017	115	1016	155	1030	195	1041	235	1039
36	1035	76	1006	116	1002	156	1008	196	1005	236	1041
37	1001	77	1041	117	1006	157	1031	197	1022	237	1040
38	1005	78	1019	118	1041	158	1032	198	1041	238	1004
39	1036	79	1021	119	1008	159	1041	199	1023	239	1009
40	1037	80	1022	120	1041	160	1007	200	1004	240	1003

Part 2 of Table 10 Glass and metal route schedule strategy 2:

Day	Route	Day	Route	Day	Route	Day	Route	Day	Route	Day	Route
241	1018	281	1001	321	1005	361	1018	401	1033	441	1002
242	1041	282	1032	322	1023	362	1039	402	1011	442	1024
243	1012	283	1041	323	1041	363	1040	403	1013	443	1041
244	1041	284	1006	324	1024	364	1003	404	1034	444	1010
245	1015	285	1033	325	1025	365	1007	405	1041	445	1025
246	1041	286	1034	326	1026	366	1012	406	1010	446	1020
247	1001	287	1041	327	1010	367	1041	407	1002	447	1026
248	1017	288	1010	328	1020	368	1010	408	1020	448	1001
249	1041	289	1005	329	1027	369	1015	409	1035	449	1027
250	1010	290	1020	330	1041	370	1020	410	1041	450	1041
251	1019	291	1035	331	1003	371	1016	411	1005	451	1008
252	1006	292	1036	332	1002	372	1002	412	1008	452	1011
253	1020	293	1041	333	1028	373	1017	413	1001	453	1013
254	1021	294	1037	334	1041	374	1019	414	1007	454	1028
255	1041	295	1038	335	1029	375	1041	415	1041	455	1003
256	1011	296	1039	336	1030	376	1008	416	1036	456	1041
257	1013	297	1002	337	1041	377	1021	417	1018	457	1006
258	1022	298	1040	338	1008	378	1022	418	1037	458	1029
259	1005	299	1018	339	1031	379	1041	419	1016	459	1030
260	1023	300	1041	340	1032	380	1001	420	1038	460	1031
261	1002	301	1003	341	1041	381	1023	421	1041	461	1032
262	1041	302	1012	342	1033	382	1005	422	1006	462	1033
263	1007	303	1008	343	1034	383	1024	423	1039	463	1041
264	1024	304	1011	344	1041	384	1041	424	1040	464	1007
265	1025	305	1013	345	1041	385	1025	425	1003	465	1034
266	1026	306	1015	346	1041	386	1026	426	1012	466	1004
267	1008	307	1041	347	1001	387	1006	427	1041	467	1016
268	1027	308	1017	348	1014	388	1027	428	1004	468	1009
269	1014	309	1014	349	1035	389	1041	429	1015	469	1041
270	1016	310	1019	350	1041	390	1004	430	1009	470	1035
271	1041	311	1041	351	1004	391	1014	431	1041	471	1005
272	1003	312	1007	352	1005	392	1009	432	1014	472	1014
273	1028	313	1004	353	1006	393	1028	433	1017	473	1018
274	1041	314	1009	354	1009	394	1003	434	1019	474	1041
275	1004	315	1021	355	1011	395	1041	435	1041	475	1036
276	1009	316	1001	356	1013	396	1029	436	1021	476	1002
277	1029	317	1041	357	1036	397	1030	437	1022	477	1037
278	1030	318	1006	358	1037	398	1031	438	1041	478	1041
279	1041	319	1016	359	1038	399	1032	439	1023	479	1038
280	1031	320	1022	360	1041	400	1041	440	1005	480	1001

Part 3 of Table 10 Glass and metal route schedule strategy 2:

Day	Route	Day	Route	Day	Route	Day	Route	Day	Route	Day	Route	Day	Route
481	1010	521	1010	561	1006	601	1039	641	1020	681	1023	721	1014
482	1039	522	1031	562	1007	602	1041	642	1031	682	1041	722	1038
483	1041	523	1032	563	1020	603	1020	643	1041	683	1024	723	1039
484	1020	524	1020	564	1024	604	1040	644	1008	684	1002	724	1041
485	1040	525	1033	565	1005	605	1003	645	1032	685	1041	725	1001
486	1003	526	1041	566	1016	606	1008	646	1013	686	1011	726	1040
487	1012	527	1006	567	1041	607	1041	647	1018	687	1025	727	1003
488	1008	528	1008	568	1008	608	1012	648	1033	688	1005	728	1012
489	1041	529	1034	569	1025	609	1015	649	1034	689	1026	729	1015
490	1015	530	1018	570	1026	610	1007	650	1041	690	1027	730	1041
491	1006	531	1035	571	1027	611	1041	651	1002	691	1041	731	1006
492	1017	532	1041	572	1041	612	1017	652	1035	692	1001	732	1017
493	1019	533	1005	573	1028	613	1002	653	1036	693	1028	733	1019
494	1041	534	1036	574	1003	614	1016	654	1037	694	1013	734	1004
495	1021	535	1037	575	1041	615	1019	655	1004	695	1004	735	1011
496	1022	536	1041	576	1004	616	1004	656	1041	696	1006	736	1021
497	1023	537	1038	577	1029	617	1021	657	1001	697	1029	737	1041
498	1041	538	1041	578	1002	618	1041	658	1005	698	1003	738	1009
499	1011	539	1039	579	1009	619	1009	659	1009	699	1041	739	1022
500	1013	540	1004	580	1030	620	1022	660	1006	700	1009	740	1013
501	1005	541	1041	581	1041	621	1023	661	1038	701	1030	741	1023
502	1024	542	1009	582	1031	622	1001	662	1007	702	1031	742	1041
503	1041	543	1040	583	1032	623	1041	663	1039	703	1018	743	1024
504	1004	544	1002	584	1001	624	1024	664	1041	704	1041	744	1025
505	1025	545	1041	585	1033	625	1006	665	1016	705	1032	745	1041
506	1009	546	1003	586	1041	626	1005	666	1003	706	1033	746	1010
507	1026	547	1011	587	1018	627	1041	667	1040	707	1034	747	1005
508	1041	548	1012	588	1034	628	1025	668	1012	708	1041	748	1026
509	1027	549	1013	589	1035	629	1026	669	1015	709	1010	749	1027
510	1002	550	1001	590	1041	630	1027	670	1041	710	1007	750	1041
511	1041	551	1015	591	1036	631	1041	671	1017	711	1035		
512	1007	552	1041	592	1006	632	1028	672	1010	712	1016		
513	1014	553	1017	593	1011	633	1003	673	1019	713	1036		
514	1028	554	1019	594	1037	634	1041	674	1041	714	1041		
515	1001	555	1014	595	1041	635	1029	675	1021	715	1020		
516	1016	556	1021	596	1005	636	1010	676	1020	716	1037		
517	1003	557	1022	597	1013	637	1041	677	1041	717	1008		
518	1041	558	1023	598	1014	638	1014	678	1014	718	1005		
519	1029	559	1041	599	1038	639	1030	679	1022	719	1041		
520	1030	560	1010	600	1010	640	1011	680	1008	720	1002		