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Strategies for Reverse Logistics related to plastic waste

By: PlastiCity Consortium, with kind support from Conundra (Ghent, Belgium) and Louis D'hondt.

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Report on Strategies for Reverse Logistics related to Plastic Waste

PlastiCity Consortium

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Summary

This report develops strategies for reverse logistics related to plastic waste using desk research, simulations and consultation with waste and logistic companies. Its core is the simulation of (reverse) logistics of (waste) plastics in the case study cities. This results in scenarios with different transport modi, including loading rates, distances, costs, and impact on CO2 emissions. 10 companies were actively sensitized and experience from actors and cases resulted in a generic methodology to develop case specific solutions. This allows transferability to other cities. The more than 100 simulations we run for PlastiCity are a tool to help decision makers and practitioners think about the plastic waste logistics in their cities. They are useful to explore "what if" scenarios and conduct thought experiments. There are however, limitations due to the lack of empirical data from the locations, this specially affecting routes and impact on CO2 emissions. Nevertheless, we hope this work can serve as a basis for further research and development as well as for practitioners to optimise their local waste logistics in innovative ways.

Acknowledgement

We would like to thank Conundra, and especially Louis D'Hondt, for their kind support with their logistics simulation software and the required training.

1 Introduction

The simulations described in this report are based on the plastic waste scenarios previously developed and presented in PlastiCity report D2.1.1, available online[1].
The scenarios looked at reverse logistic solutions that might fit the four cities from a more abstract perspective; what might be possible in the future? The simulations are more concrete, applying sophisticated software to test scenarios looking at numbers and costs for doing the collections of plastic waste with different vehicles.

Bear in mind that simulations are only as good as the data they are based on. When input data or assumptions change, the outputs change. Therefore, simulations should be seen as a tool to support thought experiments rather than as evidence-based solutions. The simulations are not capable of providing exact answers or reliable numbers, given that they are based on many assumptions - some of them more realistic, others more hypothetical, depending on the data available.. When the input data change, e.g. vehicle emissions, waste owner addresses or waste quantities, the results change. Even when all inputs stay the same, the outputs may vary as the simulations are not entirely deterministic. This is reflected in reality: for instance, traffic conditions change continuously. However, the key aspect of the simulations is the like-to-like quantitative comparison between alternative scenarios, and -ceter paribus- the simulations allow to identify the best (e.g. less cost and less pollution) scenarios developed from a set of assumptions. These best scenarios provide the starting point for strategies for reverse plastic logistics in each city

A lot of the data required to build realistic scenarios were unavailable at the time of execution, due to a variety of reasons. Therefore, the simulations must be seen as thought experiments, reflecting the ideas present in each PlastiCity city. They are all different; different types of stakeholders are involved, and different types of data are available. The overall goal is always to reduce emissions and costs whilst collecting plastic waste in an efficient and sensible way, adapted to the local situation.

We developed individual simulations for each city, depending on how the involved stakeholders (waste collection companies, city councils, etc.) see the situation. For Douai, the simulations are based on a client database provided by a waste collection company, and we investigated the lorry trips required to collect Ampliroll containers from client locations. For Southend, three simulations were conducted: two milk-run

[1] https://www.plasticityproject.eu/downloads

collection tours executed by Ford E-Transit vehicles and the lorry trips required to serve the 10 mini-hubs distributed across town. For The Hague, we considered three circular bands around the city centre: up to 5km from the city centre, CargoBikes would collect waste and drop it off at the hub; between 5 and 10km a Nissan e-nv200 would collect plastics and drop them off at the hub; and between 10 and 15km from the city centre a diesel lorry would be used, dropping off the waste at a local waste processing company. Finally, for Ghent, we explored the use of alternative vehicles and checked the necessary collection radius for gathering a certain amount of plastic waste, e.g. 5 tonnes.

The overall goal is always to determine a sensible approach to plastic waste collection that minimises emissions, impact on pedestrian zones, and costs, whilst keeping plastics in the best condition possible (e.g. compaction only, no shredding before quality-assured sorting).

2 Literature review and background information

All waste collection requires vehicles that fit the local conditions (pedestrian, residential, industrial, rural zone etc.), and they all need propulsion. Whilst diesel produces the most pollution where the lorry is, it is still the most cost-effective and arguably the most efficient fuel. Electrical vehicles emit no pollution at their location. However, depending on how the energy is generated, pollution may be generated elsewhere (e.g. at a coal power station), wild life may be harmed (e.g. wind power) and there are losses through energy conversion. There is also the question of what happens to the vehicle batteries when they reach their end-of-life. Will they really be recycled? There have been reports[2] of vehicle batteries being explosive and hence a risk for transportation, especially after an accident[3].

Other alternative fuels include gas (biogas, CNG, LPG, etc.), hydrogen, cooking oil and others[4]. Hybrid vehicles (e.g. using petrol and electric in combination) also have advantages, especially when it comes to driving long distances. For waste collection, where vehicles drive short distances but work all day long, the usefulness of hybrid motors may depend on whether vehicle batteries can be charged quickly during breaks

[2] https://www.forbes.com/sites/brookecrothers/2021/07/11/are-electric-cars-safe-another-chevy-bolt-caught-fire-a-tesla-model-s-plaid-did-too

[3] https://www.govtech.com/fs/electric-vehicle-batteries-can-explode-after-an-accident

[4] https://www.rac.co.uk/drive/advice/emissions/alternative-fuels

or not. It is also important to bear in mind that what applies to small cars does not necessarily apply to lorries.

There are many different electrical cargo vehicles, including[5] vans, pick-ups, semi-trailers, lorries, tractors, waste collection trucks and others. Some waste management companies have projects converting diesel waste collection vehicles into electrical ones[6].

2.1 Calculating carbon emissions of refuse collection vehicles (RCV)

One of the important considerations to make when deciding on the right strategy for waste collection is the resulting carbon footprint.

It is possible to calculate the carbon emissions based on fuel consumption[7] or, taking the analysis further, the carbon footprint of waste collection taking into account what happens to the waste afterwards (e.g. does food waste go to landfill or composting[8]).

Emissions generated by vehicles used for waste collections - Refuse Collection Vehicles (RCVs) - are not easy to calculate, as most available data are per kilometre. However, RVCs run long hours whilst driving only short distances. Also, operating container lifts or waste compaction presses consumes additional energy. Overall, the vehicles may emit more than assumed (Agar et al., 2007).
A study[9] commissioned by the EU (Gioria et al., 2020) explains that RVCs "(...) use engines designed for long haulage trucks and consequently not optimised for low speed stop and start driving. The very low average speeds and the frequent stops represent difficult conditions to cope with from the emission reduction perspective. In fact, for short periods, where the exhaust gas temperature is low for the aftertreatment devices (cold start, some city conditions), the emissions are relatively high."

Nguyen (2008) studied the fuel consumption and greenhouse gas emissions of waste collection vehicles, taking into account the idling whilst loading. The resulting recommendations to reduce emissions include to reduce collection frequencies for low density areas.

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[5] https://en.wikipedia.org/wiki/Electric_truck
[6] https://www.veolia.co.uk/press-releases/veolia-trial-electric-refuse-collection-vehicles
[7] https://www.commercialfleet.org/tools/van/carbon-footprint-calculator
[8] https://www.biocycle.net/connection-co2-math-for-food-waste-transport/
[9] https://publications.jrc.ec.europa.eu/repository/handle/JRC120963

Whilst engine type and year play a role in emissions, other factors are important as well, such as road characteristics and driver characteristics[10]. Overall, it is often not straightforward to calculate the real emissions generated by an RCV, but they are significant.

2.2 CargoBike and similar small vehicles

When searching for alternatives to traditional RCVs, one of the possible solutions are CargoBikes or other small vehicles. CargoBikes are often powered by human muscles assisted by batteries. Many models have small boxes or crates, e.g. to hold food for delivery. Those used for waste collection require larger loading containers and are ideally equipped with a compactor.

The CargoBike[11] used by The Hague in the PlastiCity project is powered by a replaceable battery and has a loading volume of 2.2m3. About 7m3 of plastics in their original state can be compressed down to fit into the CargoBike.

When deciding whether to use a CargoBike in a specific situation, a number of aspects need to be considered, namely:

1) Measuring delivery route cost trade-offs between electric-assist (EA) CargoBikes and delivery trucks in dense urban areas

EA CargoBikes are more cost effective than delivery trucks for deliveries in close proximity to the distribution centre (DC) / recycling depot (less than 2 miles for the observed delivery route with 50 parcels per stop and less than 6 miles for the hypothetical delivery route with 10 parcels per stop) and at which there is a high density of stops and low delivery volumes per stop. It is not quite clear how this translates from a parcel delivery routine into a waste collection scenario. Generally, delivery trucks are more cost effective for greater distances from the DC and for large volume deliveries to one stop.

Figure 2.1 provides an overview of academic literature on CargoBikes, and Figure y lists expected advantages and drawbacks of using CargoBikes. Their use remains in an early phase, as Figure 2.2 demonstrates; whilst there are various pilot projects, large scale implementations are yet to be delivered.

[10] https://erefdn.org/evaluating-air-emissions-fuel-efficiency-solid-waste-collection-vehicles-2
[11] https://www.plasticityproject.eu/the-hague-introduces-the-sustainable-cargo-bike

Table 1 Cargo bicycle literature review summary

Author	Year	City	Country	Research Question	Findings
Melo et al.	2013	Porto	Portugal	How can electric cargo cycles impact traffic, energy efficiency, and emissions in urban environments?	Replacing 10% of delivery service vans would yield in better road network efficiency and reduce wheel to wheel CO2 emissions, and costs.
Tipagornwong et al.	2014	Urban Areas	United States	How competitive are freight tricycles compared to diesel vans in terms of costs and logistical constraints?	Diesel vans are more cost effective for deliveries that include parcels weighing 50 lbs. or more and freight tricycles are more cost effective for deliveries with time windows between 2 and 4 h.
Choubassi et al.	2016	Austin	United States	How do the operating costs compare for either a pedal bike with an electric motor, e-bike, or e-trike?	An e-trike has the lowest cost of operations.
Arnold et al.	2018	Antwerp	Belgium	How can different delivery modes be compared and assessed for efficacy before deployment?	Cargo bikes reduce external costs by 40% per delivery. Driving time increases by 134% with a cargo bike.

Figure 2.1: Academic literature on CargoBikes. Source: Sheth et al. (2019)

Table 2 Advantages and disadvantages of EA cargo bikes

Anticipated Advantages of EA Cargo Bikes	Anticipated Disadvantages of EA Cargo Bikes
More quiet than an engine due to an electric motor	Higher cost of trans-loading due to smaller cargo capacity
Small enough to maneuver through narrow streets and pedestrian only zones	Lower economies of scale due to the lower carrying capacity of an EA cargo bike
Time saved finding parking because it can park on sidewalks	Limitations in some area due to inability to climb steep slopes
Money saved on parking tickets because it would not be as likely to park illegally	Road regulations (E.g. EA cargo bicycles are illegal in New York City [20])
Increase in delivery reliability because EA can avoid congested roads and can use the bike lane to meet delivery deadlines	Urban design barriers such as bollards or limited bicycle infrastructure
Improved road safety for pedestrians and cyclists as bike collisions are less severe than collisions with a delivery truck	Other limitations - driver fatigue, depleted battery charge, and extreme weather conditions (wind, rain, snow, ice, etc.)
	Collisions may be more severe for the EA cargo cyclist as compared to driver in truck

Figure 2.2: Advantages and drawbacks of CargoBikes. Source: Sheth et al. (2019)

2) Potential for CargoBikes to reduce congestion and pollution from vans in cities (Cairns and Sloman, 2019)

Estimates suggest about 10-30% of trips by delivery and service companies might be substitutable by CargoBikes. Taken together, these figures suggest that there is potential for traffic mileage in urban areas to be reduced by about 1.5-7.5%, if CargoBikes took over from delivery and service vehicles for suitable trips. Trials by DHL, where two vans are replaced by a ‘City Hub’ and four CargoBikes, are estimated to reduce CO2 emissions by 16 tonnes p.a.. As an implementation example, in London, a butcher who began using a CargoBike instead of a van whenever possible was able to reduce CO2 emissions by 75%.

For plastic waste collection logistics, this concept translates into the use of local mini-hubs served by CargoBikes that collect plastics from local businesses, as envisaged in the simulations run for Ghent and The Hague. Figure 2.3, below, summarises evidence from case studies.

Figure 7: Summary of case study evidence about the potential for (e-)cargo bikes, and associated impacts

Nature of evidence	Scale of activities/ substitution	Associated impacts
Micro-consolidation centres and cargo bikes		
Data from **Gnewt Cargo** (2015)[20] – a company using micro-hubs **in London** and electric vans to do the local part of the delivery for major parcel companies	Delivers 6-7,000 parcels a day, rising to 17-18,000 in the run up to Christmas. In Jan 2015, on average, vans delivered 125 parcels per day, making 60-80 stops, averaging 13.5km/day and 4mph. Stop time (i.e. the time between the motor stopping and being re-started) was 5.5 minutes. For one parcel company (Hermes), 35-50 diesel vans have been replaced with 8 7.5t trucks and 35 Gnewt vans.	1742km/day in the Hermes vans replaced by 335km in the trucks and 484km in the Gnewt vans. Diesel mileage reduced by 81%; fuel use reduced by 88%; distance travelled per parcel reduced by 52%.
DPD in **London** (2018/19) – a company using micro-hubs and all electric vehicles[21, 22, 23]	At the micro-depot, parcels are dropped by two 7.5 tonne electric lorries, and final deliveries are carried out by 10 electric vans and eight electrically-powered micro-vehicles (albeit not e-cargo bikes). Each micro-depot is capable of handling 2,000 parcels per day.	At the time of opening the first depot, an initial reduction of 45 tonnes CO_2 p.a. was expected.
DHL pilot of CityHub and Cubicycles **in Frankfurt and Utrecht** (2017)[19]	CityHub transports 4 containers to a central location, which are then each loaded onto a Cubicycle e-bike (which can carry 125kg, and averages 50km a day) for delivery of contents	Each hub anticipated to replace 2 conventional delivery vehicles, and save >16 tonnes CO_2 p.a.
UPS use of four micro-depots **in Hamburg** (c2016)[24]	70% of city centre covered; 500-600 parcels per swap body per day.	Use has expanded over time, from one depot in 2012, given their value, and the same model is being trialled in Dublin and Leuven.
DPD/GLS use of two micro-depots **in Nuremburg** (2016)[24]	Bikes capable of making 15 stops per hour; up to 100 stops per day, with 10 minutes to reload. Pilot phase involved switch from 10 trucks, to 5 bikes and 6 trucks. Possible shift to 8 bikes and 3 trucks.	Pilot phase (from November 2016) reported savings of "65kg NOx, 8kg PM_{10} and 56t CO_2". The pilot phase led to permanent operation in March 2017.

Figure 2.3: CargoBike pilot studies. Source: DHL (2019}

2.3 Electrical and hybrid cargo vehicles

Research by eunomia (2020) concluded that it is favourable to replace diesel waste collection vehicles by electrical ones[12]: " (...) switching the UK's fleet of diesel powered refuse collection vehicles for electric trucks would have multiple benefits. These include reducing UK greenhouse gas emissions by 290 kilotonnes of CO2 each year – the equivalent of recycling almost 16 billion plastic bottles – eliminating associated exhaust fumes, and saving local authorities money in the long run." An additional benefit is that electrical vehicles are far less noisy than diesel powered ones, contributing to a better life quality especially in cities.

In 2018, Veolia trialled the conversion of old diesel RCVs (26t) into electrical vehicles, powering them with energy gained from the incineration of non-recyclable waste[13]. In

[12] https://www.eunomia.co.uk/electric-refuse-trucks-cut-carbon-costs/

[13] https://www.veolia.co.uk/press-releases/veolia-trial-electric-refuse-collection-vehicles

2021, they announced the launch of a new fleet of electric RCVs in the City of London[14] and in Westminster[15], where also electric sweeping vehicles and trikes for collecting recycling[16]. The trikes are similar to the CargoBike used in PlastiCity but aimed at collecting street recycling[17].

There are challenges with electrical vehicles. Their high purchasing prices are high due to the cost of batteries. Assuming a lithium-ion battery capital cost equal to 90 €/kWh, acceptable pay-back periods (about 6 years) were obtained (Calise et al., 2019).

Most importantly, end-of-life solutions for the batteries are urgently required. Battery recycling is complicated and expensive, and there is a risk of batteries being sent to developing countries where health and safety regulations are less stringent and less enforced[18]. Car manufacturers are legally obliged to recycle the batteries and first pilot recycling plants are operational[19], some going beyond[20] the (very low) obligation of recycling 50% of the metals. It is also possible to give car batteries a second life before recycling, using them for energy storage[21] which is required for many renewable energy sources.

Calise et al. (2019) push this concept further by regarding electrical vehicles as a mobile energy storage system, with relatively regular charging and discharging cycles. They can be plugged into the grids during night at places where the end-users reside, and/or daytime, near commercial buildings or other tertiary sites. Therefore, they represent a flexible option for supporting the future decarbonization scenario, also reducing the energy consumption in buildings.

Mello Bandeira et al. (2019) compared the efficiency and costs of Traditional Intermodal Distribution (TID), Distribution by Electric Tricycles (DET) and Alternative Intermodal

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14 https://www.veolia.co.uk/press-releases/first-electric-vehicle-marks-step-towards-fully-electric-collection-fleet

15 https://www.veolia.co.uk/press-releases/get-show-road-west-ends-electric-recycling-fleet

16 https://www.circularonline.co.uk/news/veolia-and-westminster-city-council-unveil-fully-electric-fleet-for-the-west-end/

17 https://www.circularonline.co.uk/news/news-in-brief-veolia-trials-innovative-electric-tricycles-in-westminster/

18 https://www.bbc.co.uk/news/business-56574779

19 https://waste-management-world.com/a/electric-vehicle-battery-value-chain-collaboration-between-veolia-groupe-renault-and-solvay

20 https://www.veolia.com/en/solution/recycling-electric-car-batteries-ecological-issue

21 https://www.theguardian.com/environment/2021/aug/20/electric-car-batteries-what-happens-to-them

Distribution (AID), where a small electrical vehicle is used in addition to the conventional means of transportation. Compared with the TID strategy, they identified a cost saving of 27.9% by adopting the DET strategy. Concerning the level of service, they observed a 26% increase in productivity, when comparing the DET strategy with TID/AID strategies. It was verified that the DET strategy, besides taking less time, was able to carry out a greater number of deliveries: 39 deliveries per hour in comparison to 31 deliveries per hour by the TID/AID strategies.

Figure 2.4 details studies conducted to assess the use of electrical vehicles in a number of countries. This shows us that there is a wide-spread trend towards exploring the use of alternative vehicles for delivery and collection vehicles.

Author	Country	Data collection method	Assessment method	Type of vehicle or equipment used	Source of energy	Barriers	Benefits/opportunities		
							Economics	Environmental	Social
Dampier and Marinov (2015)	England	Literature review and Field observations	Case study	Bicycle/Tricycle	Human	Cargo consolidation center	Delivery time; Traffic congestion	Reduction of CO2 emissions and atmospheric pollutants	–
Schau et al. (2015)	Germany	Public policy	Simulation	LDV	Electric	Cargo consolidation center; Road and recharge infrastructure; Capacity (weight and dimensions); vehicles charging time	–	Reduction of CO2 emissions and atmospheric pollutants	–
Margaritis et al. (2016)	Greece	Literature Review	Case study	LDV	Electric	–	–	–	–
Navarro et al. (2015)	Italy	Field observations	Case study	Bicycle/Tricycle	Electric	Cargo consolidation center; Road and recharge Infrastructure; Capacity (weight and dimensions)	–	Reduction of CO2 emissions, atmospheric pollutants and noise	–
Rizet et al. (2015)	France	Literature Review	Simulation	LDV	Electric	Recharge infrastructure (electric)	Traffic congestion	Reduction of CO2 emissions and atmospheric pollutants	–
Gruber and Kihm (2016)	Germany	Field observations	Case study	Bicycle/Tricycle	Electric	–	–	–	–
Heitz and Beziat (2016)	France	Field observations	Case study	Bicycle/Tricycle	Electric	Cargo consolidation center;	Operational cost	Reduction of CO2 emissions and atmospheric pollutants	–
Anderluh et al. (2016)	Austria	Literature Review	Simulation	Bicycle/Tricycle	Electric	–	Traffic congestion	Reduction of CO2 emissions, atmospheric pollutants and noise	–
Taniguchi et al. (2014)	Japan	Literature Review	Case study	LDV	Diesel	Cargo consolidation center	–	Reduction of CO2 emissions, atmospheric pollutants and noise	–
Schier et al. (2016)	Germany	Field observations	Case study	Bicycle/Tricycle	Electric	–	–	Reduction of CO2 emissions and atmospheric pollutants	Quality of life

[a] Vehicles for the shipment of goods and having a maximum total gross weight (TGW) not exceeding 3.5 t.
[b] A bicycle specially designed for shipping loads.
[c] Two wheel vehicles without a sidecar (category L3e) or with a sidecar (category L4e), fitted with an engine having a cylinder capacity of more than 50 cm^3 with a maximum design speed of more than 45 km/h.
[d] Small vehicles with two or four wheels that can be used to transport large or heavy loads.

Figure 2.4: Case studies on the use of electrical vehicles. Source: Kester et al (2018)

Electric vehicles are an important instrument to decarbonize transportation, offering a range of co-benefits such as reductions in local pollution, noise emissions, and oil dependency. However, their wider adoption currently faces a number of obstacles including high price, limited range, limited availability of infrastructure, technological uncertainty, varying political interests, existing business cases, as well as a lack of consumer knowledge and practical driving experience (Kester et al., 2018). However, electric vehicles also have environmental impacts that are directly related to the country's electricity generation mix. Woo, Choi and Ahn (2017) warn that in countries without an environmentally friendly electricity generation mix, electric vehicles may not be effective in lowering greenhouse gas (GHG) emissions. Woo et al (2017) analyzed the extent to which the GHG emissions associated with electric vehicles differs among 70 countries in the world, in relation to their domestic electricity generation mix. Then, they compared the results with the GHG emissions from internal combustion engine vehicles (ICEVs). Countries with a high percentage of fossil fuels in their electricity generation mix showed high GHG emissions for EVs, and for some of these countries, EVs were associated with more GHG emissions than ICEVs. Woo et al (2017) compared emissions of 4 types of vehicles, including vans and trucks. For this type, the average CO2 emissions for gasoline vehicles was 210 gC02/km and for diesel vehicles was 164 gC02/km. European countries show lower emissions for EV, with marked differences from country to country. For the countries involved in Plasticity, information is provided by Woo et al (2017) for the UK and France. The data provided showcases that in France (average emission 12.7 gC02.km, maximum emission 24.5 gC02/km) electric vehicles are always more environmentally friendly than diesel. The UK (average 100, 7 gC02/km, max 165. 6) is singled out as one European country where in certain circumstances electric vehicles can have more emissions than diesel powered vehicles.

Another aspect to consider is the carbon footprint of vehicle battery manufacturing. The International Council of Clean Transportation concluded[22] that these carbon emissions are expected to be balanced out quickly during vehicle operations, but also admit that estimates of battery manufacturing emissions vary by a factor of 10, hence further research is required.

2.4 Gas-powered cargo vehicles

Gas used to fuel vehicles[23] is typically either Liquefied Petroleum Gas (LPG), Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG) or biogas (from decomposing waste).

Gas powered lorries are less expensive to run than diesel powered engines, but they are also less efficient and overall pollute roughly the same, although more research is needed[24]. However, as gas prices are lower, there is a money saving potential. Biomethane[25] seems like the best option, but it is not widely available.

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[22] https://theicct.org/sites/default/files/publications/EV-life-cycle-GHG_ICCT-Briefing_09022018_vF.pdf
[23] https://auto.howstuffworks.com/fuel-efficiency/hybrid-technology/10-alternative-fuels-on-the-road.htm
[24] https://www.zemo.org.uk/assets/reports/LowCVP%202016%20DfT%20Test%20Programme%20Final%20Report.pdf
[25] https://www.local.gov.uk/sites/default/files/documents/sloughs-rcv-options-appra-d7c.pdf

Some reports state that gas lorries are definitely not a good idea - not even as an intermediary solution on the way towards more environmentally friendly lorries[26]. Table X compares the emissions from different gas powered vehicles, with discouraging results. Additionally, a shift to gas would also create a risk of technology lock-in, diverting scarce (public) funds away from these technologies with the potential to decarbonise light-duty vehicles (Transport Environment, 2016).

Gioria et al. (2020) compared a Diesel Euro VI step C and a Compressed Natural Gas (CNG) Euro VI step C refuse collection heavy-duty vehicle both in the laboratory and on the road using a cycle similar to the in-service conformity (ISC) trips for this type of vehicles. They concluded that “in general, diesel technology presented important advantages with regards to the NOX, PN, CO2 emissions as compared to the CNG engine, while the CNG vehicle provided a better CO emission behaviour. This trade off needs to be carefully analysed prior to deciding if a fleet should be shifted towards either technology” and also cautioned that this comparison cannot necessarily be generalised to other vehicles than those studied. Figure 2.5 summarises evidence of emissions (wheel to wheel) per type of contaminant and technology compared to GNC.

Vehicle	Comparison	Carbon dioxide (CO2)	Nitrogen oxides (NOx)	Particulate matter (PM)
Metric		WTW emissions	Emissions reduction for a 5% NGV share	Emissions reduction for a 5% NGV share
Petrol car	CNG	-18%	0%	-4.0%
Diesel car	CNG	+6%	-3.5%	-4.5%
Van	CNG	+8%	-3.6%	-4.0%
Small rigid truck	CNG	+13%	0%	-4.5%
Large rigid truck 26t	LNG	+16%	0%	-3.2%
Articulated truck >32t	LNG	+2%	0%	-1.8%
Coach	LNG	+15%	0%	-4.4%
Bus	LNG	+6%	0%	-5.4%

Source: Ricardo Energy & Environment, 2016

Figure 2.5: Comparison of emissions. Source: Transport Environment (2016)

For smaller trucks and vans a shift to gas engines would result in significantly higher overall GHG emissions. For bigger (articulated) trucks a shift to LNG powered trucks would in all cases result in higher overall GHG emissions. Compared to modern EURO VI trucks, gas powered

26 https://www.transportenvironment.org/sites/te/files/publications/2019_09_do_gas_trucks_reduce_emissions_paper_EN.pdf

trucks (CNG or LNG) perform only marginally better when it comes to air pollution (Transport Environment, 2016).

Stettler et al. (2019) compared the emissions of different lorries across their life-time (Figure 2.6) and found that whilst gas powered engines may make sense for long haul vehicles, they are counter-productive for waste collection vehicles as well as buses due to their start-stop operations.

Table 4: Well-to-wheel CO2-equivalent emissions for three different heavy goods vehicle types using compressed and liquefied natural gas compared to an equivalent diesel vehicle. Percentages indicate the proportion of emissions across the well-to-wheel lifecycle, from [21].

WTW Stage	LNG Short Haul Freight		CNG Refuse Truck		CNG Transit Bus	
	[gCO2e/tonne-km]	[%]	[gCO2e/tonne-km]	[%]	[gCO2e/tonne-km]	[%]
Supply Chain	8	13%	35	19%	40	19%
Fuel Production	7	11%	7	4%	7	4%
Vehicle Operation	48	76%	138	77%	160	77%
Total	63	100%	180	100%	208	100%
Diesel-Equiv. Vehicle	63		169		193	
Natural Gas/Diesel Ratio	1.00		1.07		1.08	

Figure 2.6: WTW C02 emissions of CNG and LNG compared to Diesel . Source: Stettler et al (2019)

2.5 Alternatively fuelled cargo vehicles: hydrogen and other fuels

Another alternative to propel vehicles is hydrogen, and some claim this is the best solution for the future[27] as using hydrogen is emission-free. However, hydrogen production is still rather inefficient nowadays[28] and often relies on fossil fuel either as a primary material (and source of energy) or only for providing energy to convert the primary material into hydrogen. Several ways to make hydrogen are being explored[29],

[27] https://www.commercialmotor.com/news/buying-advice/closer-look-hydrogen-fuelled-trucks

[28] https://www.greentechmedia.com/articles/read/the-reality-behind-green-hydrogens-soaring-hype

[29] https://www.energy.gov/eere/fuelcells/hydrogen-fuel-basics

and further developments are definitely required before using hydrogen-powered vehicles can be recommended without reservations.

Cooking oil is often disposed improperly. Using it to fuel lorries would solve this problem at the same time as reducing emissions. There are several pilot projects under way, such as the waste collection lorries operated by Bournemouth Borough Council[30]. Portsmouth[31] has gone a step further and is converting their waste collection lorry fleet to operating on hydrogenated cooking oil. United Biscuits[32] (manufacturers of many major snack brands in the UK) are doing the same. McDonald's[33] are currently powering half of their fleet on cooking oil, and DAF[34] is a lorry manufacturer equipping their lorries with motors that can accept this fuel. They explain: "Unlike previous generations of biodiesels, the production of HVO does not affect food production. This was an important reason why DAF was reluctant in the past to promote the use of biodiesel. Hydro-treated Vegetable Oil (HVO) is made by hydrogenating plant-based oils and waste. Because this process uses hydrogen instead of methanol, it makes HVO a more environmentally friendly diesel alternative."

Drawbacks include[35] that emissions are reduced but not eliminated; a higher price than diesel; the risk that virgin palm oil might be used instead of waste oils and fats; and there is a certain reluctance to adoption from regulators, vehicle manufacturers and fuel providers.

2.6 Summary:

The literature provides a strong case for environmental gains to be achieved by reducing emissions when switching to electric vehicles (large and small). However, the actual impact on wheel to wheel emissions depends on the country's energy mix. In countries where the generation of energy is heavily dependent on fossil fuels, the use of electric vehicles does not reduce the country's total emissions (Woo, Chong, Ahn, 2017). In the UK this could be the case, while in France electric vehicles will deliver substantial gains. Natural Gas vehicles (CNG and LNG) do not bring significant

[30] https://collectandrecycle.com/running-lorries-on-vegetable-oil

[31] https://www.portsmouth.co.uk/news/environment/clean-air-zone-portsmouth-bin-lorries-will-be-converted-to-run-on-vegetable-oil-3434922

[32] https://www.confectionerynews.com/Article/2014/09/30/United-Biscuits-to-roll-out-waste-cooking-oil-for-lorries

[33] https://www.mcdonalds.com/gb/en-gb/help/faq/19243-how-does-bio-diesel-power-your-delivery-trucks-and-how-many-lorries-are-powered-by-used-cooking-oil.html

[34] https://www.daf.co.uk/en-gb/trucks/alternative-fuels-and-drivelines/clean-diesel-technology/hvo

[35] https://www.commercialfleet.org/fleet-management/environment/alternative-trucks-fuels-with-few-drawbacks

improvements. Hydrogen vehicles are potentially the most environmentally beneficial but there is not yet evidence to support the most optimistic claims.

3 Simulations

Based on the logistics scenarios discussed for each of the PlastiCity cities, a number of simulations were performed for each city. It is possible to use spreadsheet software for simple simulations, for example generating numbers to compare the emissions of vehicles or the distances travelled between hub locations and drop-off locations. When a large number of orders are to be considered, a software that can automatically generate optimal routing between stops is required.

For PlastiCity, we compared a number of different simulation software programmes available on the market, taking into account their capabilities, user licence fees and available support. On this basis, we chose OptiFlow offered by Conundra in Ghent. Conundra[36] has kindly agreed to let us use their OptiFlow[37] software, which is a logistics routing simulation tool.

3.1 Limitations

The simulations presented subsequently need to be understood as a tool for thinking about waste logistics. They cannot provide absolute answers or complete solutions. Given that each city is different, the scenarios may not be transferable without adaptations. Furthermore, a large number of assumptions had to be made as a lot of essential data was unavailable. Critically , only for Douai we worked with actual company data individualized per company, while in the other cities we used typical, representative waste volumes.

Post-consumer plastic waste usually has a very low density, meaning that it takes up a lot of space but weighs very little. Given that volume is more restrictive than weight when it comes to transporting plastic waste, most of our simulations are run in volumes, although OptiFlow can use both.

For more complete simulations and calculating which solution makes most sense economically, actual costing per city along several fixed cost categories need to be known. As we did not have access to these data, the following costs were neglected:

Fixed Costs:

[36] https://www.conundra.eu/about-us

[37] https://www.conundra.eu/optiflow-route-optimization-software

- Vehicle purchasing costs
- Installation costs for electrical charging points
- Maintenance costs
- Overnight parking space
- Taxes

Costs that were considered, where the main variable costs

- Fuel / battery charging costs
- Costs per km for running a vehicle, where known
- Salaries for driver / loader

3.2 Simulations for Douai

The PlastiCity partner in Douai is Theys Recyclage, and hence the simulation was built from their perspective to enhance the take up of strategies proposed. Theys provided access to databases with actual volumes of waste collected yearly from their clients, As a result, the simulations and strategies produced have a business perspective and will provide particularly useful insights for plastic waste business models. Theys is currently building an innovative recycling sorting plant at their base, expanding their existing capacity.

Theys has a distinctive waste collection strategy as part of their business model. We call this the “fetch strategy”. Their clients notify Theys when the ampliroll containers are (almost) full, and according to contract, Theys needs to collect them within two days. Our simulations use Theys’ client database in anonymised form. However, only the collection frequency per client per year was recorded, not the dates when the collections happened. Hence it was not possible to run simulations taking into account collection distribution over time. Instead, we assumed all collections needed to be done subsequently, in random order, and calculated the time required, distance travelled, emissions generated and costs incurred.

Due to the nature of ampliroll containers, each requires an individual trip, and a milk-run scenario is not possible (See deliverable 2.1.1 for details on scenarios). However, the literature suggested potential cost and emission efficiencies when lorries with trailers are used. Lorries with trailers are not suitable for collecting waste in city center areas with narrow and twisty streets but Theys clients do not operate in old central areas. This suggested that while Theys is using lorries without trailers, substantial gains could be obtained if they changed this. Thus we compared the calculations on their current basis

(lorries without trailers) to a situation where all lorries pull trailers, and can hence transport two ampliroll containers at the same time.

Theys informed that the use of wheeled waste containers, typically containing 1100l, is more expensive and hence not interesting for most of their clients, as they have enough space for ampliroll containers. Wheeled waste containers are more interesting for companies in city centres, where space is valuable.

The simulations conducted for Douai, conducted on the basis of Theys' actual data, were done before the collection trials, hence the numbers presented in Table 3.1 are only informative and were not used for the simulations. Cross-docking facilities typically generate large volumes of packaging waste; cardboard, plastic film, paper, and other materials.

Table 3.1: Collection trial in Douai locations, at logistics (cross-docking) facilities

Location	**Weight [kg]**
Dourges	31
Lauwin planque	270
Libercourt	123
Henin Beaumont	95

3.2.1 Simulation details

Theys' database contains 108 clients with a varying number of collections. Collectively, they generate 2700 orders. OptiFlow allows for a maximum of 2000 orders to be calculated simultaneously, and therefore, not all orders could be included in the simulation. However, this should not influence the validity of the results; e.g. if using trailers could save 50% of distance travelled, this applies whether 80% or 100% of the orders are considered.

For fixed costs, we assumed the driver's salary at €100/day. The variable costs were assumed as €0.5/km. All other costs had to be neglected due to the relevant information not being available.

The base scenario includes 5 lorries without trailers. We compare this against scenario 1, where the 5 trailers travel with trailers. In scenario 2, we use only 4 lorries with trailers.

- Start and end location of the lorry journeys: Rue Edmond Gosselin, Douai
- Waste drop-off location: Theys Recyclage 815 rue du Faubourg d'Esquerchin, Cuincy
- Daily working hours: 7
- Vehicle loading volume: 40m3
- As it is typical for France, all recycling materials are mixed and the proportion of plastics is unknown. Theys collect these mixed materials and sort them at their plant.

Further input used the simulation (Actual data from Theys):

- Time to access a client pickup location: 10min
- Time to load at a client location : 5min
- Time to unload at the drop-off location: 15 minutes (including possible waiting times due to the plant being busy)

Assumption made to calculate emissions

- Emission factor[38]: 100.3 gr/ton.km (Only emissions caused during operation of refuse vehicle)

Additional assumption: On average, the use of a trailer causes the loss of 15 minutes for the second container due to manipulations and manoeuvring the lorry.
Since this simulation is a baseline for the rest and we do not compare diesel vehicles with electric vehicles, only operational emissions per ton.km are tabulated. A comparison of different vehicles will require a well to wheel analysis (that is considering the emissions generated while producing energy and manufacturing the vehicles)

3.2.2 Simulation results

The original configuration assumes 5 lorries without trailers. Details and results for this simulation are shown in Figure 3.1 and Figure 3.2, with possible routes in Figure 3.3.

[38] https://business.edf.org/insights/green-freight-math-how-to-calculate-emissions-for-a-truck-move/

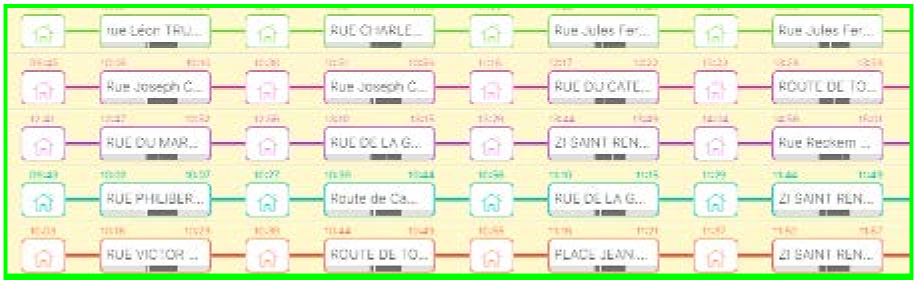

Figure 3.1: Simulation details for Douai with 5 lorries without trailer

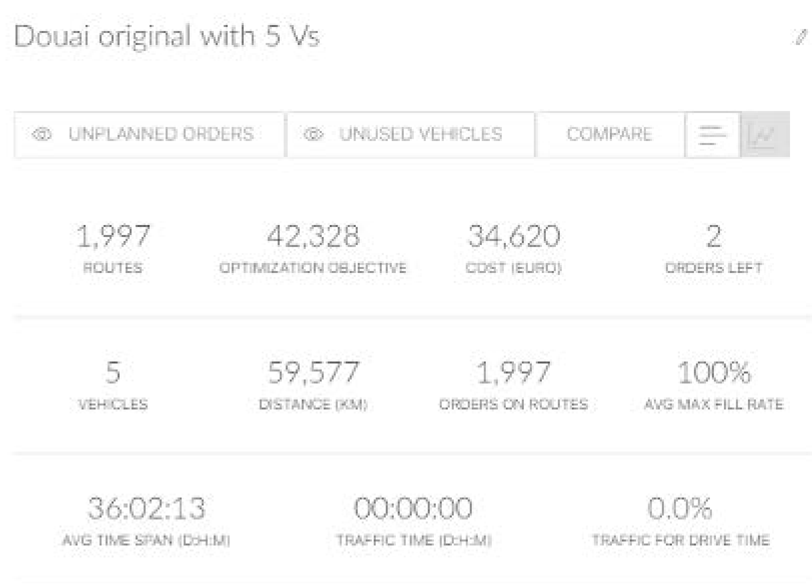

Figure 3.2: Simulation results for Douai with 5 lorries without trailer

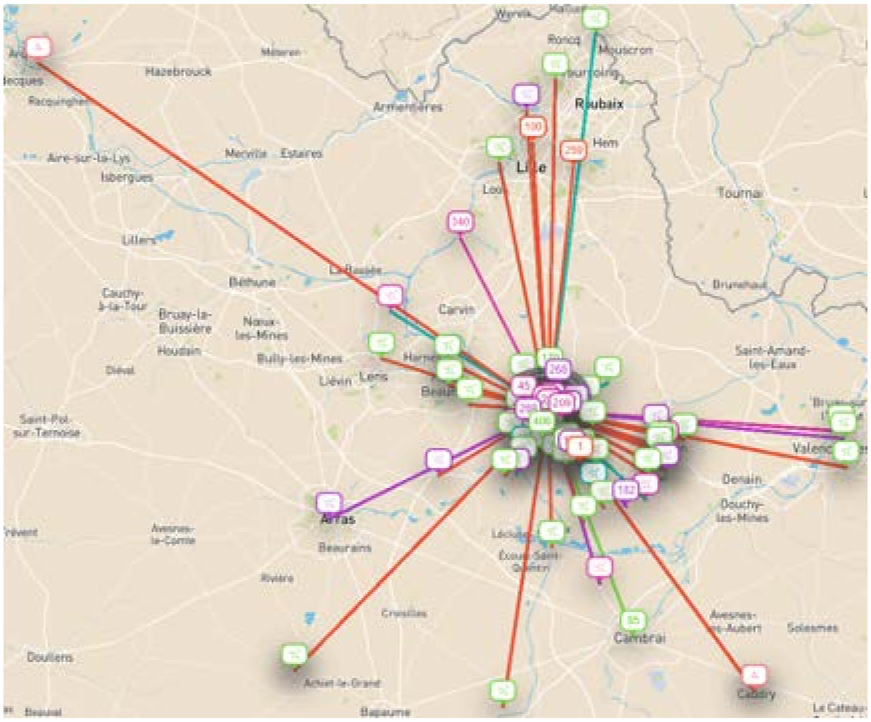

Figure 3.3: Possible routes for Douai with 5 lorries without trailer

Scenario 1 consists of adding trailers to the 5 lorries; see Figures 3.4 and 3.5.

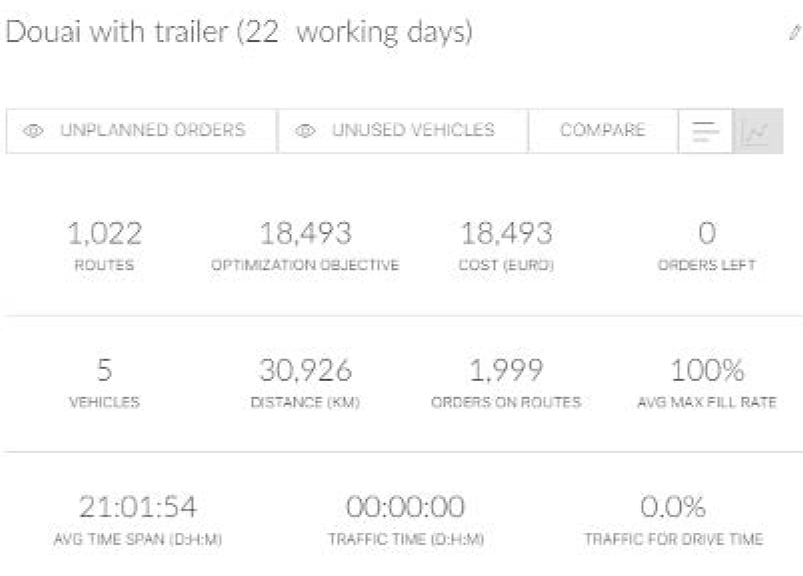

Figure 3.4: Simulation results for Douai with 5 lorries with trailers

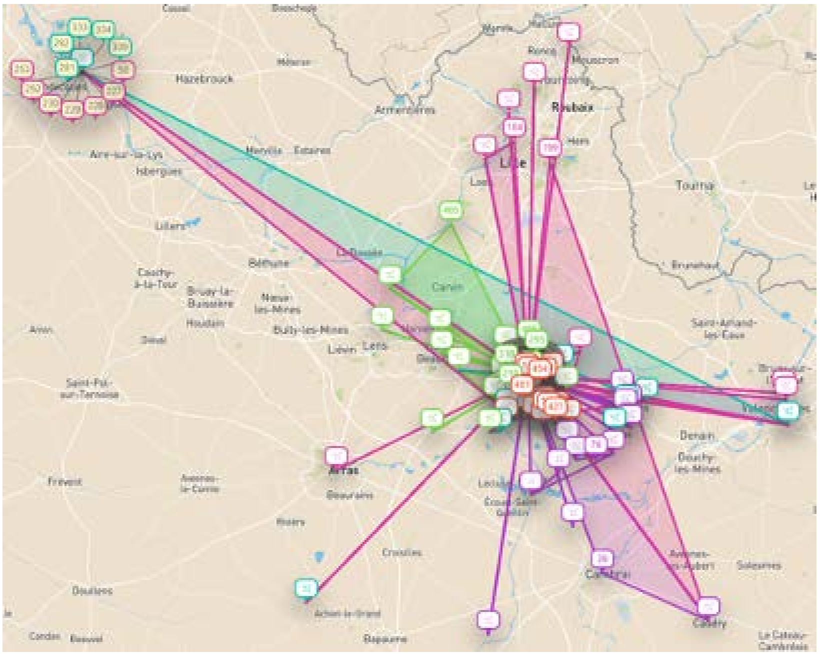

Figure 3.5: Possible routes for Douai with 5 lorries with trailers

In scenario 1, four of the lorries will be working 22 days, whereas the fifth will work only 21 days.

Scenario 2 considers only 4 lorries with trailers; see Figures 3.6 and 3.7.

Figure 3.6: Simulation results for Douai with 4 lorries with trailers

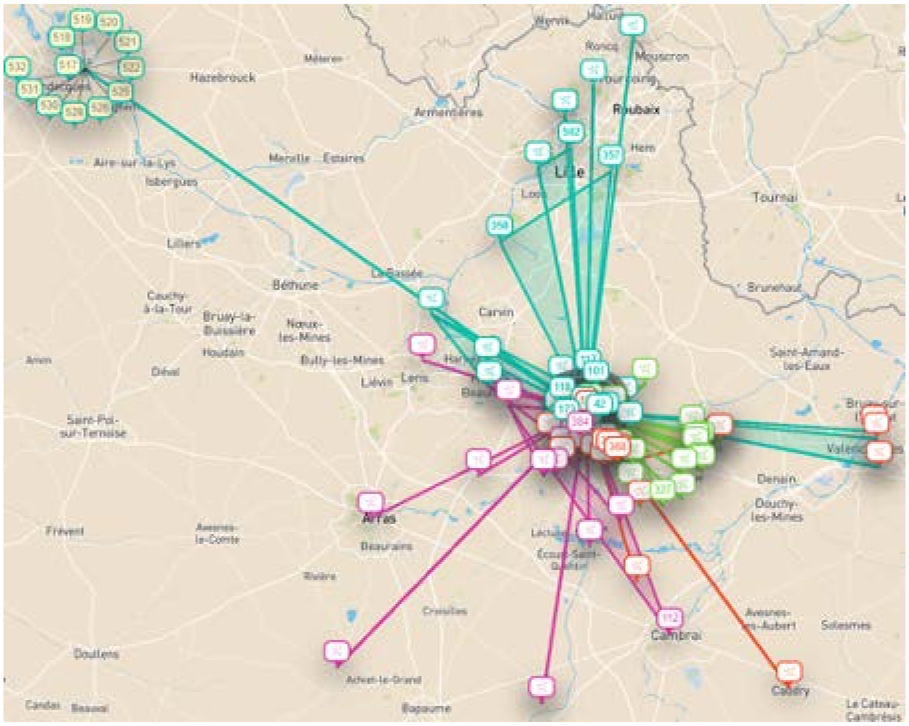

Figure 3.7: Possible routes for Douai with 4 lorries with trailers

Comparison of scenarios

Table 3.2: Comparison of Douai scenarios

	Douai original	Douai S1	Douai S2
Cost (Euro)	**34,620**	**18,493**	**18,216**
Distance (km)	**59,577**	**30,926**	**30,435**
C02 emissions (Kg/ton)	**5976.52**	**3102.37**	**3053.12**
Number of working days	**37 days**	**22 days**	**28 days**
Number vehicles	**5, without trailers**	**5, with trailers**	**4, with trailers**
Routes	**1,997**	**1,022**	**1,019**

Table 3.2 shows the results in terms of distance travelled, costs incurred and time used if all orders were executed consecutively. The emissions are assumed to be proportional to the distance travelled, as we do not have any information about traffic congestion; Theys stated that this was not a significant factor in Douai. Emissions were estimated for the total distance travelled by the float of trucks, using the equation and emission factor of the US Environmental Defense Fund. These are emissions per ton of waste transported.
The results agree with common sense: with a trailer, the distance and costs are roughly half.
However, the time is only reduced by 40%. This is mainly due to the time it takes to load and unload, which remains the same, whilst travelling is reduced and the time added to manoeuvres by handling the trailer.

Our conclusion is that If the goal is to reduce costs, distance travelled and emissions, scenario 2 is the best choice. However, scenario 1 requires fewer days to complete the waste collection, given that there is one more lorry, and still reduces costs, distance and emissions compared to 1. When the business model is based on speed of collection, scenario 1 would be the best choice.

3.3 Simulations for Southend

Southend-on-Sea Borough Council (SBC) is the local PlastiCity partner in the UK and interested in improving plastics waste logistics in various ways. Three simulations were built to explore a concept with 10 mini-hubs distributed across the town, each with a roll-on/roll-off container requiring individual lorry trips similar to the scenario in Douai.
However, the simulations are more complex because Southend wanted to explore the use of electric vehicles, which -as we have seen in the literature review- present substantial reductions in emissions compared to fuel-based vehicles. Accordingly, the other two simulations in Southend are milk-runs executed by electrical vans: one route in an industrial area called Temple Farm and one route in the town centre, where a CargoBike is used additionally. Both locations also host a mini-hub, where the collected plastics can be accumulated. The electrical van is assumed to be a Ford e-Transit[39] with a loading volume of 15m3.

[39] https://www.autocar.co.uk/car-news/new-cars/new-electric-ford-e-transit-revealed-217-mile-range

3.3.1 Simulation details for the mini-hubs service

The mini-hubs are essentially containers where people from local businesses can drop off their plastic waste. Ideally, there would be some sorting into different types of plastics, but our simulation does not take this into account. The 14 mini-hub locations are shown in Table 3.3.

Table 3.3: Southend mini-hubs locations

Name	Address	Postcode
Barons Court Primary School	Avenue Road, Westcliff-on-Sea, Southend-on-Sea, Westcliff-on-Sea	SS0 7PJ
Sacred Heart Primary School	Windermere Rd, Southend-on-Sea	SS1 2RF
Milton Hall School	Salisbury Ave, Westcliff-on-Sea, Southend-on-Sea, Westcliff-on-Sea	SS0 7AU
Heycroft School	Benvenue Ave, Southend-on-Sea, Leigh-on-Sea	SS9 5SJ
The Eastwood Academy	Rayleigh Rd, Leigh-on-Sea, Southend-on-Sea, Leigh-on-Sea	SS9 5UU
Thorpe Hall School	Wakering Rd, Southend-on-Sea	SS1 3RD
Fairways Primary School	The Fairway, Leigh-on-Sea, Southend-on-Sea, Leigh-on-Sea	SS9 5UU
Edwards Hall Primary School	Macmurdo Rd, Leigh-on-Sea, Southend-on-Sea, Leigh-on-Sea	SS9 5AQ
The Royals shopping centre	High St, Southend-on-Sea	SS1 1DG
Victoria shopping centre	362 Chartwell Square, Southend-on-Sea	SS2 5SP
The Pier	Western Esplanade, Southend-on-Sea	SS1 2EE
Civic Centre	Victoria Avenue, Southend-on-Sea, Essex	SS2 6ER
The Forum	The Forum, Elmer Ave, Southend-on-Sea	SS1 1NE

Temple Farm	Keymed house, Stock Rd, Southend-on-Sea	SS2 5QH

The roll-on/roll-off containers have integrated compactors and are typically 40 yards long, although a 20 yards version exists. As with the Amplirolls used in Douai, each container requires an individual lorry trip; a trailer can double transportation capacity. We assume that each mini-hub needs weekly transport to a materials recycling facility (MRF). There are three potentially involved MRFs considered in the simulations. Each one would serve as a vehicle starting and waste drop-off location.

- Veolia Central Depot, Eastern Ave, Southend-on-Sea SS2 5QX
- TLM waste management company, Hovefields Ave, Basildon SS13 1EB
- James Waste Management, 2 Brickfields Way, Purdeys Industrial Estate, Rochford SS4 1NB

We assume the collections are executed by a one-person crew; the driver also transfers the containers and makes £11/h. There is one lorry available, either diesel or electrical.

As no data was available about waste volumes at the time of running these simulations, we assumed that plastic waste would be collected once per fortnight. It does not matter how much plastics have been accumulated; the whole container is transported to a waste management facility.

Further assumptions used in the simulation:

- Time to access a client pickup location: 4min
- Time to load at a client location: 5 minutes
- Time to unload at the drop-off location: 15 minutes (including possible waiting times due to the location being busy)
- Cost of running a diesel lorry: £0.5/km
- Costs of running a Ford e-Transit: £0.03/km
- Emission factor diesel [40]: 100.3 gr/ton.km
- Well to Wheel emissions: 164.6 gr/km (diesel)- Woo et al (2017)
- Well to Wheel emissions: 165.6 gr/km (electric truck)- Woo et al (2017)
- Well to Wheel emissions: 40 gr/km (e-cargo bikes- estimation)

3.3.2 Simulation results for the mini-hubs service

Intuitively, it is most efficient to use Veolia's Central Depot, located in Southend town centre, for serving all mini-hubs. The simulations confirm this and give us numbers to compare, using lorries with trailers to move two containers at once.

[40] https://business.edf.org/insights/green-freight-math-how-to-calculate-emissions-for-a-truck-move/

The simulation results for TLM are shown in Figure 3.8, with Figure 3.9 showing the suggested routes. Figures 3.10 and 3.11 show this for Veolia, and Figures 3.12 and 3.13 for James Waste Management.

7 SUBROUTES	- SHIPMENTS	212 OPTIMIZATION OBJECTIVE	212 COST (EURO)
0 ORDERS LEFT	1 VEHICLES	256 DISTANCE (KM)	14 ORDERS ON ROUTES
100% AVG MAX FILL RATE	00:07:37 AVG TIME SPAN (D:H:M)	00:00:00 TRAFFIC TIME (D:H:M)	0.0% TRAFFIC FOR DRIVE TIME

Figure 3.8: Simulation results for taking the mini-hub containers to TLM

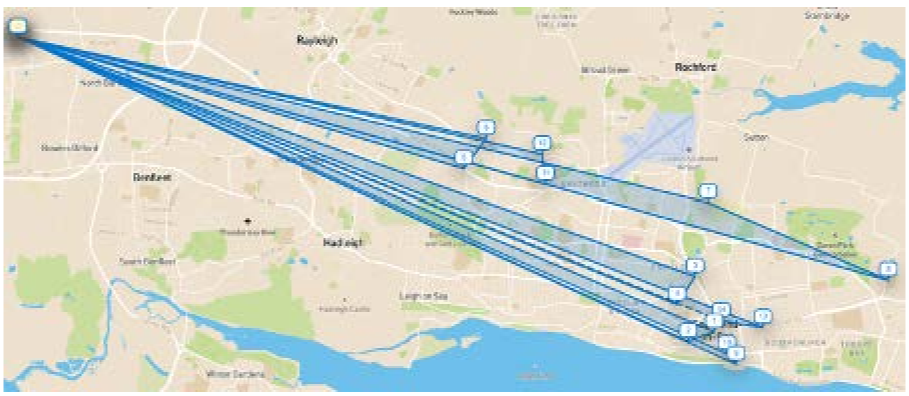

Figure 3.9: Possible routes for taking the mini-hub containers to TLM

7 SUBROUTES	- SHIPMENTS	90 OPTIMIZATION OBJECTIVE	90 COST (EURO)
0 ORDERS LEFT	1 VEHICLES	69 DISTANCE (KM)	14 ORDERS ON ROUTES
100% AVG MAX FILL RATE	00:05:01 AVG TIME SPAN (D:H:M)	00:00:00 TRAFFIC TIME (D:H:M)	0.0% TRAFFIC FOR DRIVE TIME

Figure 3.10: Simulation results for taking the mini-hub containers to Veolia

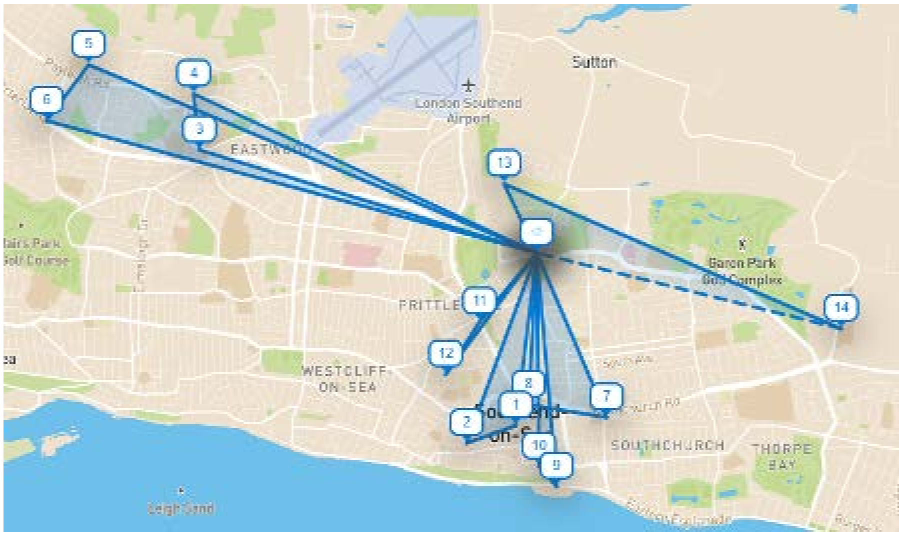

Figure 3.11: Possible routes for taking the mini-hub containers to Veolia

7 SUBROUTES	- SHIPMENTS	121 OPTIMIZATION OBJECTIVE	121 COST (EURO)
0 ORDERS LEFT	1 VEHICLES	103 DISTANCE (KM)	14 ORDERS ON ROUTES
100% AVG MAX FILL RATE	00:06:16 AVG TIME SPAN (D:H:M)	00:00:00 TRAFFIC TIME (D:H:M)	0.0% TRAFFIC FOR DRIVE TIME

Figure 3.12: Simulation results for taking the mini-hub containers to James Waste Management

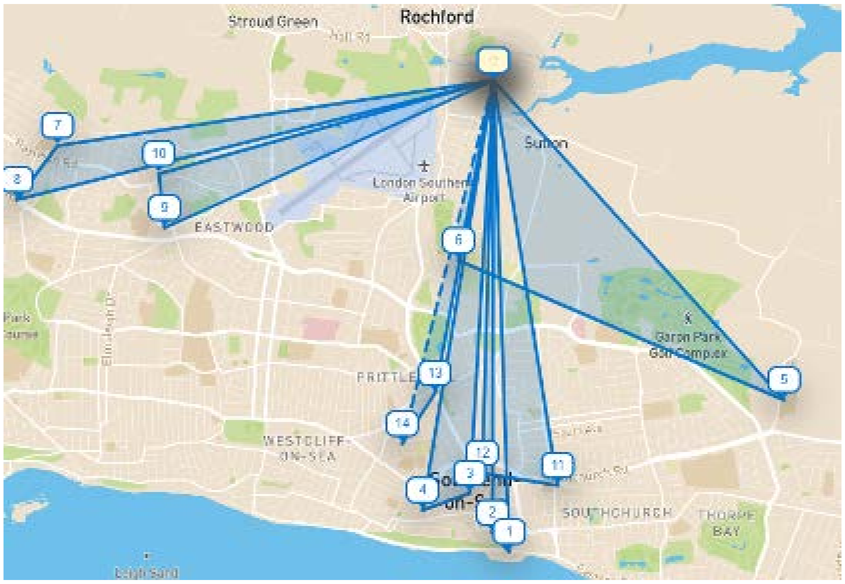

Figure 3.13: Possible routes for taking the mini-hub containers to James Waste Management

Comparison of scenarios for Southend

Tables 3.4 and 3.5 provide some of the data used for the simulations as well as a summary of the results. Unsurprisingly, the distance travelled, the emissions caused by transport and the costs incurred double when the collection frequency doubles (fortnightly versus weekly collections). To be able to access which frequency is better, it is necessary to know how fast the mini-hub containers get filled up. If they do not overflow within 2 weeks, there is no point in more frequent collections. If they do overflow, depending on the magnitude of overflow, it will still be a better solution to maintain fortnightly collections and either increase the capacity of mini-hub containers or double the number of containers in the locations with overflow. This second solution can then be combined with the use of trucks with trailers as in Douai.

Table 3.4: Simulation details and results for fortnightly collections in Southend

Collect fortnightly	**TLM**	**Veolia**	**James Waste Management**
Total number of stops	14	14	14
Number of working days per year	26	26	26

Number of vehicles (lorry with trailer)	1	1	1
Time window	08:00-18:00	08:00 -18:00	08:00 -18:00
Time required	07:37 hours	05:00 hours	06:16 hours
Labour cost per hour	£11	£11	£11
Cost per km	£0.5	£0.5	£0.5
Cost per collection service	£212	£90	£121
Annual cost	£5512	£2340	£3146
Distance travelled per collection	256km	69km	105km
Distance travelled per year	6656km	1794km	2730km
C02 Emissions per ton of waste transported.	667.7 kg/ton	179.76 kg/ton	273.86 kg/ton

Table 3.5: Results for weekly collections

Collect weekly	**TLM**	**Veolia**	**James Waste Management**
Number of working days per year	52	52	52
Annual cost	£11,024	£4,680	£6,292
Distance travelled per year	13,312km	3,588km	5,460km
CO2 Emissions per ton of waste transported.	1335.4 kg/ton	360 kg/ton	546.7 kg/ton
WTW CO2 emissions	2191 kg	585 kg	898 kg

As expected, the simulations have confirmed that the ideal solution is to take all containers to Veolia at the Central Depot, as taking them to James Waste Management would increase the distance travelled and emissions caused by 34%; taking them to TLM would mean 73% more travel and emissions in comparison to dropping off at the Central Depot.

3.3.3 Simulation details for the Temple Farm milk-run

In this scenario, a van collects plastics in the Temple Farm industrial area and takes it to the Temple Farm mini-hub (SS2 5QH). The electro-truck is assumed to be a Ford E-Transit[41]. It does not have a compactor on board, although in practice it probably would need to be fitted with a press to make collections more efficient. The load it can take is limited by volume rather than weight.

We assume the collections are executed by a one-person crew; the driver also loads the plastics into the van and makes £11/h. There is one van available, and the milk-run is executed once a week or once a fortnight. Further details are provided in Table 3.6.

Table 3.6: Data used for the milk-run simulations

Vehicle	**Volume**	**Depot capacity**	**Fixed cost (per day)**	**Time to access client location**	**Service time (loading)**	**Depot unloading time**
Ford E-Transit	15m3	100 m3	£11/per hour	4mins	5mins	15mins

Further assumptions required for the simulation:

- The time to unload at the drop-off location includes possible waiting times due to the mini-hub being busy.
- The vans do not have an integrated compaction press.
- Running costs of the van per km: £0.03, based on the following information:

[41] Ford E-Transit https://www.autocar.co.uk/car-news/new-cars/new-electric-ford-e-transit-revealed-217-mile-range

The Ford E-Transit has a range of 217 miles, which corresponds to 349 km; the available battery power is 67kWh[42]. The estimated cost of charging in the UK is about £10, assuming 17p per kWh[43]. We assume that in a worst scenario the emission factor is at the higher range of Woods et al (2017) for the UK: 165,6 gCO2/km, in a best case scenario the lowest range is : 71.4 CO2gr/km.

SBC provided us with a list of 65 businesses located in the Temple Farm area; most of them are industrial companies (hence neither retail nor restaurants, schools, hospitals or leisure centres.

As no data was available about waste volumes at the time of running these simulations, we generated random numbers. Most of them represent between 0.05 and 1m3, with 3 data points between 1.5 and 3.5m3 representing companies with higher plastic waste volumes, such as cross-docking / logistics companies. It was assumed that plastic waste would be collected once per fortnight.

We explored two versions of this scenario. In both cases the van starts at the Central Depot and goes on its journey to Temple Farm companies. Then there are two potential drop-offs:

- Scenario 1: The Candlemakers, Southend-On-Sea, SS2 5RX
- Scenario 2: HRWC Stock Road, Southend-on-Sea, SS2 5QF

Table 3.7, below, details data used in the Temple Farm simulations.

Table 3.7: Data used for Temple Farm simulations

Southend Temple Farm	
Number of stops to collect from	56
Collect mode	Fortnightly / monthly
Number of working days/per year	26 / 12
Number of staff	1
Time window	08:00 -18:00

[42] Ford E-Transit data: https://www.autocar.co.uk/car-news/new-cars/new-electric-ford-e-transit-revealed-217-mile-range

[43] https://pod-point.com/guides/driver/cost-of-charging-electric-car

Labour costs per hour	£11
Cost of electricity per km	£0.03
Stop service time (access and loading)	5 mins
Depot service time (unloading)	15mins
Start location (depot)	Central depot (SS2 5BS)
End location (depot)	Stock road mini-hub
Loading capacity of the van	15m3

3.3.4 Simulation results for the Temple Farm milk-run

Scenario 1: drop-off at The Candlemakers

Scenario 1.1: Figures 3.14 and 3.15 show the results and possible route for the Temple Farm run with fortnightly collections from Temple Farm businesses, dropping off the waste at a mini-hub located at the Candlemakers.

Figure 3.14: Southend Temple Farm, results for fortnightly collections

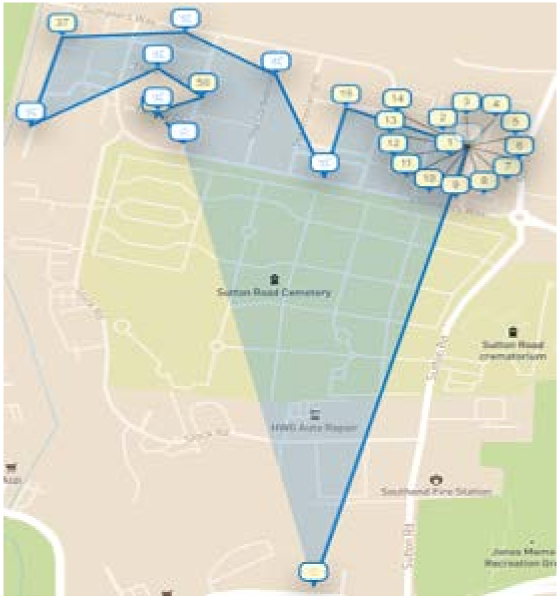

Figure 3.15: Southend Temple Farm, possible route for fortnightly collections

For scenario 1.2, collections are monthly; see Figures 3.16 and and 3.17.

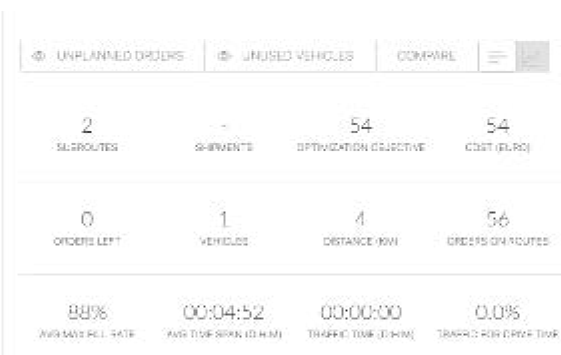

Figure 3.16: Southend Temple Farm, results for monthly collections

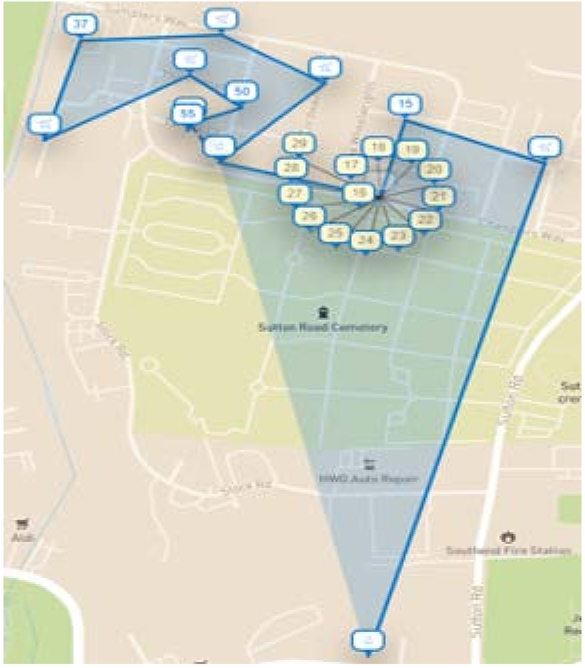

Figure 3.17: Southend Temple Farm, possible route for monthly collections

As there is no data available regarding the expected waste volumes, we tripled the assumed yearly waste to observe what would happen in such a case. Hence, Figures 3.18 and 3.19 show the results and possible route for the Temple Farm run with fortnightly collections. This is scenario 1.3.

Figure 3.18: Southend Temple Farm, results for fortnightly collections with triple waste volume. Note that one order remains unfulfilled.

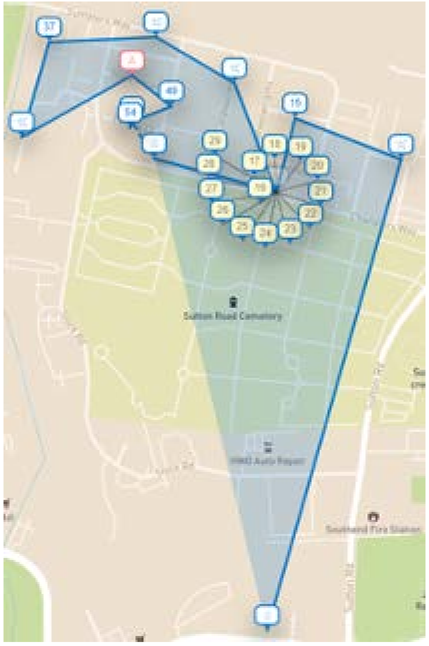

Figure 3.19: Southend Temple Farm, results for monthly collections with triple waste volume

Given that one order remained unfulfilled, for scenario 1.3.1, we now assume that there are two containers at the mini-hub where the waste is dropped off. The capacity of each container is 30m^3. This collection runs fortnightly. Figures 3.20 and 3.21 show results and route, respectively.

Figure 3.20: Southend Temple Farm, results for fortnightly collections with triple waste volume and two containers at the mini-hub

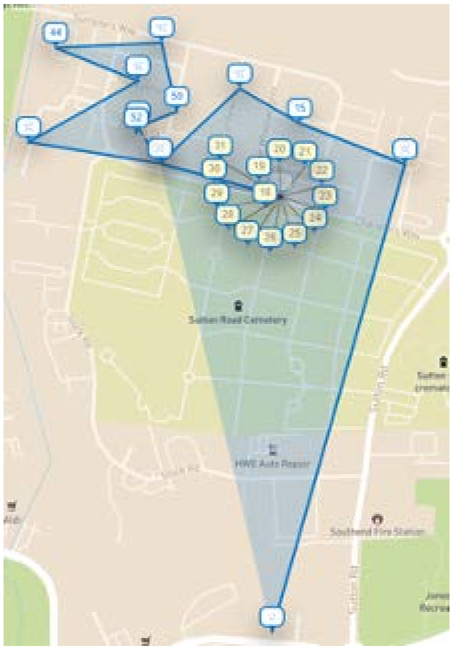

Figure 3.21: Southend Temple Farm, possible route for fortnightly collections with triple waste volume and two containers at the mini-hub

Scenario 1.4 is a monthly collection with triple waste volume and only one container at the mini-hub. Figures 3.22 and 3.23 show the simulation results and a possible route.

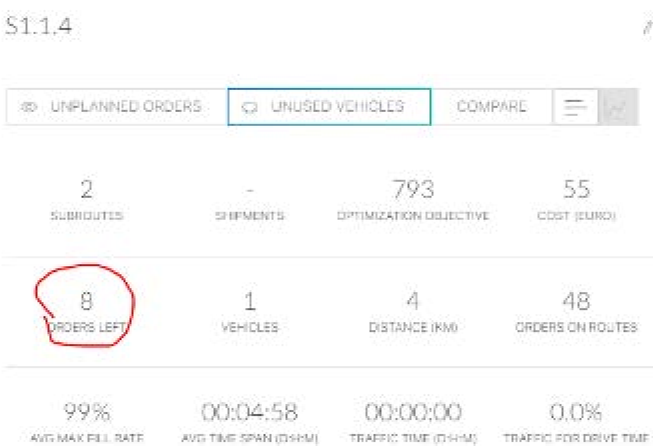

Figure 3.22: Southend Temple Farm, results for monthly collections with triple waste volume and one container at the mini-hub.

Eight orders remain unfulfilled, hence this solution is not workable.

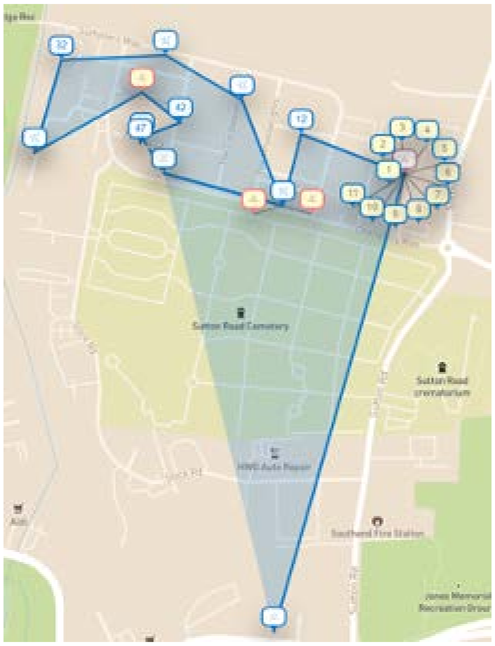

Figure 3.23: Southend Temple Farm, possible route for monthly collections with triple waste volume and one container at the mini-hub

Scenario 1.4.1 is a monthly collection with triple waste volume and two containers at the mini-hub. Figures 3.24 and 3.25 show the simulation results and a possible route.

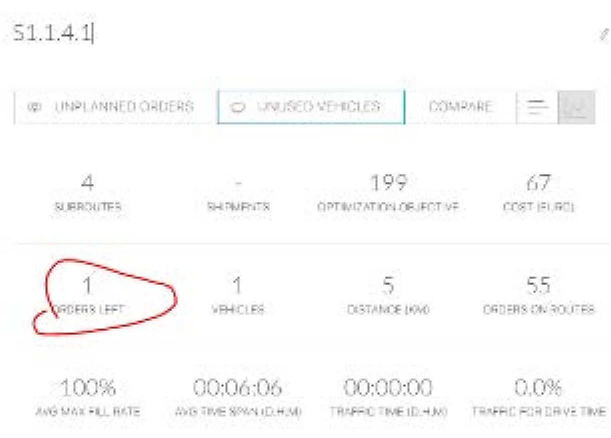

Figure 3.24: Southend Temple Farm, results for monthly collections with triple waste volume and two containers at the mini-hub.

One order remains unfulfilled.

Figure 3.25: Southend Temple Farm, possible route for monthly collections with triple waste volume and two containers at the mini-hub

Scenario 1.4.2 is a monthly collection with triple waste volume and three containers at the mini-hub. Figures 3.26 and 3.27 show the simulation results and a possible route.

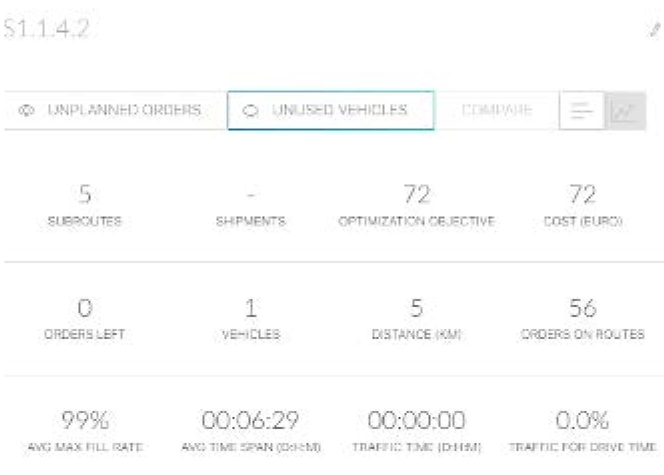

Figure 3.26: Southend Temple Farm, results for monthly collections with triple waste volume and three containers at the mini-hub

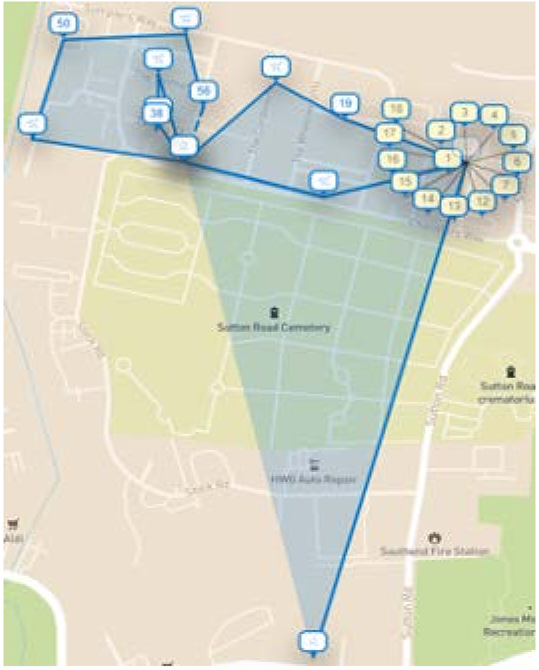

Figure 3.27: Southend Temple Farm, possible route for monthly collections with triple waste volume and three containers at the mini-hub

Scenario 2: drop-off at Stock Road

Figures 3.28 and 3.29 show the results and possible route for the Temple Farm run with fortnightly collections (scenario 2.1) from Temple Farm businesses, dropping off the waste at a mini-hub located on Stock Road. Figures 3.30 and 3.31 show this for monthly collections (scenario 2.2).

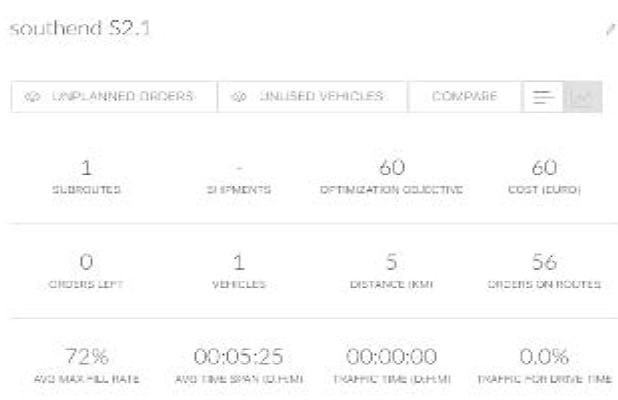

Figure 3.28: Southend Temple Farm, results for fortnightly collections

Figure 3.29: Southend Temple Farm, possible route for fortnightly collections

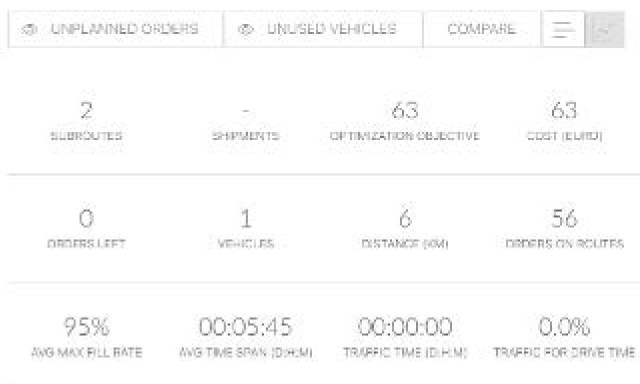

Figure 3.30: Southend Temple Farm, results for monthly collections

Figure 3.31: Southend Temple Farm, possible route for monthly collections

Scenario 2.3 assumes that the yearly waste amount is the triple of the among in scenarios 1.1 and 1.2. The waste is collected fortnightly. Results are shown in Figure 3.32 while Figure 3.33 shows possible routes.

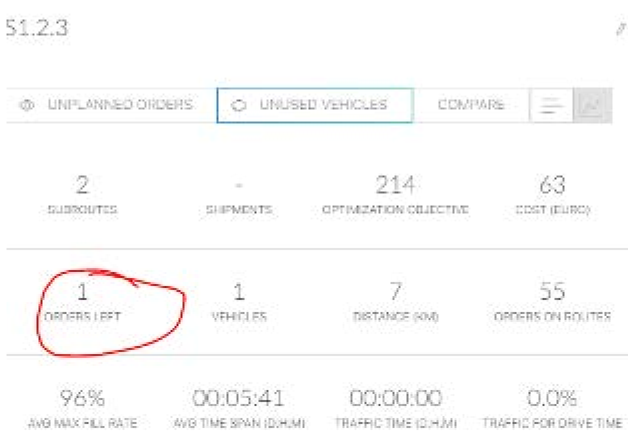

Figure 3.32: Southend Temple Farm, results for fortnightly collections with triple volume

Figure 3.33: Southend Temple Farm, possible route for fortnightly collections with triple volume

The assumption for scenario 2.3.1 is that there are two containers at the depot. The capacity of each container is 30m3. Results and possible routes are shown in Figures 3.34 and 3.35

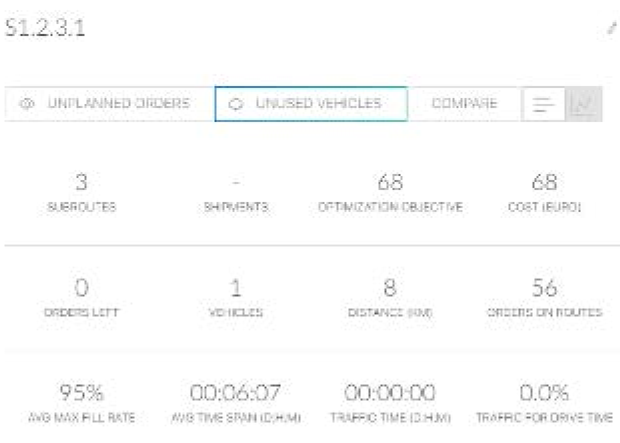

Figure 3.34: Southend Temple Farm, results for fortnightly collections with triple volume and two containers at the depot

Figure 3.35: Southend Temple Farm, possible route for fortnightly collections with triple volume and two containers at the depot

In scenario 2.4, Figures 3.36 and 3.37 the yearly waste amount is assumed to be triple, there is a monthly collection and only one container at the depot.

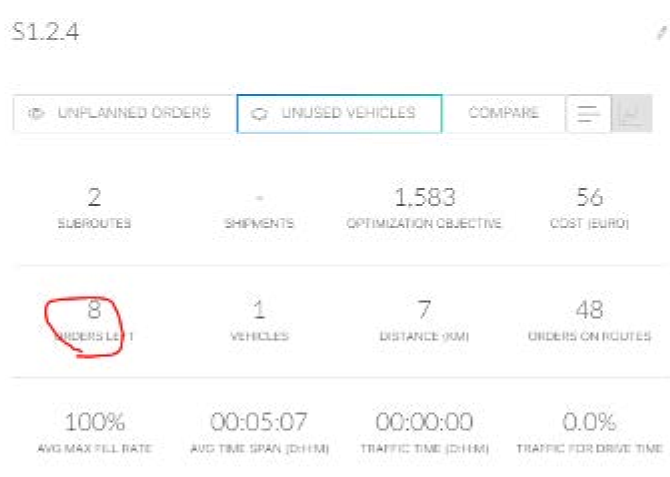

Figure 3.36: Southend Temple Farm, results for monthly collections with triple volume and one container at the depot

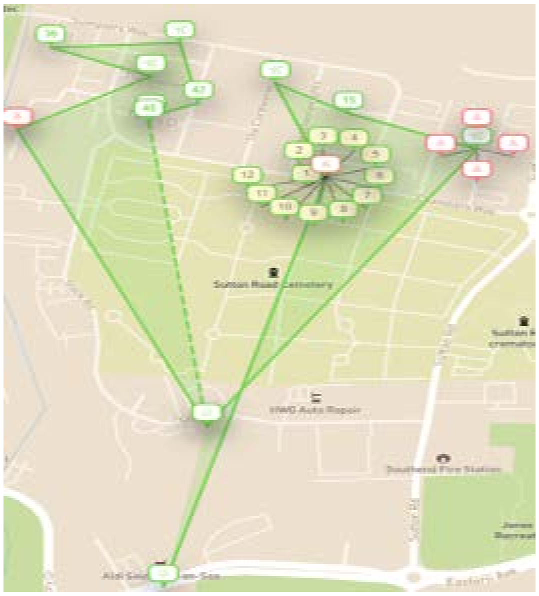

Figure 3.37: Southend Temple Farm, possible route for monthly collections with triple volume and one container at the depot

In scenario 2.4.1, figures 3.38 and 3.39, there are two 30m3 containers at the depot.

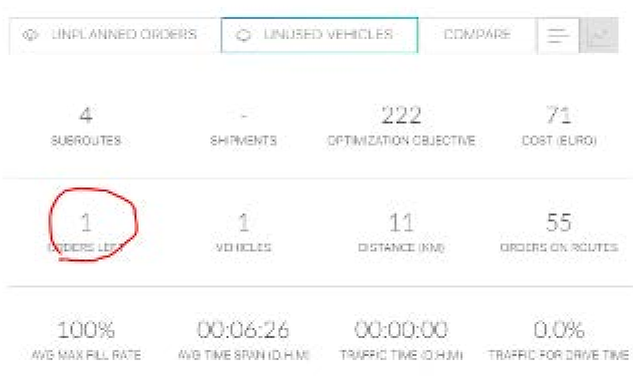

Figure 3.38: Southend Temple Farm, results for monthly collections with triple volume and two containers at the depot.

One order remains unfulfilled.

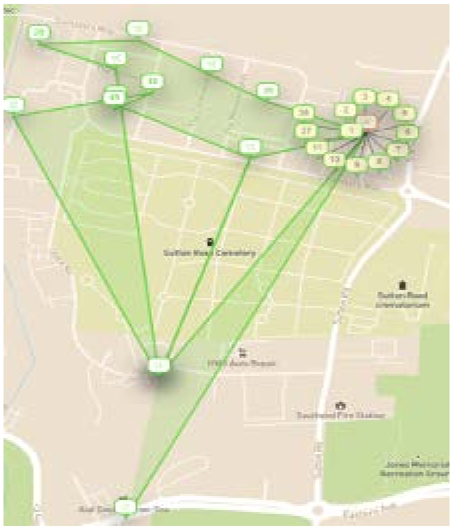

Figure 3.39: Southend Temple Farm, possible route for monthly collections with triple volume and two containers at the depot

In scenario 2.4.2, figures 3.40 and 3.41. there are three containers at the depot.

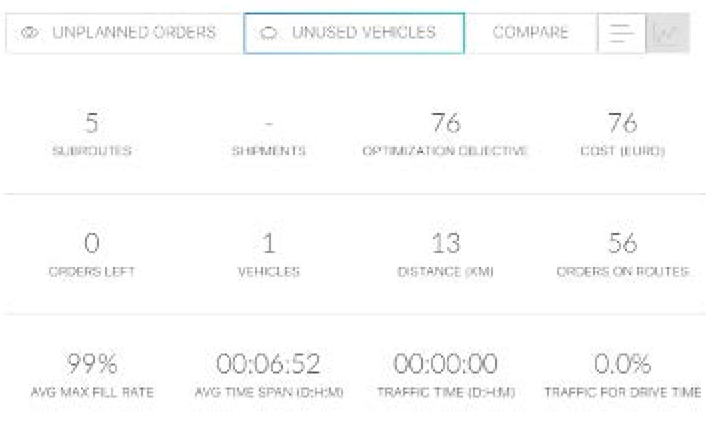

Figure 3.40: Southend Temple Farm, results for monthly collections with triple volume and three containers at the depot.

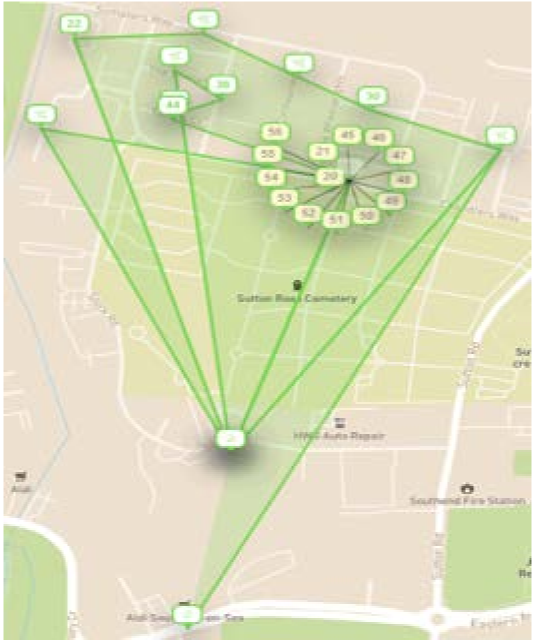

Figure 3.41: Southend Temple Farm, possible route for monthly collections with triple volume and three containers at the depot.

Comparison of scenarios for Temple Farm Milk Run,

Tables 3.8, 3.9 and 3.10 show how the different scenarios compare. The assumption for Southend scenario 1 (S1.1 and S1.2) is to collect waste from Temple Farm companies, starting from the Central depot and taking the waste to the pilot hub at The Candlemakers. The assumption for Southend scenario S2 (S2.1 and S2.2) is to collect waste from Temple Farm companies, starting from the Central depot and taking the waste to the HRWC Stock Road.

Southend S1.1 and S2.1 collect waste fortnightly, whereas Southend S1.2 and S2.2 collect waste monthly. These scenarios use the initially assigned waste quantities, whereby there is no knowing how realistic this might be.

Table 3.8: Comparisons between Scenarios 1 and 2 with the basic assumed amount of waste

	S1 (to The Candlemakers)		**S2 (to HRWC Stock Road)**	
	S1.1	S1.2	S2.1	S2.2
Total number of stops	56	56	56	56
Collect mode	fortnightly	monthly	fortnightly	monthly

Number of working days/per year	26	12	26	12
Number vehicles	1	1	1	1
Routes(how many stops)	56	56	56	56
Time span	4:51	4:52	5:25	5:45
Cost /hour	£11	£11	£11	£11
Cost (electricity)/km	£0.03/km	£0.03/km	£0.03/km	£0.03/km
Cost	£54	£54	£60	£63
Cost (Pound)/ year	£1404	£648	£1560	£756
Distance (km)	4km	4 km	5 km	6 km
Distance (km)/year	104 km	48 km	130 km	72 km
WTW CO_2 emissions	Min: 74 kg Max: 172	Min:34 kg Max: 74 kg	Min:93 kg Max: 215 kg	Min:51kg Max: 119 kg

According to the results obtained from simulating these scenarios, the best solution is Southend S1.2, where the waste is taken to the Candlemaker hub monthly, as this leads to the lowest cost and shortest distances travelled.

To explore the effect of larger waste volumes on the results, the yearly waste amount assumed in Southend S1.3, S1.4, S2.3 and S2.4 is triple compared to Southend S1.1 and S1.2. Given the bigger waste volumes, one 30m3 container at the hub is no longer sufficient, and further sub-variants of the scenarios needed to be explored.

Table 3.9. Comparison across scenarios of waste collection from Temple Farm (original waste)

	S1 (to The Candlemakers)				
	S1.3	S1.3.1	S1.4	S1.4.1	S1.4.2
Total number of stops	56	56	56	56	56

Collect mode	fortnightly	fortnightly	monthly	monthly	monthly
Number of working days/per year	26	26	12	12	12
Number vehicles	1	1	1	1	1
Routes (how many stops)	55	56	48	55	56
Time span (hours)	05:33	05:53	05:07	06:26	06:52
Cost /hour	£11	£11	£11	£11	£11
Cost (electricity)/km	£0.03/km	£0.03/km	£0.03/km	£0.03/km	£0.03/km
Cost	£61	£65	£55	£67	£72
Cost (Pound)/ year	£1586	£1690	£660	£804	£864
Distance (km)	4km	4km	4 km	5km	5km
Distance (km)/year	104 km	104km	48 km	60km	60km
Capacity of Depot	1 container	2 containers	1 container	2 containers	3 containers
Unfulfilled orders	**1**	0	**8**	**1**	0

Table 3.10: Comparing scenarios with triple waste volumes

	S2 (to HRWC Stock Road)				
	S2.3	S2.3.1	S2.4	S2.4.1	S2.4.2
Total number of stops	56	56	56	56	56

Collect mode	per fortnight	per fortnight	per month	per month	per month
Number of working days/per year	26	26	12	12	12
Number vehicles	1	1	1	1	1
Routes (how many stops)	55	56	48	55	56
Time span (hours)	05:51	06:00	05:07	06:26	06:52
Cost /hour	£11	£11	£11	£11	£11
Cost (electricity)/km	£0.03/km	£0.03/km	£0.03/km	£0.03/km	£0.03/km
Cost	£63	£68	£56	£71	£76
Cost (Pound)/ year	£1638	£1768	£672	£852	£912
Distance (km)	7km	8km	7 km	11km	£13
Distance (km)/year	182 km	208km	84 km	132km	156km
Depot capacity	1 container	2 containers	1 container	2 containers	3 containers
Unfulfilled orders	1	0	8	1	0

Southend S1.3 dnd S1.4 collect waste, starting from Central depot and taking it to The Candlemakers. Southend S2.3 and S2.4 collect waste, starting from the central depot and taking it to Stock Road. There are two containers at the depot. The capacity of each container is 30m3.

S1.3 and 2.3 collect the waste once every two weeks, and S1.4 and S2.4 collect the waste once a month.

According to the results of these simulations, to collect the triple amount of annual waste, the depot needs to have at least two containers. If the depot has two containers, the best solution is Southend S1.3.1, which takes the waste to The Candlemakers once per fortnight. If the depot has three containers, the best solution is Southend S1.4.2, which takes the waste to the Candlemakers monthly.

3.3.5 Simulation details for the town centre milk-run

Southend's town centre includes a high street with lots of small and some bigger shops, restaurants and cafes as well as a shopping centre. The Royals shopping centre also hosts a mini-hub. The high street is reserved for pedestrians during the day, hence a CargoBike is used for serving this location. The town centre milk-runs are executed once a week or once a fortnight.

SBC provided us with a list of businesses in their town centre. As there is no data on waste volumes, random numbers were used.

We assume the collections are executed by a two-person crew; the driver makes £11/h whereas the loader makes £9/h. There is one van available. It starts and ends its journey at Short Street (SS2 5BS) and drops off the waste at the Royals mini-hub, where it is compacted.

All other assumptions are as described in 3.3.3.

The CargoBike is not the same model as used in The Hague and Ghent; the British version has a loading volume of 0.5m3 only. The van is a Ford e-Transit.

3.3.6 Simulation results for the town centre milk run

100 businesses with a postcode starting with SS1 were randomly selected from the provided Southend business database. Table 3.11 provides more details about the simulation.

Table 3.11 Southend Town Centre simulations

Southend Town Centre Scenario	
Number of stops intend to collect	100
Collection mode	fortnightly
Number of working days per year	26
Number of staff	Max. 2

Time window	08:00 -18:00
Labour cost	£11 /h
Cost of electricity to charge the vehicle (Ford e-Transit or CargoBike)	£0.03/km
Stop service time (access and loading)	5 mins
Depot service time (unloading)	15mins
Start location (depot)	Short Street (SS2 5BS)
End location (depot)	Short Street (SS2 5BS)
The capacity of the van (volume)	15m3
The capacity of CargoBike (volume)	0.5m3

For Scenario 1, only one van is available, operated by one person.

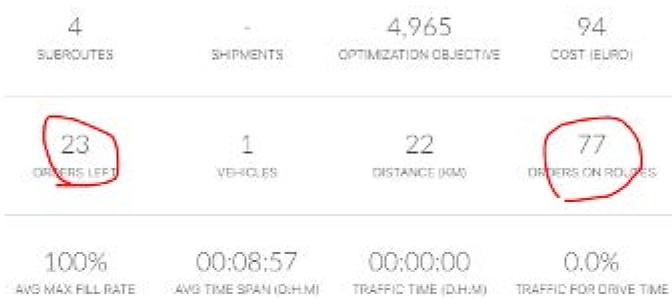

Figure 3.41: Southend town centre, results for one van. Note that 23 orders are left unfulfilled.

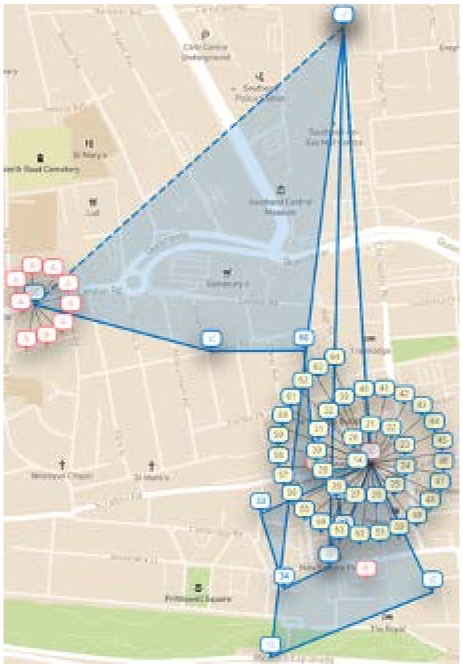

Figure 3.42: Southend town centre, possible route for one vehicle

The result shows that it will take nearly 9 hours to collect 77 companies’ waste fortnightly if only one van is available. The waste of the remaining 23 companies are left without collection, hence this scenario is not workable.

Scenario 2 assumes that Southend can recruit two persons to collect the waste: one drives the van, and the other rides a CargoBike.

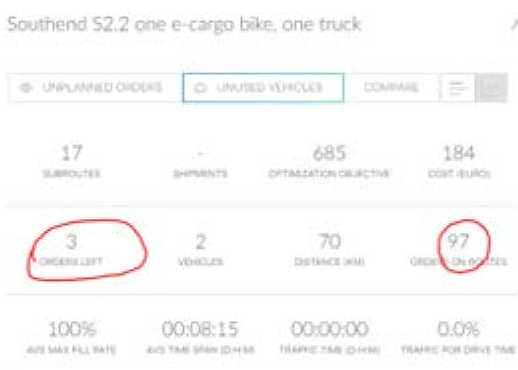

Figure 3.43: Southend town centre, results for one van and one CargoBike. Note that 3 orders are left unfulfilled.

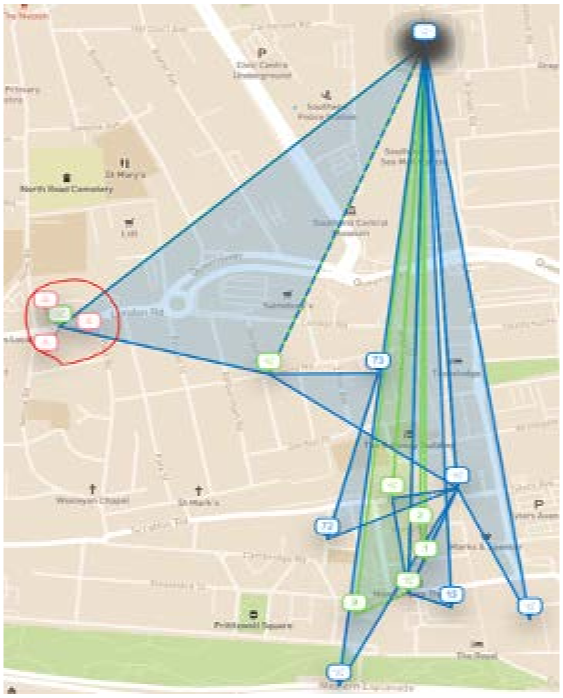

Figure 3.44: Southend town centre, possible routes for one van and one CargoBike

Only 97 companies' waste are collected within the constraints, whereas three companies' waste are left uncollected.

For scenario 3 we assume that Southend can recruit two persons to collect waste by CargoBike, and there is no van. However, many companies have more waste than what fits into the capacity of the CargoBike. For example, Company A has 1m3 waste, while the capacity of the CargoBike is 0.5m3. Therefore, Company A requires two stops. Based on this modification, 180 collection stops need to be made.

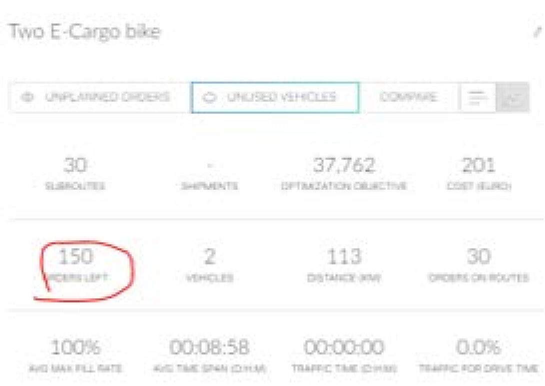

Figure 3.45: Southend town centre, results for two CargoBikes. Note that 150 orders are left unfulfilled.

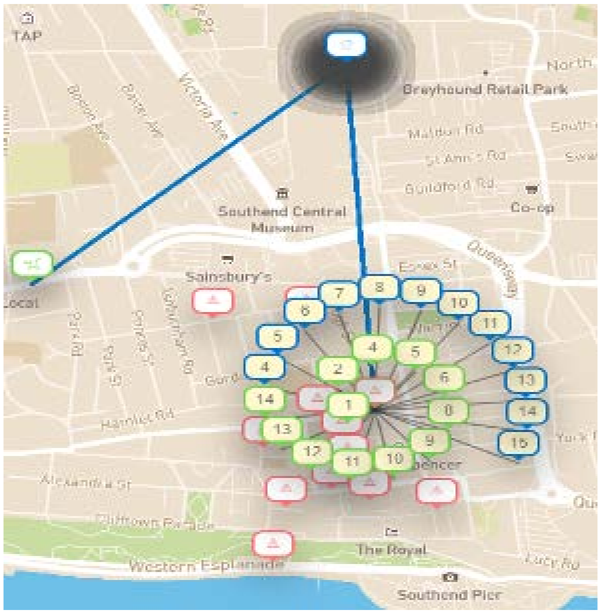

Figure 3.46: Southend town centre, possible routes for two CargoBikes

Southend Town Centre Scenario 3 shows that the waste of only 30 stops can be collected in one day, and 150 stops are left out. Therefore, this scenario is not workable. To serve all stops, the crew would need to work 6 days with 2 CargoBikes, or 3 days with 4 CargoBikes.

Comparison of scenarios

Table 3.12: Comparison of scenarios

	S1	S2	S3
Initial number of stops	100	100	100
Total number of stops	100	100	180 (due to loading capacity limit)
Collection mode	Fortnightly	Fortnightly	Fortnightly
Number of working days/per year	26	26	26

Number vehicles	1 van	1 CargoBike, 1 van	2 CargoBikes
Time window	08:00-18:00	08:00 -18:00	08:00-18:00
Routes (how many stops)	77	97	30
Time span (hour)	08:57	08:15	08:58
Labour cost	£11/h	£11/h	£11/h
Cost of electricity for charging	£0.03/km	0.03/km	0.03/km
Cost per collection with a driver only	£94	£184	£201(unfinished)
Additional cost for a loader	£81	£81	n/a
Cost per year	£2444	£4784	£5226
Distance travelled per collection	22km	70km	113km
Distance travelled per year	572km	1820km	2938km
Emissions (WTW)	Min: 41 Kg Max: 94 kg		Min: 48.7 kg Max: 97 kg CO_2

Three scenarios were considered for Southend's Town Centre waste collection. According to Table 3.12, the most appropriate solution is S1, which uses one van and incurs the lowest cost. S2 requires the least time for the collection. Overall, the more cargo bikes are used the more costly the strategy and the higher the distance travelled.

However, it must be remembered that there was no actual data on waste volumes available; hence the results may be different in reality. Time spent due to road congestion might be considered in this scenario as well. Any information that is changed will affect the result of the simulation.

In terms of emissions, in the worst case scenario highlighted by Woo et al (2017), there is little difference between the emission factor for electric vans and diesel trucks. Following Woo et al (2017) the emission factor for small compact electric vehicles in UK is between 1.6 and 3.6 times lower than that of vans. We do not have data about the emission factor of cargo bikes, but based on the simulations, the increase in distance brought about by using cargo bikes will require the emission factor of cargo bikes to be more than 5.2 times lower than that of diesel vehicles, for the scenario with cargo bikes to have comparative savings in emissions.

3.4 Simulations for The Hague

The Hague conducted a waste collection trial to get an idea of plastic waste quantities. The targeted business types were based on a survey conducted in Ghent at the beginning of the project to find out how much plastic waste can be found at different types of NACE codes. The results suggested focusing on retail and offices. However, due to the pandemic lock-down, offices were not occupied and therefore did not respond to our query. Therefore, waste could only be collected from retail businesses, and the number of participants was small. The collected data is summarised in Table 3.13. The trial was conducted over a period of 6 weeks, with weekly collections, but some companies were closed during some weeks and hence did not have any plastics to collect. Whilst this trial gives a glimpse of possible waste numbers, there is not enough data to provide typical waste volumes per retail business type,or even for retail as a whole.

Table 3.13: Plastic waste collection trial conducted in The Hague

Name	Business type	Min vol [litres]	Max vol [litres]	Average [litres] per week
A: HUB	Logistics (last mile cross-docking hub)	70	210	105
B: Made in Moerwijk	Upcycling centre	140	140	140
C: Kringloop Den Haag	2nd hand shop	0	1330	805
D: Residentie Apotheek	Pharmacy	210	280	257
E: WWen	Fashion boutique	70	140	105
F: Heemskerk Bloemisten	Flower shop	560	1120	840

G: Brabants Lederwarenhuis	Leather shop	210	700	392
G: Dierenwinkel Rene van der Westen	Pet shop	70	140	105
H: DuOOptiek	Optician	0	280	128
I: Reakt	Work agency	280	280	280
J: Van den Dop	Electrician	70	280	175

During the trial, both volume and weight of the collected waste was recorded. This allows us to calculate the density of the plastics after compression for loading onto the CargoBike, as shown in Table 3.14.

Table 3.14: Density of plastic waste collected in the The Hague trial

Week	46	47	48	49	50	51	Average
Weight [kg]	53	32	32	28	25	37	
Volume [m3]	3.57	2.73	2.66	2.31	2.17	2.31	
Density [kg/m3]	14.85	11.72	12.03	12.12	11.52	16.02	13.04

The average density of plastic waste collected in the The Hague trial is rather low (13 kg/m3) in comparison to the 13-14 kg/m3 for HDPE and 18-24 kg/m3 for PET indicated by WasteAid[44]. This discrepancy is likely due to the collected waste containing a large proportion of LDPE film.

The core idea of the simulation for The Hague was to explore the use of different vehicles for different circular zones around the city centre. The local partner is the city council. They supplied a database with businesses in the city, which was filtered for relevant potential waste owners per zone.

[44] https://wasteaid.org/wp-content/uploads/2017/10/7-How-to-prepare-plastics-to-sell-to-market-v1.pdf

3.4.1 Simulation details

At first, we assumed the tram stop “Gravenstraat" as the city centre point. Within a radius of 5km from that point (Zone 1), a CargoBike would be used to collect plastic waste only. The drop-off point is the Hub. Within a radius of 5-10km (Zone 2), an electrical van would be used, and in Zone 3, from 10 to 15km from the center point, a diesel lorry would be used. In Zones 2 and 3, mixed recyclables would be collected. However, it turned out that these radii were too big for The Hague. To focus on the city and its immediate agglomeration only, the zones were defined as up to 1km, 1-3km, and 3-5km, instead. Furthermore, whilst Gravenstraat is a central point in the city, The Hague does not extend evenly to all sides. Lijnbaan 32 was assumed as the centre point of the zones instead, leading to a better fit of the zones. Figure bbb shows the approximate zones, and the postcodes per zones are listed below

:

Zone 1:
2512, 2513, 2514, 2515, 2525, 2526, 2562, 2572, 2574.

Zone 2:
2511, 2517, 2518, 2521, 2522, 2523, 2524, 2532, 2546, 2561, 2563, 2566, 2571, 2573, 2582, 2593, 2594, 2595, 2596, 2597.

Zone 3:
2491, 2492, 2493, 2516, 2531, 2533, 2541, 2542, 2543, 2544, 2545, 2547, 2548, 2551, 2552, 2553, 2554, 2555, 2564, 2565, 2581, 2583, 2584, 2585, 2586, 2587.

Note that there is a big area of The Hague that drops out of the circles, called Leidschenveen-Ypenburg (postcodes 2491, 2492 and 2493), which we have included in zone 3. On the other hand, some areas with postcodes starting with 22 are located within the zones we defined but do not politically belong to the City of The Hague; these areas are in Voorburg, Leidenschendam or Rijswijk, and their waste collections are organised independently. It could be argued that areas that are geographically close to each other should be served by the same waste collection organisation, but this discussion is beyond the scope of this simulation exercise.

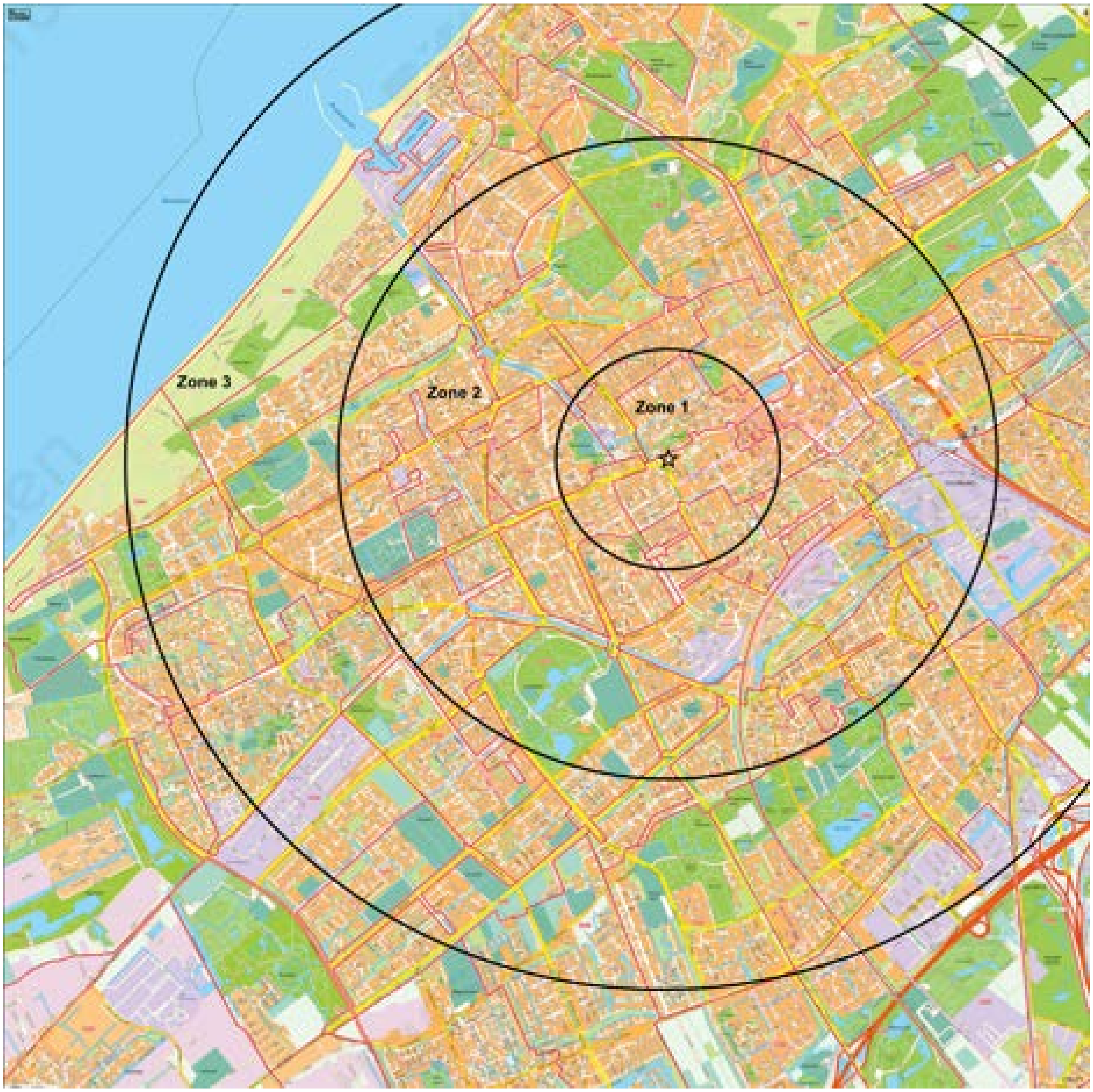

Figure 3.47: The Hague centre point and zones 1-3 as defined for the simulations

During the trial collections with a CargoBike, handling times as well as volume and weight of the collected plastics were measured. This showed that there can be large fluctuations, e.g. one company had two weeks with 18 / 19 bags of 70 litres, and later two weeks with zero plastics to be collected. It would be interesting and relevant to understand whether this is typical / a frequent occurrence or an odd exception due to temporary shop closures. Given that only a very small number of companies participated in this trial, we generated plausible data based on the data from the trial collections in The Hague and Herentals in Belgium. We generated random numbers between 0 and 1, which represent the plastics volume in m3. (If multiplied by 1000, they correspond to a plausible number of litres when compared to the collected data.)

The Hub is assumed to be at the following location, in a business area called ZKD (Zichtenburg, Keketuinen, Dekkershoek): HUBBEL, Zinkwerf 27, 2544 EC Den Haag

Waste from Zones 2 and 3 are dropped off at one of the following locations, which also serve as start and end points for the collection vehicles:

- Renewi, Zonweg 13, 2516 AK Den Haag
- Omega, Bedrijventerrein Westvlietweg, Prisma 10, 2495 AR Den Haag

The following vehicle details were assumed:
A CargoBike battery has a range of 25-40km, but additional batteries can be added; therefore this constraint was neglected for the simulations. We assume one CargoBike is available. The start and end location of the CargoBike is the Hub. There is a compaction press on the bike. About 7m3 plastics in their original state can be compressed down to fit into the 2.2m3 loading space of the CargoBike. The payload that the resource bike is able to carry is 191 kg, based on the full payload of 250 kg minus the weight of the press, which is 59 kg. However, during the collection trial, the maximal weight carried was 53kg using 60.7% of the available volume. Table qwe shows a reflection on this: assuming a material density of 14.85 kg/m3, as was the case in week 47, the maximum weight carried with a full container would have been 87kg. This is less than half the weight that can be carried, and hence, simulations must be run using volumes rather than weight.

Table 3.15: Reflections on the payload of the CargoBike, using the load carried in week 47

	Volume carried [litres]	% of available vol	Weight carried [kg]	% of available payload weight
Actual numbers	3570 before compression?	60.7	53	27.7
Calculated numbers	5881	100	87.3	45.6

The electrical van assumed to be used is a Nissan E-NV200[45], with one van available for collecting plastics.

[45] https://www.nissan.co.uk/vehicles/new-vehicles/e-nv200/technical-information.html

- The loading space is 4.2m3, and the loading capacity is limited by volume rather than weight.
- The running cost[46] per mile is assumed[47] to be 4.6 - 5.8p, with an average of 5.2p/m. This corresponds to €0.061/m or €0.038/km.
  This number is confirmed as being reasonable, with about €3/100km in Austria[48]

An alternative vehicle to consider is the Iveco Daily 7 Tonnes pickup truck: https://www.iveco.com/uk/products/pages/daily-7-tonne.aspx#overview

We simulated three scenarios to be able to make comparisons between the vehicles:

- Scenario 1 (base line): all by diesel lorry
- Scenario 2: zone 1 collection of plastics by CargoBike, zone 2 and 3 by diesel lorry
- Scenario 3: zone 1 collection of plastics by CargoBike, zone 2 by electro-truck, zone 3 by diesel lorry
- Scenario 4: zone 1 collection of plastics by CargoBike, zone 2 and 3 by electro-truck

Further, we made the following assumptions:

- Time to access a client pickup location: we assume 2min on average.
  In practice, at most places it took only 1 minute (DuOOptiek, Residentie Apotheek, Heemskerk Bloemisten, WWen). At some places (Kringloop Den Haag, Brabants Lederwarenhuis), people had to gather the plastics or the team had to collect it from a special room inside; in those cases it took between 5 and 10 minutes.
- Time to load a CargoBike at a client location: 6min
  The total handling time per week was measured. This includes access time at a client and the time to load (including pressing) at the cargobike.
- Time to unload a CargoBike at the drop-off location: 5 minutes
  Another 15 minutes was needed to weigh the bags and add name stickers. However, we assume that this is done by the staff at the Hub and therefore not taken into account by the simulations, as they are focused on logistics only.

[46] https://pod-point.com/guides/vehicles/nissan/2018/e-nv200
[47] https://leccy.net/cost/nissan_e_nv200_combi/visia#:~:text=Charging%20a%20Nissan%20e%2DNV200,mile%2C%20when%20charging%20at%20home%20.
[48] https://www.nissan.at/fahrzeuge/neuwagen/e-nv200-evalia/fragen-antworten.html

- Costs per hour to run a CargoBike: € 25,-

3.4.2 Simulation results

Initially, there were 3,232 companies in Hague. There were two restrictions for the simulations: Some of the data were invalid, and Optiflow can only handle 2000 companies. Therefore, 60% of the samples from each zone were randomly selected (see Table 0-1). A total of 1,897 companies were used for simulation.

Table 3.16: Descriptive analysis

	Frequency	Percentage	Cumulative
Zone 1	420	22.14	22.14
Zone 2	684	36.06	58.2
Zone 3	793	41.8	100
Total	1,897	100	

There are three types of vehicles:

Table 3.17: Three types of vehicles

	IVECO Lorry (Diesel)	NISSAN E-NV200	CargoBike
Estimated range	Unlimited	200km (per day)	Unlimited (battery replaceable)
Fuel price [€]	0.5/km	0.06/km	0.03/km
CO2 emission	132g CO2/Km	0* (does not consider energy mix emissions)	0* (does not consider energy mix emissions)
Loading Capacity	20m3	4.2m3	2.2m3

Service time for each company	Average 8 mins	Average 8 mins	Average 8 mins
Unloading time at depot	15 mins	15mins	15 mins
Driver cost [€]	20.56/hour	20,11/hour	25/hour

There is a compaction press on the bike. About 7m3 plastics in their original state can be compressed down to fit into the 2.2m3 loading space of the CargoBike. On this basis, we assumed that 63.6m3 plastic waste can be compressed down to fit into IVECO Truck; and 13.3m3 plastic waste can be compressed down to fit into the NISSAN E-NV200.

The collection is scheduled to be done weekly. To find the optimal number of vehicles for this request, a trial and error process was used. Scenarios 1.1, 2.1, 3.1, and 4.1 show that only three vehicles could not handle the waste accumulated in one week. In Scenarios 1.2, 2.2,3.2, and 4.2, the number of vehicles was doubled to 6, which was found to still be insufficient. In the end, 7 vehicles were applied in Scenario 1.3, 2.3, 3.3, and 4.3. The detailed information is provided in the following sections.

Scenario 1

Base line: all by diesel lorry

Scenario 1.1

- Three vehicles: 3 diesel lorries (1 for zone 1 and 2 for zone 2)

As the following figures show that the waste of 962 companies has not been collected, Scenario 1.1 is not workable.

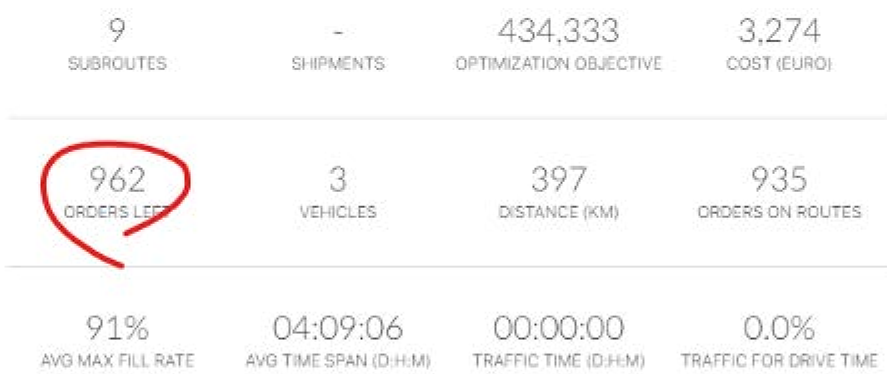

Figure 3.48: The Hague scenario 1.1 results

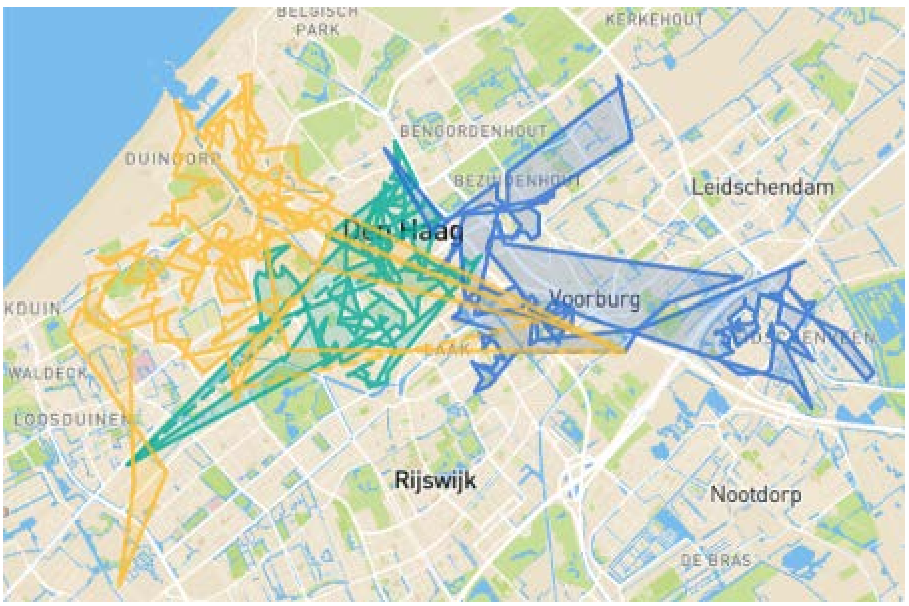

Figure 3.49: The Hague scenario 1.1, possible route

Scenario 1.2

- Six vehicles: 6 diesel lorries (2 for zone 1 and 4 for zone 2 and 3)

As the following figures show that 158 companies' waste have not been collected, scenario 1.2 is not workable.

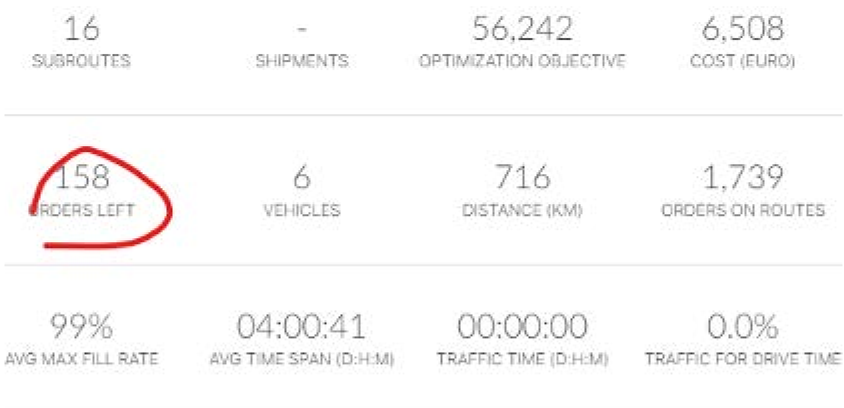

Figure 3.50: The Hague scenario 1.2 results

Figure 3.51: The Hague scenario 1.2, possible route

Scenario 1.3

- 7 vehicles: 7 diesel lorries (2 for zone 1 and 5 for zone 2 and 3)

As the figure 3.52 shows all orders are fulfilled, meaning that all waste was collected. Therefore, this scenario is workable.

20 SUBROUTES	- SHIPMENTS	7,629 OPTIMIZATION OBJECTIVE	7,629 COST (EURO)
0 ORDERS LEFT	7 VEHICLES	907 DISTANCE (KM)	1,897 ORDERS ON ROUTES
99% AVG MAX FILL RATE	03:22:40 AVG TIME SPAN (D:H:M)	00:00:00 TRAFFIC TIME (D:H:M)	0.0% TRAFFIC FOR DRIVE TIME

Figure 3.52: The Hague scenario 1.3 results

Figure 3.53: The Hague scenario 1.3, possible route

Scenario 2

Zone 1 collection of plastics by CargoBike, zone 2 and 3 by diesel lorry

Scenario 2.1

- Three vehicles: 1 Cargo bike (zone 1) and 2 diesel lorries (zone 2&3)

As the following figures show that the 1003 companies' waste have not been collected, scenario 2.1 is not workable.

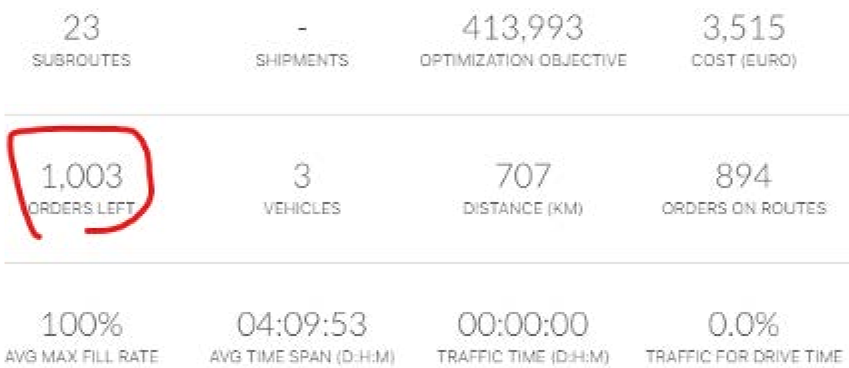

Figure 3.54: The Hague scenario 2.1 results

Figure 3.55: The Hague scenario 2.1, possible route

Scenario 2.2

- Six vehicles: 2 Cargo bikes (zone 1) and 4 diesel lorries (zone 2&3)

As the following figures show that the 160 companies' waste have not been collected, Scenario 2.2 is not workable.

45 SUBROUTES	- SHIPMENTS	63,385 OPTIMIZATION OBJECTIVE	6,924 COST (EURO)
160 ORDERS LEFT	6 VEHICLES	1,149 DISTANCE (KM)	1,737 ORDERS ON ROUTES
97% AVG MAX FILL RATE	04:09:33 AVG TIME SPAN (D:H:M)	00:00:00 TRAFFIC TIME (D:H:M)	0.0% TRAFFIC FOR DRIVE TIME

Figure 3.56: The Hague scenario 2.2 results

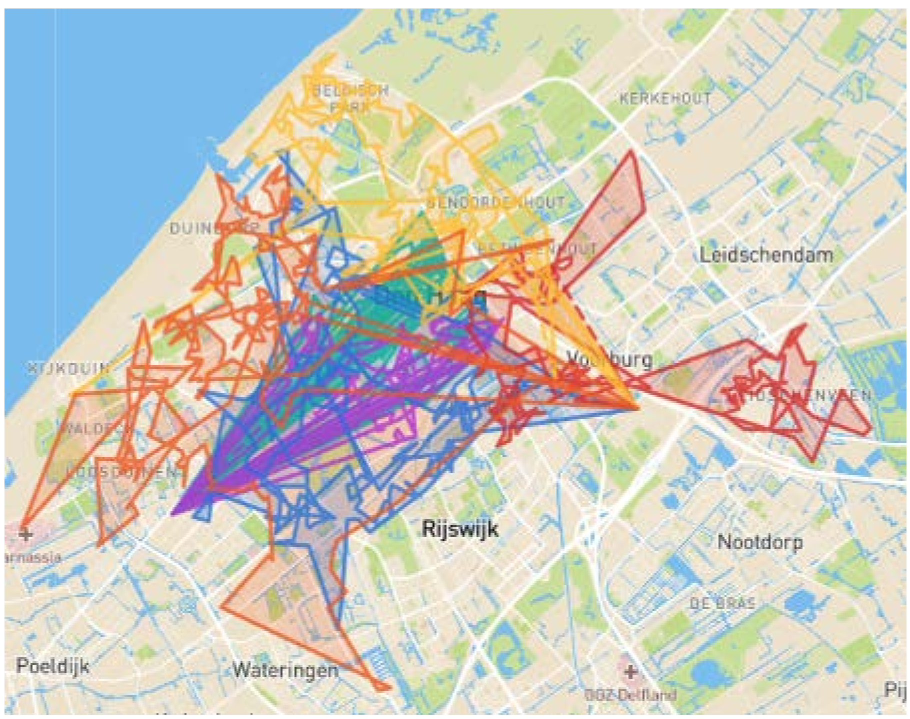

Figure 3.57: The Hague scenario 2.2, possible route

Scenario 2.3

- 7 vehicles: 2 Cargo bikes (zone 1) and 5 diesel lorries (zone 2&3)

As figure 3.58 shows, all orders are fulfilled, meaning that all waste was collected. Therefore, this scenario is workable.

47 SUBROUTES	- SHIPMENTS	8,003 OPTIMIZATION OBJECTIVE	8,003 COST (EURO)
0 ORDERS LEFT	7 VEHICLES	1,270 DISTANCE (KM)	1,897 ORDERS ON ROUTES
99% AVG MAX FILL RATE	04:08:25 AVG TIME SPAN (D:H:M)	00:00:00 TRAFFIC TIME (D:H:M)	0.0% TRAFFIC FOR DRIVE TIME

Figure 3.58: The Hague scenario 2.3 results

Figure 3.59: The Hague scenario 2.3, possible route

Scenario 3

Zone 1 collection of plastics by CargoBike, zone 2 by electro-truck, zone 3 by diesel truck

Scenario 3.1

- Three vehicles: 1 Cargo bike (zone 1), 1 electro-lorry (zone 2) and 1 diesel truck(zone 3)

As the following figures show that the 985 companies' waste has not been collected, scenario 3.1 is not workable.

31 SUBROUTES	- SHIPMENTS	450,656 OPTIMIZATION OBJECTIVE	3,360 COST (EURO)
985 ORDERS LEFT	3 VEHICLES	686 DISTANCE (KM)	912 ORDERS ON ROUTES
95% AVG MAX FILL RATE	04:09:48 AVG TIME SPAN (D:H:M)	00:00:00 TRAFFIC TIME (D:H:M)	0.0% TRAFFIC FOR DRIVE TIME

Figure 3.60: The Hague scenario 3.1 results

Figure 3.61: The Hague scenario 3.1, possible route

Scenario 3.2

- Six vehicles: 2 Cargo bike(zone 1), 2 electro-lorries (zone 2) and 2 diesel lorries (zone 3)

As the following figures show that the 211 companies' waste has not been collected, scenario 3.2 is not workable.

62 SUBROUTES	- SHIPMENTS	103,475 OPTIMIZATION OBJECTIVE	6,763 COST (EURO)
211 ORDERS LEFT	6 VEHICLES	1,425 DISTANCE (KM)	1,686 ORDERS ON ROUTES
97% AVG MAX FILL RATE	04:01:50 AVG TIME SPAN (D:H:M)	00:00:00 TRAFFIC TIME (D:H:M)	0.0% TRAFFIC FOR DRIVE TIME

Figure 3.62: The Hague scenario 3.2 results

Figure 3.63: The Hague scenario 3.2, possible route

Scenario 3.3

- 7 vehicles: 2 Cargo bike(zone 1), 3 electro-lorries (zone 2) and 2 diesel lorries (zone 3)

As the following figures show that the 137 companies' waste has not been collected in one week, scenario 3.3 is not workable.

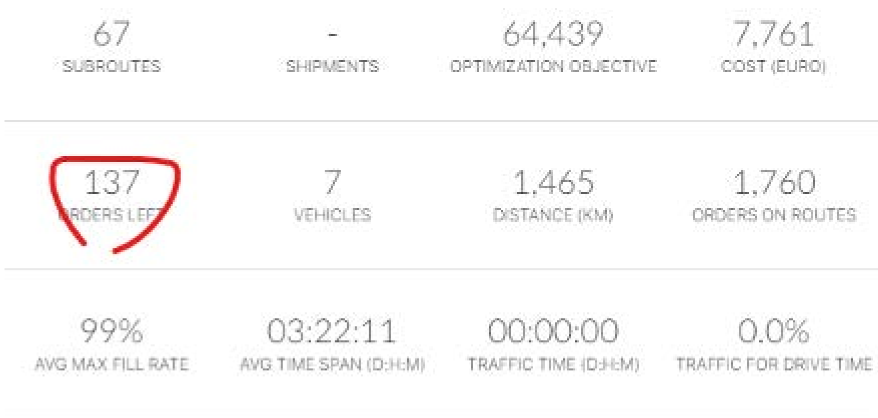

Figure 3.64: The Hague scenario 3.3 results

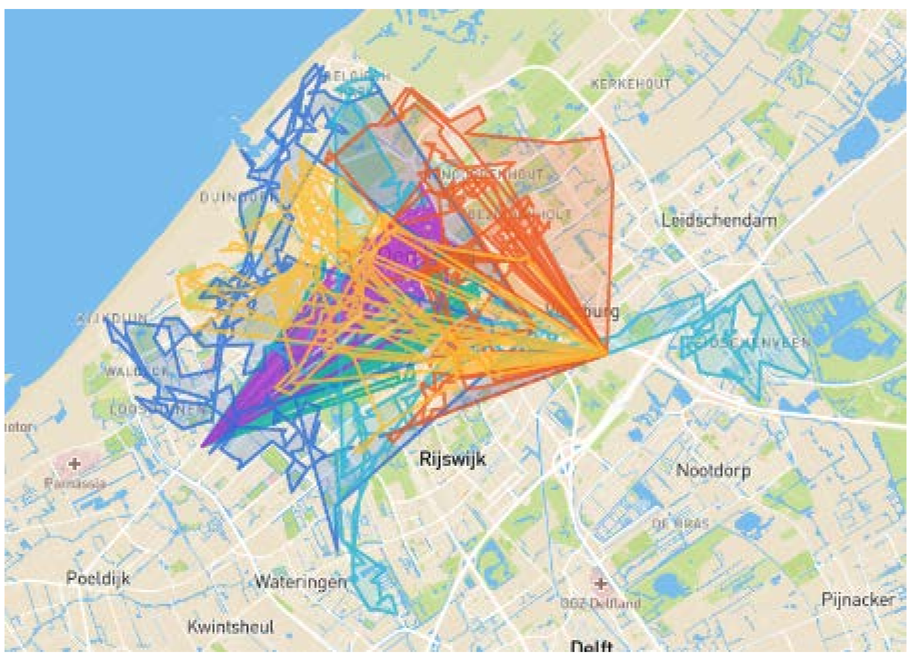

Figure 3.65: The Hague scenario 3.3, possible route

Scenario 3.4

- 8 vehicles: 2 Cargo bike(zone 1), 3 electro-lorries (zone 2) and 3 diesel lorries (zone 3)

All orders are fulfilled, meaning that all waste was collected. Therefore, this scenario is workable.

67	-	8,811	8,811
SUBROUTES	SHIPMENTS	OPTIMIZATION OBJECTIVE	COST (EURO)
0	8	1,541	1,897
ORDERS LEFT	VEHICLES	DISTANCE (KM)	ORDERS ON ROUTES
99%	03:19:59	00:00:00	0.0%
AVG MAX FILL RATE	AVG TIME SPAN (D:H:M)	TRAFFIC TIME (D:H:M)	TRAFFIC FOR DRIVE TIME

Figure 3.66: The Hague scenario 3.4 results

Figure 3.67: The Hague scenario 3.4, possible route

Scenario 4

Zone 1 collection of plastics by CargoBike, zone 2 and 3 by electro-truck

Scenario 4.1

- Three vehicles: 1 Cargo bike (zone 1) and 2 electro-lorries (zone 2&3)

As the following figures show that the 1016 companies' waste has not been collected, scenario 4.1 is not workable.

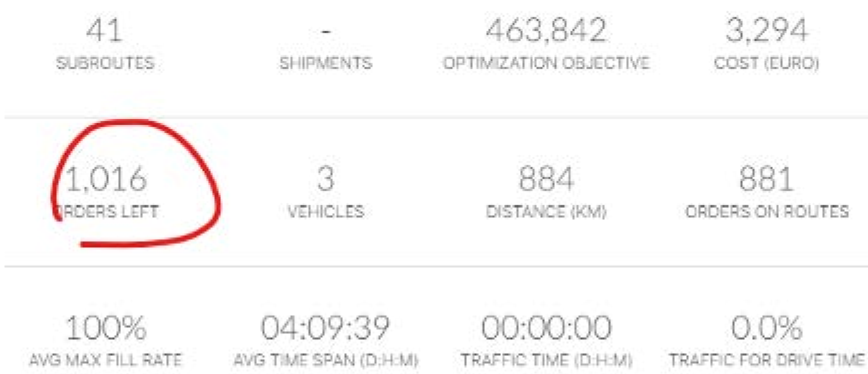

Figure 3.68: The Hague scenario 4.1 results

Figure 3.69: The Hague scenario 4.1, possible route

Scenario 4.2

- Six vehicles: 2 Cargo bikes (zone1) and 4 electro-lorries (zone 2&3)

As the following figures show that the 276 companies' waste has not been collected, scenario 4.2 is not workable.

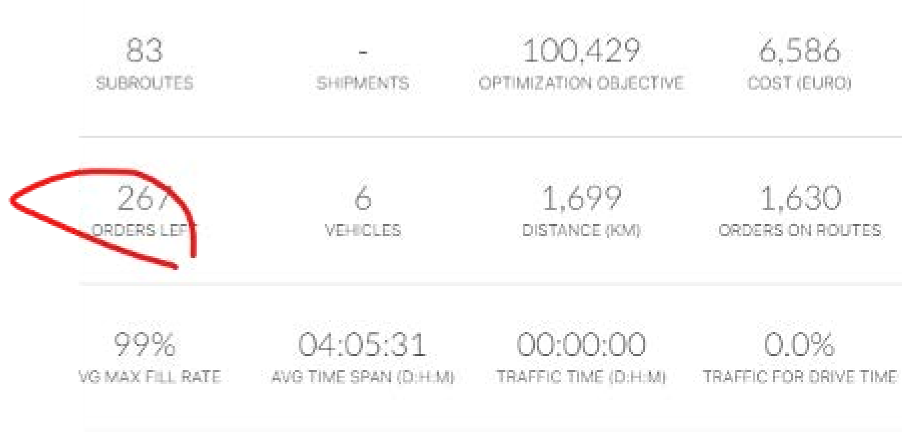

Figure 3.70: The Hague scenario 4.2 results

Figure 3.71: The Hague scenario 4.2, possible route

Scenario 4.3

- 7 vehicles: 2 Cargo bike(zone 1), 5 electro-lorries (zone 2 &3)

All orders are fulfilled, meaning that all waste was collected. Therefore, this scenario is workable.

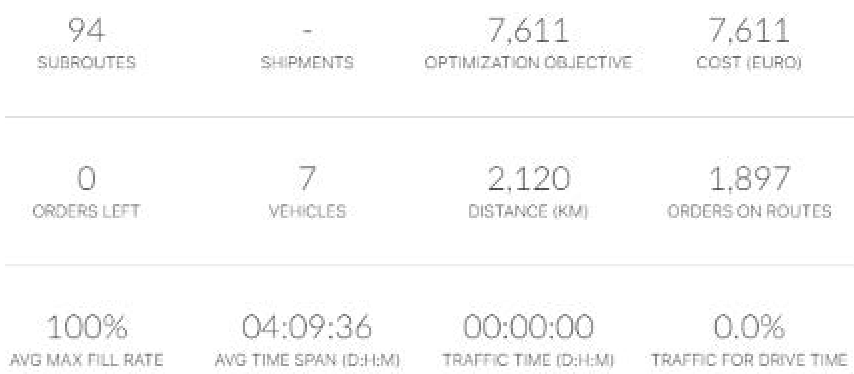

Figure 3.72: The Hague scenario 4.3 results

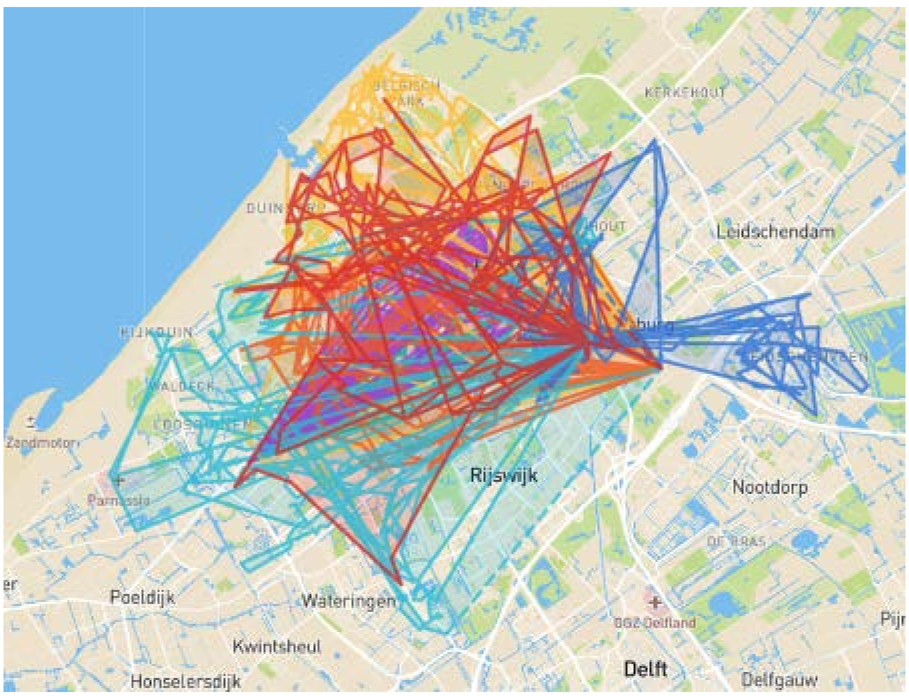

Figure 3.73: The Hague scenario 4.3, possible route

Comparison of scenarios

Table 3.18, below shows that scenario 1.1, 2.1, 3.1, and 4.1, with only three vehicles, can not collect all companies’ plastic waste in one week. So those scenarios are not suitable.

Table 3.18: Scenarios with 3 vehicles

Collect weekly	S1.1	S2.1	S.3.1	S.4.1

Total number of stops	1,897	1,897	1,897	1,897
Collect mode	Weekly	weekly	Weekly	Weekly
Number of working days/per year	52	52	52	52
Number of vehicles	3	3	3	3
· **Zone 1**	1 (IVECO)	1 (E-Cargo bike)	1 (E-Cargo bike)	1 (E-Cargo bike)
· **Zone 2**	1 (IVECO)	1 (IVE CO)	1 (NISSAN E-NV200)	1 (NISSAN E-NV200)
· **Zone 3**	1 (IVECO)	1 (IVECO)	1 (IVECO)	1 (NISSAN E-NV200)
Time window	08:00-18:00	08:00 -18:00	08:00 -18:00	08:00 -18:00
Cost/per week	€3,274	€3,515	€3,360	€3,294
Cost (Pound)/ year	€ 170,248	€ 182,780	€ 174,720	€ 171,288
Distance (km)/week	397km	707km	686km	884km
Distance (km)/year	20,644km	36,764km	35,672km	45,968km
The number of companies' waste has not been collected	**926**	**1003**	**985**	**1016**

Table 3.19, in turn, shows that again, cenarios 1.2, 2.2, 3.2, and 4.2 can not collect all companies' plastic waste in one week. So those scenarios are not suitable.

Table 3.19. Scenarios with 6 vehicles

Collect weekly	**S1.2**	**S2.2**	**S.3.2**	**S.4.2**
Total number of stops	1,897	1,897	1,897	1,897

Collect mode	Weekly	weekly	Weekly	Weekly
Number of working days/per year	52	52	52	52
Number of vehicles	6	6	6	6
· **Zone 1**	2 (IVECO)	2 (E-Cargo bike)	2 (E-Cargo bike)	2 (E-Cargo bike)
· **Zone 2**	4 (IVECO)	4 (IVECO)	2 (NISSAN E-NV200)	4 (NISSAN E-NV200)
· **Zone 3**			2 (IVECO)	
Time window	08:00-18:00	08:00 -18:00	08:00 -18:00	08:00 -18:00
Cost/per week	€6,508	€6,924	€6,763	€6,586
Cost / year	€ 338,416	€ 360,048	€ 351,676	€ 342,472
Distance (km)/week	716km	1,149 km	1,425 km	1,699 km
Distance (km)/year	37,232km	59,748 km	74,100 km	88,348 km
The number of companies' waste has not been collected	**158**	**160**	**211**	**267**

Next, in the following table 3.20, with 7 vehicles, we can see that In Scenario 3.3, 137 companies' waste has not been collected, so Scenario 3.3 is not suitable. In turn, scenario 2.3 is the most expensive one, which is also not appropriate. The other 3 scenarios collect waste for all companies, therefore they are all feasible. However, they vary considerably in terms of operational costs and emissions generated. Among them, the most desirable scenario is 4.3 (second lowest cost and lowest emissions). In this scenario all vehicles are electric, with 2 cargo bikes in zone 1 and 5 e-vehicles in zone 2.

Table 3.20. Scenarios with 7 vehicles

Collect weekly	S1.3	S2.3	S.3.3	S.4.3
Total number of stops	1,897	1,897	1,897	1,897
Collect mode	Weekly	weekly	Weekly	Weekly
Number of working days/per year	52	52	52	52
Number of vehicles	7	7	7	7
· **Zone 1**	2 (IVECO)	2(E-Cargo bike)	2 (E-Cargo bike)	2 (E-Cargo bike)
· **Zone 2**	5 (IVECO)	5 (IVECO)	3 (NISSAN E-NV200)	5 (NISSAN E-NV200)
· **Zone 3**			2 (IVECO)	
ime window	08:00-18:00	08:00 -18:00	08:00 -18:00	08:00 -18:00
Cost/per week	€ 7,629	€ 8,003	€ 7,761	€ 7,611
Cost / year	€ 396,708	€ 416,156	€ 403,572	€ 395,772
Distance (km)/week	907km	1,270km	1,465 km	2,120km
Distance (km)/year	47,164km	66,040km	76,180km	110,240km
The number of companies' waste has not been collected	**0**	**0**	**137** 8 vehicles required (scenario 3.4)	**0**
Emission (C02)	**Highest (All diesel)**			**Lowest (All electricity)**
WTW emissions (C02)	**Lowest (All diesel)**			**Highest (All electricity)**

Of course, the wheel to wheel emissions are only lowest for electricity-powered vehicles if we assume that the electricity is fully generated by renewable energy sources . Otherwise the emissions are just moved out of the city. As noted before, a country-specific analysis of the energy generation mix is needed to assert the extent to which electric vehicles produce less emissions than diesel vehicles. We do not have quantitative information about WTW emissions of cargo bikes vehicles in Woo et al (2017) for the Netherlands, but we know that in 2021 The Netherlands was ranked 27th out of 27 european countries in share of renewables, and has the highest rate of emmissions per KW generated. 46% of its energy mix came from oil (38%) and coal (11%) with a further 38th from natural gas and only 11% from nuclear, wind, solar, hydropower and geothermal.[49] Such an energy mix is unlikely to result in gains in emissions from the use of electric vehicles compared to diesel, and very likely to result in electric vehicles contributing more than diesel vehicles to emissions. An scenario where only cargo bikes are used could result in less emissions but our simulations show that such scenario is unfeasible,

The cheapest scenario is that with all electric vehicles. However, the savings compared to the second cheapest scenario - all diesel vehicles- amount to only € 1000/year, suggesting savings are not significant from the operational cost of view. However, there is, as noted during the interviews carried out for sensitization, a significant difference in acquisition costs between electric vans and diesel lorries, with the former being more pricey. This suggests that policy intervention subsidizing costs of electric vehicles may be needed to scale up its use. However, our preliminary WTW emissions analysis based in Woo et al (2017) suggests that such interventions may be counterproductive if the country does not radically change its energy mix to reduce dependence on oil, coal and gas. Further calculations are required to determine the actual WTW emissions produced by using electric vehicles, taking into account the actual WTW emission factor for cargo bikes and electric vehicles vans in the Netherlands.

3.5 Simulations for Ghent

The simulations conducted for Ghent include 5 different scenarios including alternative transportation modes and alternative vehicles like the CargoBike.

To determine plastic waste quantities, a waste collection trial was conducted in Herentals, Belgium, amongst retail businesses. Two collections were executed: the first collection in the period of July-August 2020 and the second one in the period from Sept 2020 to January 2021. It is not known for how long the businesses were accumulating

[49] US International Trade Administration 2021: Netherlands, Country Commercial Guide, Energy.

the waste collected in the first round - potentially 1-2 months, but the waste collected in the second round was likely accumulated during 1-5 months. This wide variation makes it impossible to create typical values for waste volumes. For the sake of the exercise, we shall assume 2 months on average, and hence the volume for a monthly collection would be half.

Table 3.21 shows the kilograms of plastics collected from retail companies in Herentals. For conversion, we assume an average density (mass [kg] / vol [m3]) of 13kg/m3 after compression by the press installed on the CargoBike, based on what is discussed in section 3.3.

Table 3.21: Plastic waste collection trial conducted in Herentals

Name	Business type	Min weight [kg]	Max weight [kg]	Average weight [kg]	Average vol [litres] assumed for 2 months	Average vol [litres] assumed for 1 week
Apotheek Vermylen K. BV	Pharmacy	26	36	31	2385	133
Blik in't Groen BV	Flower shop	17	17	17	1308	73
Carens Oils BV	Retail of oils	28	28	28	2154	120
Christel Dierenspeciaalzaak	Pet supply shop	4	4	4	308	17
Jenne Van den Berghe	Pet supply shop	14	31	22.5	1731	96
Maalderij Van Hool-Schroyens	Grain mill + retail of milled products	116	357	236.5	18192	1011
Schoenen Van Tendeloo BV	Shoe retail	1	1	1	77	4
Veloke	Bike shop	14	14	14	1077	59
Wieleke BV	Bike shop	10	17	13.5	1038	58
anders@home	interior & decoration retail	2	-	2	154	9
Carre NV/ Van	Clothing retail	23	-	23	1769	98

Orshaegen						
Coffee and Sweets	Food retail / Café	1	-	1	77	4
Hunkemuller	Clothing retail	7	-	7	538	30
keymusic	Retail music instruments and supply	13	-	13	1000	56
Limo&Co	Food retail	7	-	7	538	30
marieposa	Clothing retail	1	-	1	77	4
Optiek smets	Optician	3	-	3	231	13
Passe partout	Food retail	4	-	4	308	17
speculaasje Heyns	Food retail	5	-	5	385	21
Standaard boekhandel	Book store	1	-	1	77	4
Sublim	Retail beauty products	3	-	3	231	13

The relatively large variations between companies can be explained by varying company sizes and different types of businesses.

3.5.1 Simulation details

The database used for the simulations contained 10136 entries in total. Those without plastic waste volume data and those with 0.000 tons per year (which might be zero because of rounding) were removed. 9930 addresses remained in the database. Out of these, three zones were defined for the simulations, based on the shopping areas[50]. The details and mini-hubs for each zone are as shown in Table 3.22.

Table 3.22: Local areas and mini-hubs

	Areas	Number of addresses	Lorry mini-hub	Water mini-hub	Tram mini-hub

50 https://data.stad.gent/explore/dataset/sfeergebieden-puur-gent/map/?location=13,51.04636,3.73492&basemap=jawg.streets

Zone South	Quartier Sint-Pieters and Ontmoeten	2035; 35 removed randomly	Sint Pietersstation	n/a	Sint Pietersstation
Zone East	SoGo and East District	1787	Korenmarkt	Graslei	Korenmarkt
Zone Centre	Linkerover, Central, Rond Sint-Jacobs	1765	Korenmarkt	Graslei	Korenmarkt

The PlastiCity Hub is situated at Farmanstraat 40. This is a site in the southern part of the North Sea Port district, situated in the middle between the historical city centre with a lot of retail and gastronomic venues and the major companies along the harbor.

All plastic waste is being separated at source by the waste owner and sorted into colour-coded bags. These can be collected together.

As waste quantities were given in tons per year, conversion to volume was required. For this purpose, a density of 15 kg/m3 was assumed. Depending on the composition of the plastic waste, this may be more or less accurate. Collections are assumed to be weekly. For the sake of these simulations, we assume that there is space for a 40m3 container to receive the collected plastics at the mini-hub locations. These containers then get taken to the hub at Farmanstraat in scenarios 5/6/7. The building at Farmanstraat can be reached by road, tramway (there are rails next to the road) and boat (closest access: Noorddok).

The scenarios are shown in Table 3.23. Each scenario was simulated for each of the 3 zones.

Table 3.23: Ghent scenarios

Number	Scenario details
1	Innercity milk-run by lorry (diesel or CNG) to Farmanstraat
2	Innercity milk-run by electric van (GRCT van) to Farmanstraat
3	Innercity milk-run by CargoBike to mini-hubs (suitable for onwards transport by road and tramway)
4 (*)	Innercity milk-run by CargoBike to water mini-hubs
5	Mini-hub service by lorry (diesel / CNG) from lorry mini-hubs to Farmanstraat

6 (*)	Mini-hub service by tram to tramdepot, then by lorry to Farmanstraat; direct transport to Farmanstraat on rails might be possible, as there are rails next to the road in front of the building - to be explored
7 (*)	Mini-hub service by e-boat from water mini-hubs to Noorddok

(*) Scenarios 6 and 7 could not be simulated as OptiFlow can only operate road transport. Also, operational details for these modes of transport were unknown. These scenarios are, however, interesting thought experiments. Scenario 4 was not simulated; the water mini-hubs are close to the mini-hubs, and therefore the results would have been almost identical. Comparing the different vehicles is more interesting as their loading volumes vary.

The vehicles to be explored as well as their details are shown in Table 3.24. Note that this CargoBike has a smaller loading volume than the one used in The Hague. Given that the costs for running a diesel lorry and a CNG lorry are assumed to be identical, and they are able to take the same cargo, they are covered by the same scenarios (1 and 5). The only difference is the emissions, which are calculated at the end, per kilometre travelled.
The costs include: salary for the driver, fuel, insurance and maintenance.

Table 3.24: Vehicles and their details

	Costs per km [€]	Costs per hour [€]	Loading volume [m3]	Waste volume before compression [m3]	Time to unload at hub	Speed limit in city centre
CargoBike		26	1.5	4.78	15	30km/h
Diesel lorry	2.06 (GRCT)	60 (Ivago) 51.50 (**)	40	127 (****)	10	30km/h
CNG lorry		60 (Ivago)	40	127 (****)	10	30km/h
Electric van	1.50 (GRCT)	19.50 (***)	10.7	34 (****)	15	30km/h

(**) Converted based on the following assumptions by GRCT: 1250km per week, 50h per week. This is less expensive than the costs indicated by Ivago, which were used for the simulations.
(***) Converted based on the following assumptions by GRCT: 650km per week, 50h per week.
(****) Assuming the same compression factor as with the CargoBike.

3.5.2 Simulation results

A small number of data provided were not compatible with OptiFlow and had to be excluded. Table 3.25 provides an overview.

Table 3.25: Number of addresses used per zone in Ghent

	Number of addresses	Number of invalid addresses	Number of valid addresses
Zone Centre	1765	12	1753
Zone South	2000	23	1977
Zone East	1787	5	1782
Total	5552	40	5512

The details used for the three types of vehicles are detailed in Table 3.26.

Table 3.26: Vehicle details used for Ghent

	Lorry (Diesel or CNG)	Electric van	CargoBike
Estimated range	Unlimited	200km (per day)	Unlimited (battery replaceable)
Operational cost	€0.74/km	€0.18/km	€0.03/km
CO2 emission (during transport only)	132g CO2/km	0	0
WTW C02 emission**	164.6g CO2/km	44.15 g CO2/km	17.6 g CO2/km

Loading capacity	40m3	10.7m3	1.5m3
Average service time per stop	8 mins	8 mins	8 mins
Unloading time at depot	10 mins	15mins	15 mins
Driver cost	€60/hour	€19.5/hour	€26/hour
Speed limit	30km/h	30km/h	30km/h

** Well to wheel emissions for diesel vehicles based on Woo et al (2017), well to wheel emissions for electric vehicles are own calculation following Woo et al (2017) methodology for emissions by country and energy mix for Belgium in 2020 (https://www.energyprice.be/blog/energy-mix-belgium/) . Ratio electric van/ cargo bike based on Fraselle et al (2021) and Büttgen et al (2021)

Table 3.27 provides an overview of the simulation scenarios set up for Ghent.

Table 3.27: Overview of scenarios set up for Ghent.

	Zone Centre	Zone South	Zone East
Weekly, 6 lorries	1.1.1	1.1.2	1.1.3
Fortnightly, 3 lorries	1.2.1	1.2.2	1.2.3
Monthly, 2 lorries	1.3.1	1.3.2	1.3.3
Weekly, 7 electric vans	2.1.1	2.1.2	2.1.3
Fortnightly, 4 electric vans	2.2.1	2.2.2	2.2.3
Monthly, 3 electric vans	2.3.1	2.3.2	2.3.3
Weekly, 7 CargoBikes	3.1.1	3.1.2	3.1.3 (8 CargoBikes)
Fortnightly, 3 CargoBikes	3.2.1	3.2.2	3.2.3
Monthly 2 CargoBikes	3.3.1	3.3.2	3.3.3
Minihub service, weekly	5.1		
Minihub service, fortnightly	5.2		

The more time between collections, the more waste will have been accumulated, hence the more vehicles might be needed if we assume that the waste needs to be picked up in one go. However, these simulations reduce the number of vehicles, hence pushing vehicle utilisation rates up and using them for more than one round, to explore the boundaries of the system.

Scenario 1

This is an innercity milk-run by lorry (diesel or CNG) to Farmanstraat. In Scenario 1.1, each Zone has six vehicles to collect waste weekly (Monday to Friday). In Scenario 1.2, there are three vehicles, and in Scenario 1.3, there are two.

Scenario 1.1.1 is for Zone Centre, with results in Figures 3.74 and 3.75.

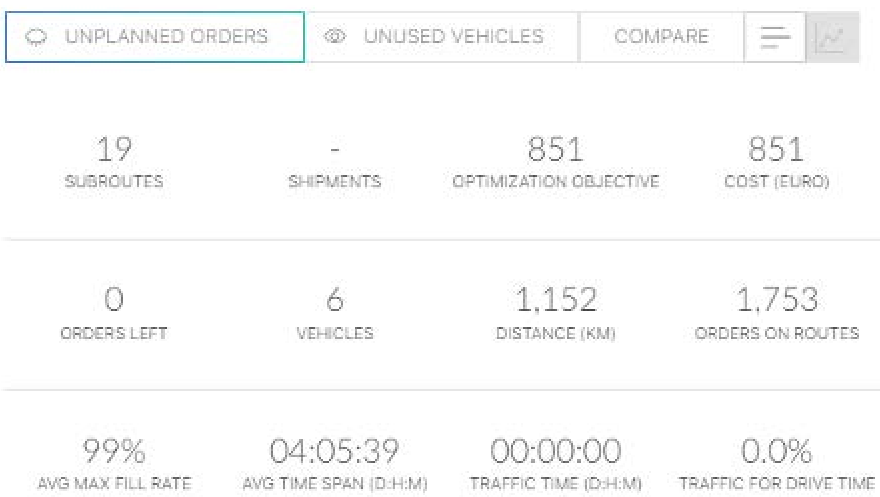

Figure 3.74: Results for Ghent scenario 1.1.1

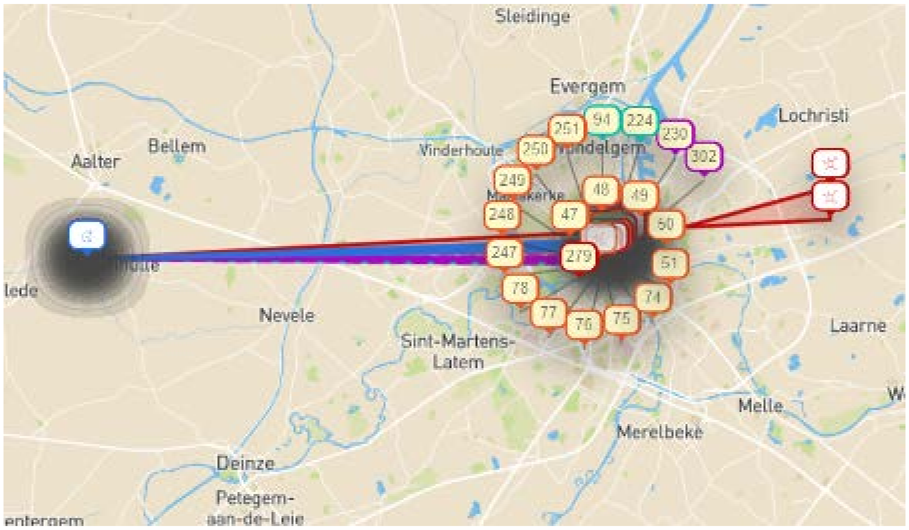

Figure 3.75: Possible routes for Ghent scenario 1.1.1

Scenario 1.1.2 is for Zone South, with results in Figures 3.76 and 3.77.

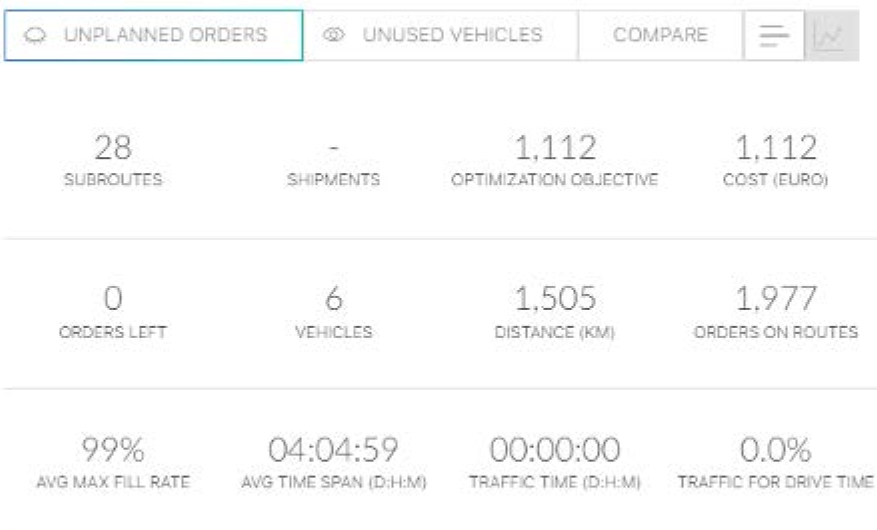

Figure 3.76: Results for Ghent scenario 1.1.2

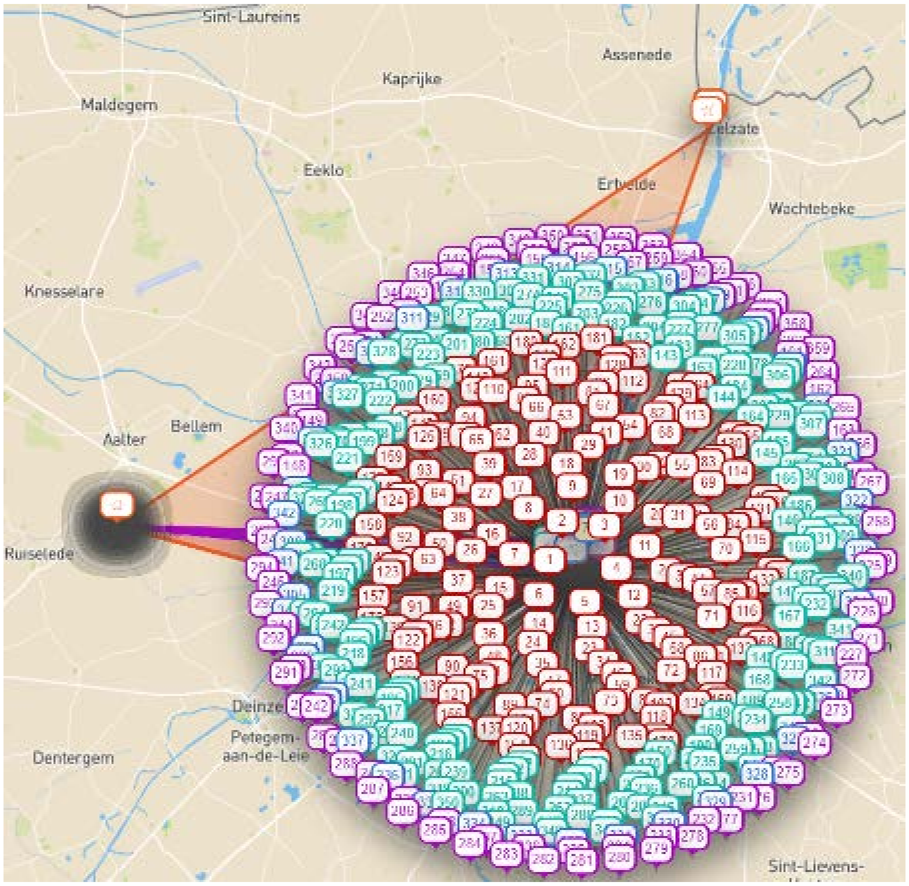

Figure 3.77: Possible routes for Ghent scenario 1.1.2

Scenario 1.1.3 is for Zone East, with results in Figures 3.78 and 3.79.

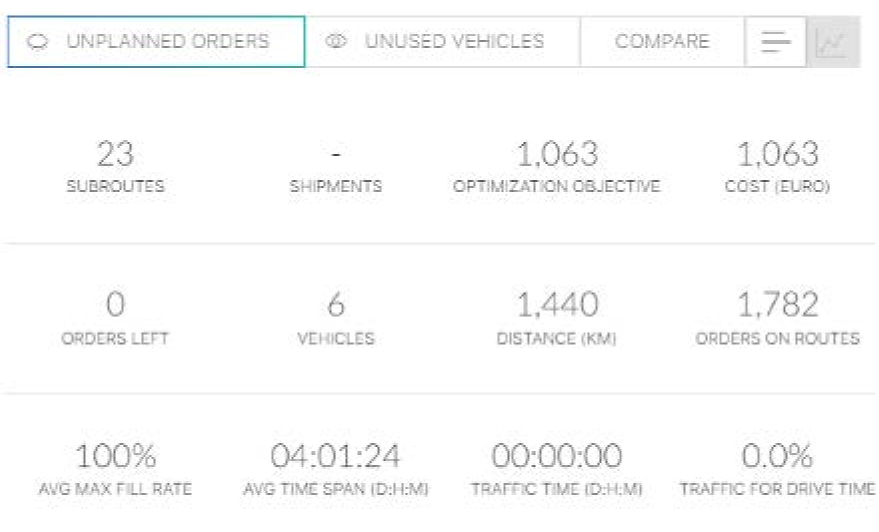

Figure 3.78: Results for Ghent scenario 1.1.3

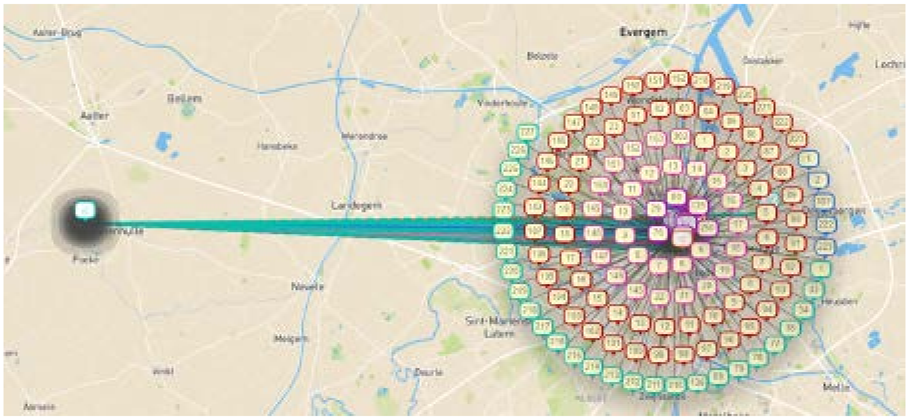

Figure 3.79: Possible routes for Ghent scenario 1.1.3

Scenario 1.2.1 is for Zone Centre, with results in Figures 3.80 and 3.81.

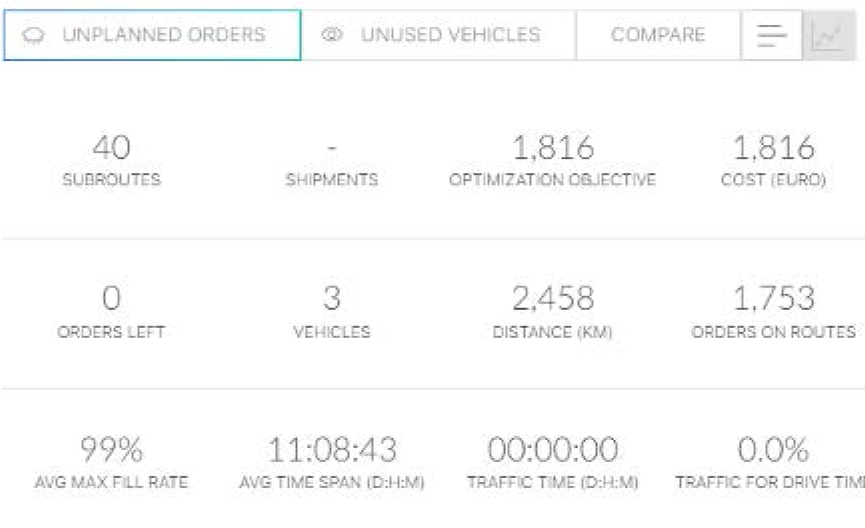

Figure 3.80: Results for Ghent scenario 1.2.1

Figure 3.81: Possible routes for Ghent scenario 1.2.1

Scenario 1.2.2 is for Zone South, with results in Figures 3.82 and 3.83. Note that 52 companies have not been served, hence this scenario is not workable in the current configuration. There are many ways to solve this: for instance, paying extra for the overtime collection or adding another vehicle. For example, if we want to pay extra for the overtime collection, we could calculate roughly how many extra hours we need. As highlighted in the table "Comparison of Scenario 1", on average, each vehicle (three in total) spends 100 hours in two weeks to collect 1925 companies' waste in 1.2.2. This means that on average, three vehicles could collect 19.25 companies' waste per hour. So, if we want to collect the remaining 52 companies' waste, each vehicle may take about 3 hours (52/19.25=2.7).

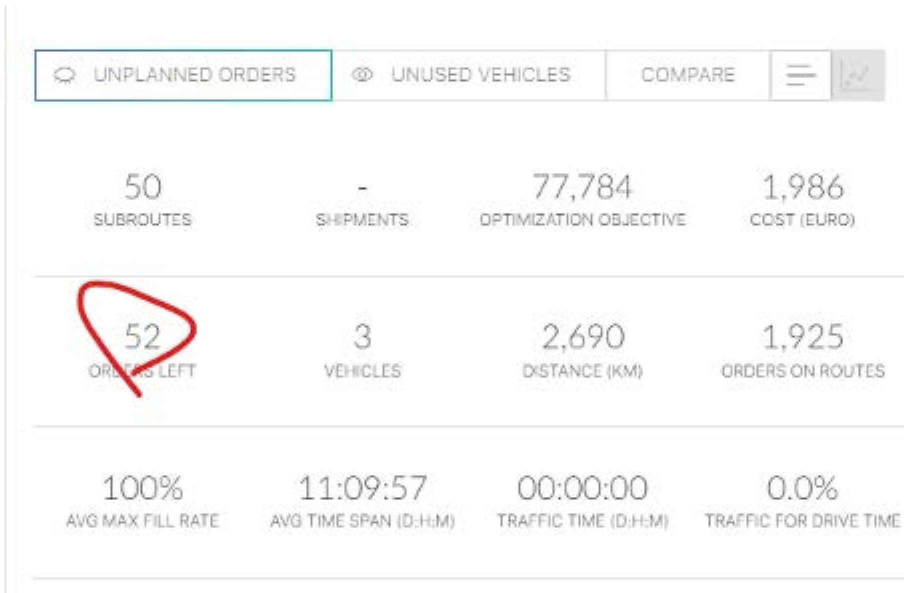

Figure 3.82: Results for Ghent scenario 1.2.2

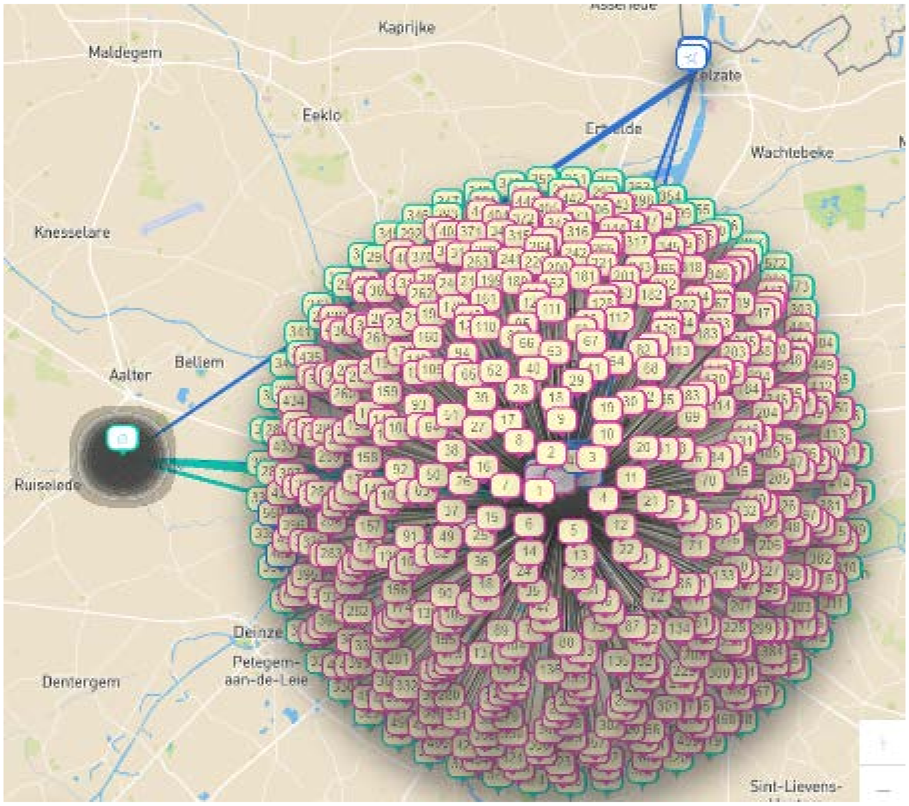

Figure 3.83: Possible routes for Ghent scenario 1.2.2

Scenario 1.2.3 is for Zone East, with results in Figures 3.84 and 3.85.

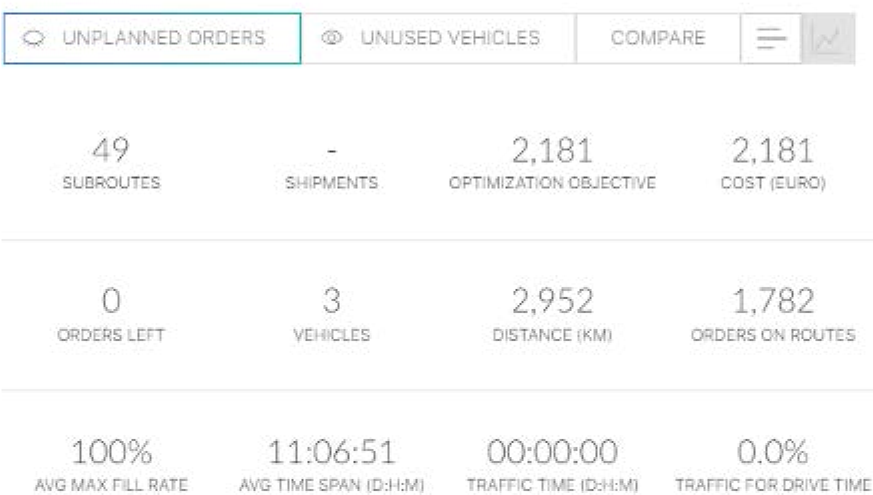

Figure 3.84: Results for Ghent scenario 1.2.3

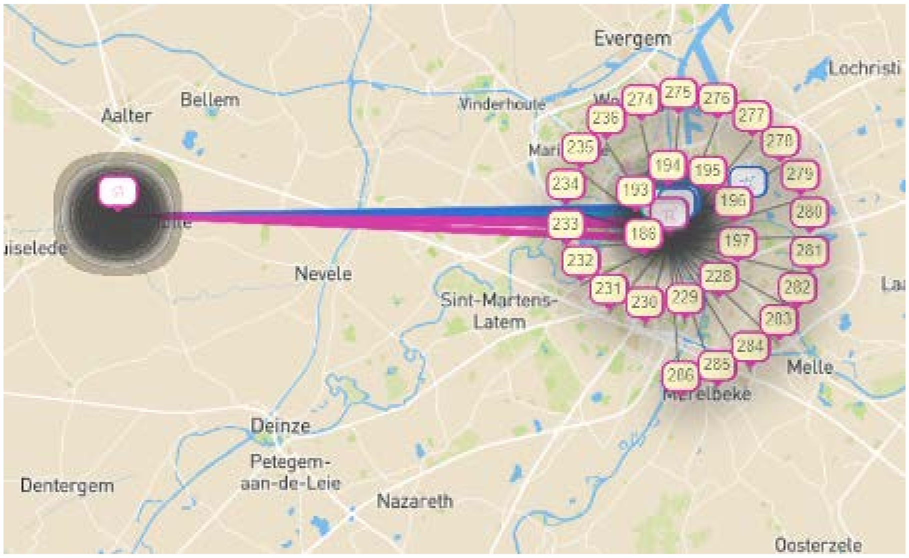

Figure 3.85: Possible routes for Ghent scenario 1.2.3

Scenario 1.3.1 is for Zone Centre, with results in Figures 3.86 and 3.87.

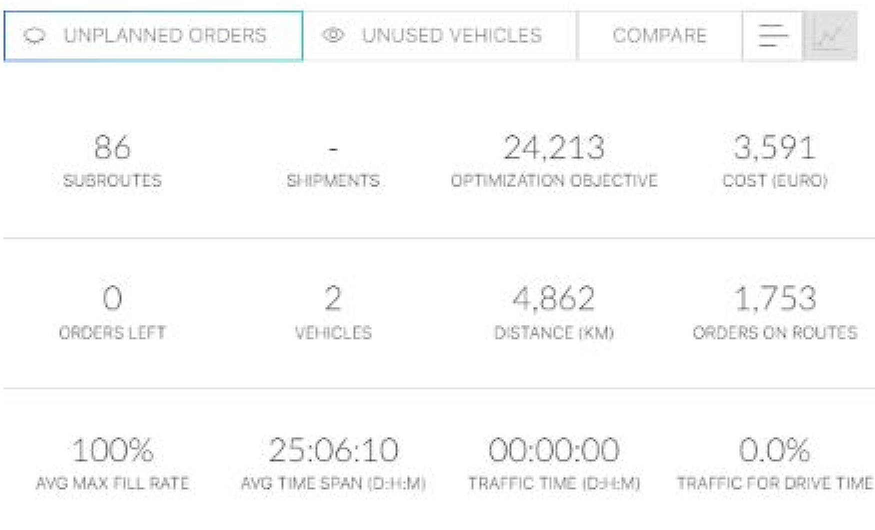

Figure 3.86: Results for Ghent scenario 1.3.1

Figure 3.87: Possible routes for Ghent scenario 1.3.1

Scenario 1.3.2 is for Zone South, with results in Figures 3.88 and 3.89

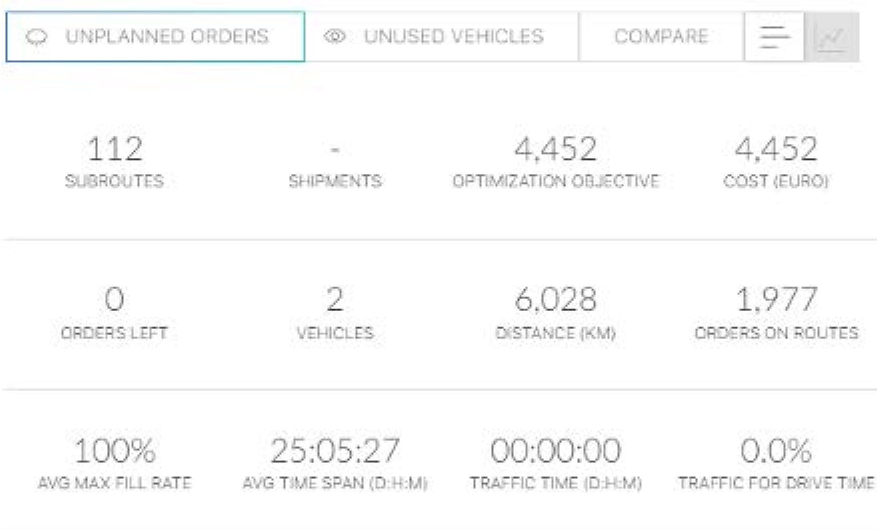

Figure 3.88: Results for Ghent scenario 1.3.2

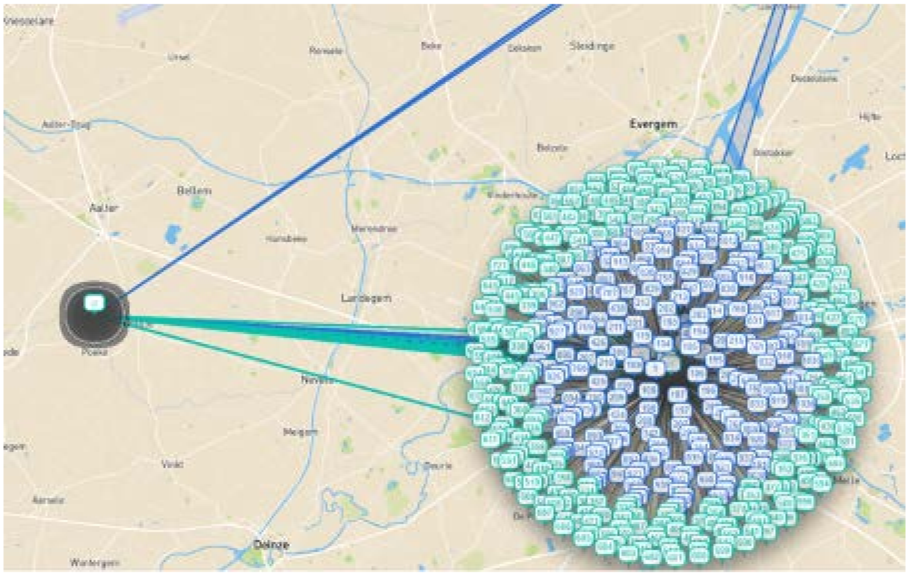

Figure 3.89: Possible routes for Ghent scenario 1.3.2

Scenario 1.3.3 is for Zone East, with results in Figures 3.90 and 3.91

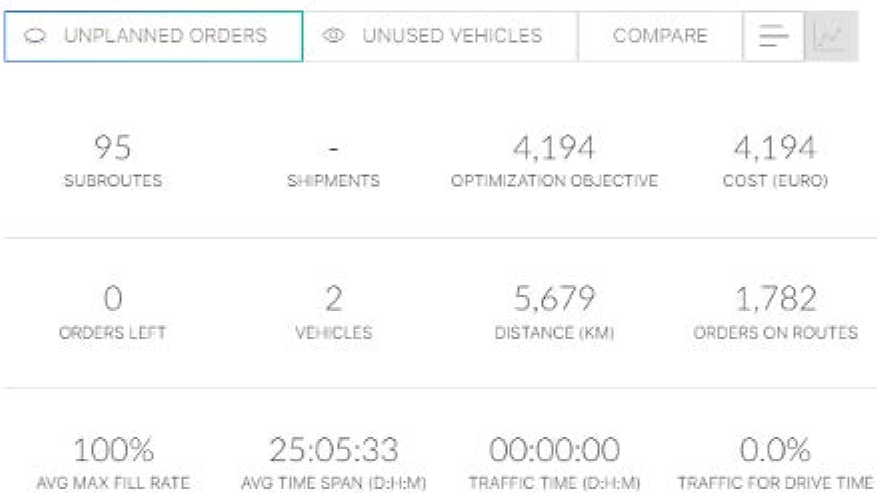

Figure 3.90: Results for Ghent scenario 1.3.3

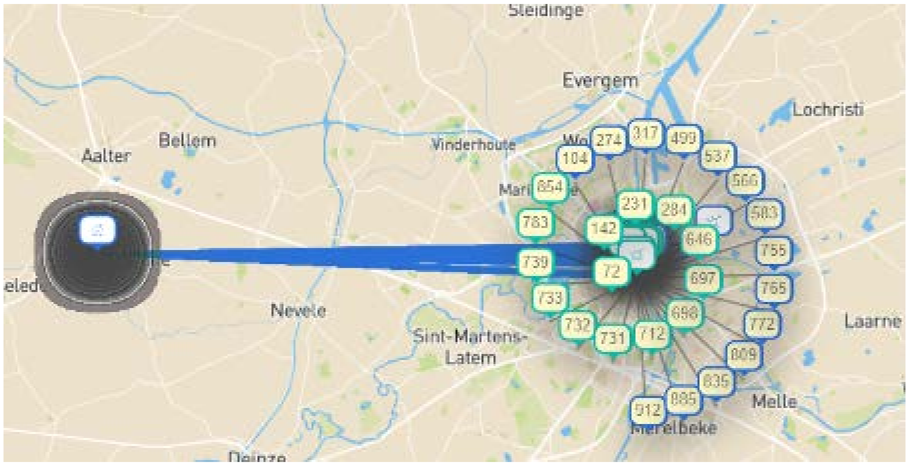

Figure 3.91: Possible routes for Ghent scenario 1.3.3

Comparison of zones in Scenario 1

As shown in Tables 3.28-3.30, Scenarios 1.1.1, 1.1.2, and 1.1.3 are the most expensive for each zone. Scenario 1.3.1, 1.3.2, and 1.3.3 are the most appropriate scenarios (2 diesel lorries), which collect waste monthly with the lowest cost and shortest routes.

Table 3.28: Weekly collections for Ghent scenario 1

Collect weekly	**Zone Centre**	**Zone South**	**Zone East**
Scenario	**1.1.1**	**1.1.2**	**1.1.3**
Total number of stops	1,753	1,977	1,782
Number of collections per year	52	52	52
Number of working days per week	5	5	5
Number of vehicles	6	6	6
Time window (Monday-Friday)	08:00-18:00	08:00 -18:00	08:00 -18:00
Cost per km (operational cost)	€ 851	€ 1,112	€ 1,063
Cost per hour (labour cost)	€ 60	€ 60	€ 60
Working hours required per week	46	45	42
Utilisation rate	92%	90%	84%
Cost per week	€ 17,411	€ 17,312	€ 16,183
Cost per year	€ 905,372	€ 900,224	€ 841,516

Total distance per week	1,152 km	1,505 km	1,440 km
Total distance per year	59,904 km	78,260 km	74,880 km

Table 3.29: Fortnightly collections for Ghent scenario 2

Collect fortnightly	Zone Centre	Zone South	Zone East
Scenario	**1.2.1**	**1.2.2**	**1.2.3**
Total number of stops	1,753	1,977	1,782
Number of collections per year	26	26	26
Number of working days per week	5	5	5
Number of vehicles	3	3	3
Time window (Monday-Friday)	08:00-18:00	08:00 -18:00	08:00 -18:00
Cost per km (operational cost)	€ 1,816	€ 1,986	€ 2,181
Cost per hour (labour cost)	€ 60	€ 60	€ 60
Working hours required per fortnight	98	100	97
Utilisation rate	98%	100%	97%
Cost per fortnight	€ 19,456	€ 19,986	€ 19,641
Cost per year	€ 505,856	€ 519,636	€ 510,666
Total distance per fortnight	2,458 km	2,690 km	2,952 km
Total distance per year	63,908 km	69,940 km	76,752 km
The number of companies' waste has not been collected	0	**52**	0

Table 3.30: Monthly collections for Ghent scenario 3

Collect monthly	Zone Centre	Zone South	Zone East
Scenario	**1.3.1**	**1.3.2.**	**.1.3.3**

Total number of stops	1,753	1,977	1,782
Number of collections per year	12	12	12
Number of working days per week	5	5	5
Number of vehicles	2	2	2
Time window (Monday-Friday)	08:00-18:00	08:00 -18:00	08:00 -18:00
Cost per km (operational cost)	€ 3,591	€ 4,452	€ 4,194
Cost per hour (labour cost)	€ 60	€ 60	€ 60
Working hours required per month	197	196	196
Utilisation rate (assuming 22 working days per week)	90%	89%	89%
Cost per month	€ 27,231	€ 27,972	€ 27,714
Cost per year	€ 326,772	€ 335,664	€ 332,568
Total distance per month	4,862 km	6,028 km	5,679 km
Total distance per year	58,344 km	72,336 km	68,148 km

Scenario 1.3.3 is the cheapest given that it uses the lowest number of vehicles and leaves the waste to accumulate for the longest periods.

Scenario 2

This is an innercity milk-run by electric van to Farmanstraat. In Scenario 2.1, each Zone has seven vehicles to collect waste weekly (Monday to Friday). In scenario 2.2, there are four vehicles, and in Senario 2.3, there are three. Companies that have accumulated waste quantities above what a previously empty vehicle can load at once are not served. See the discussion at the end of this section regarding the best strategy to adopt in these cases.

Scenario 2.1.1 is for Zone Centre, with results in Figures 3.92 and 3.93.

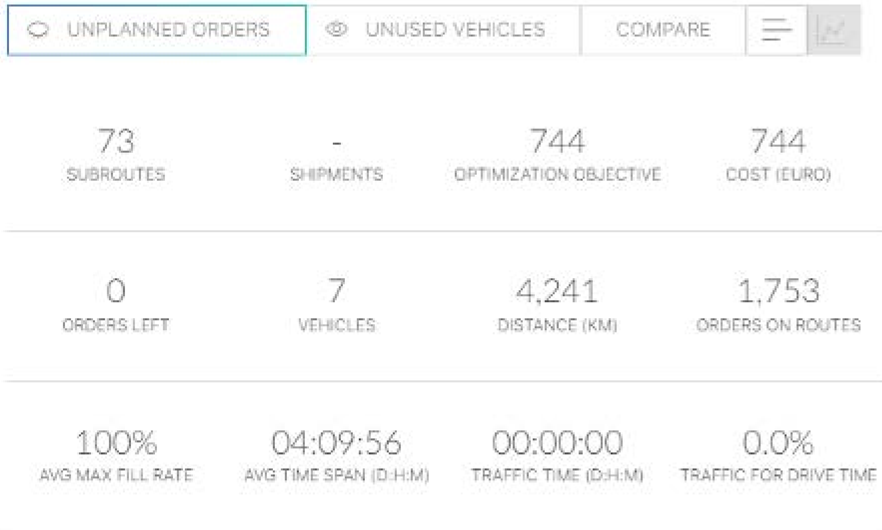

Figure 3.92: Results for Ghent scenario 2.1.1

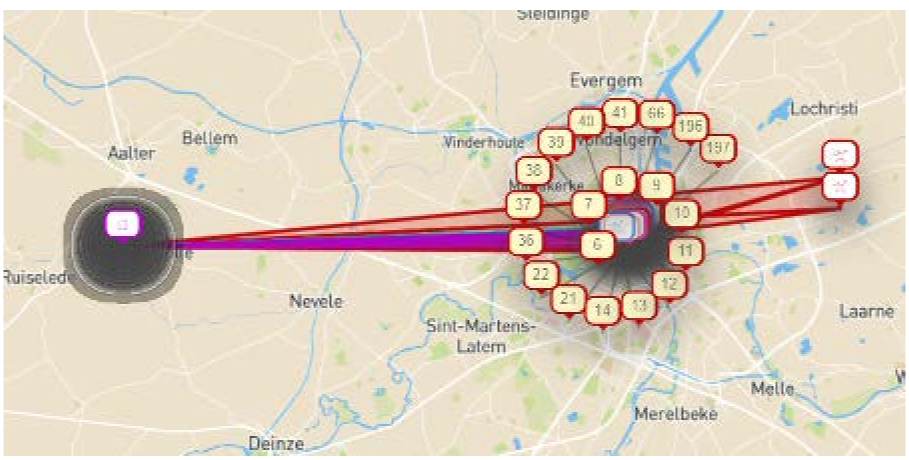

Figure 3.93: Possible routes for Ghent scenario 2.1.1

Scenario 2.1.2 is for Zone South, with results in Figures 3.94 and 3.95.

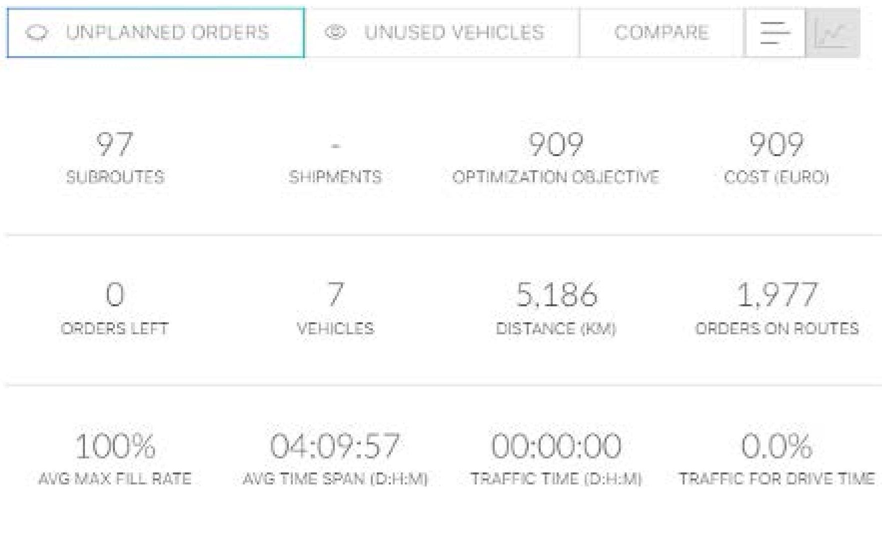

Figure 3.94: Results for Ghent scenario 2.1.2

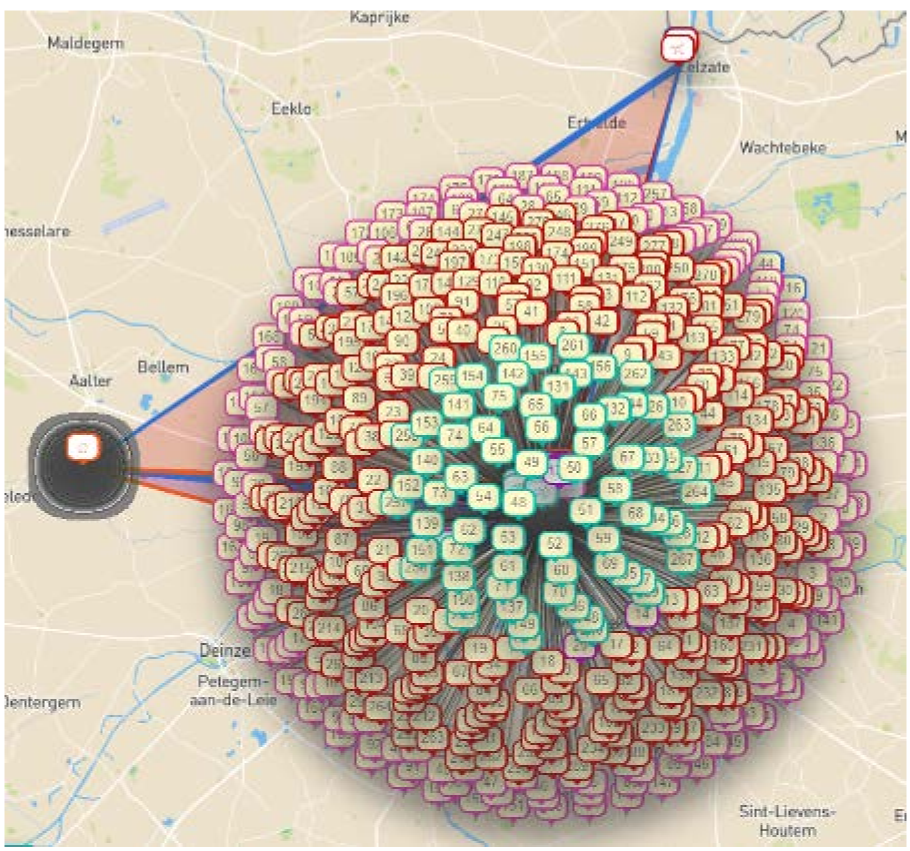

Figure 3.95: Possible routes for Ghent scenario 2.1.2

Scenario 2.1.3 is for Zone East, with results in Figures 3.96 and 3.97.

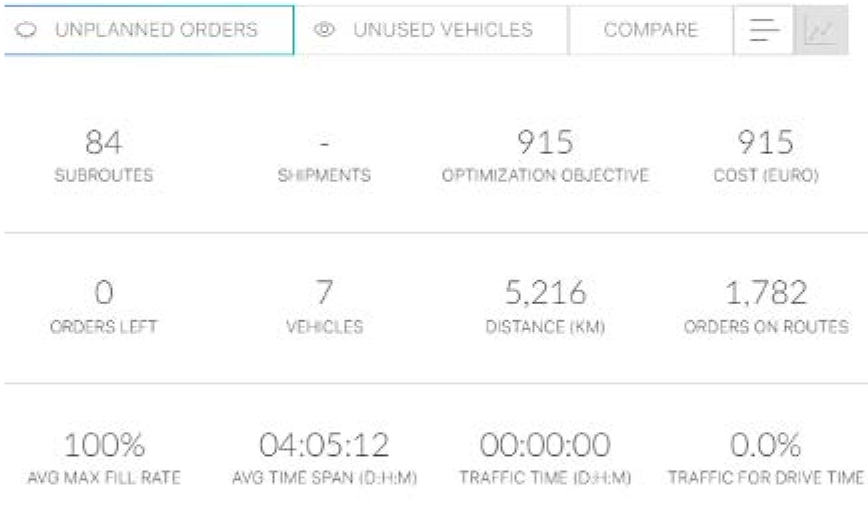

Figure 3.96: Results for Ghent scenario 2.1.3

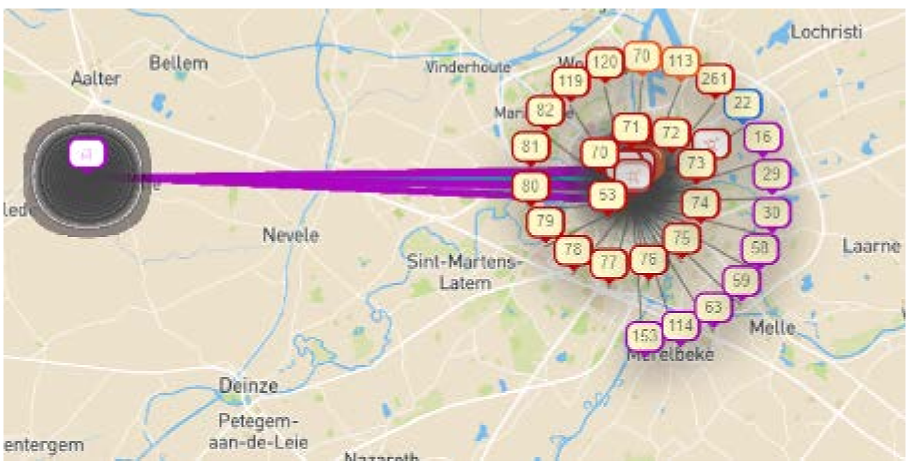

Figure 3.97: Possible routes for Ghent scenario 2.1.3

Scenario 2.2.1 is for Zone Centre, with results in Figures 3.98 and 3.99. There are 18 companies' waste that do not fit on any vehicle because the vehicle's capacity (10.7m3) is less than the amount of the company's waste.

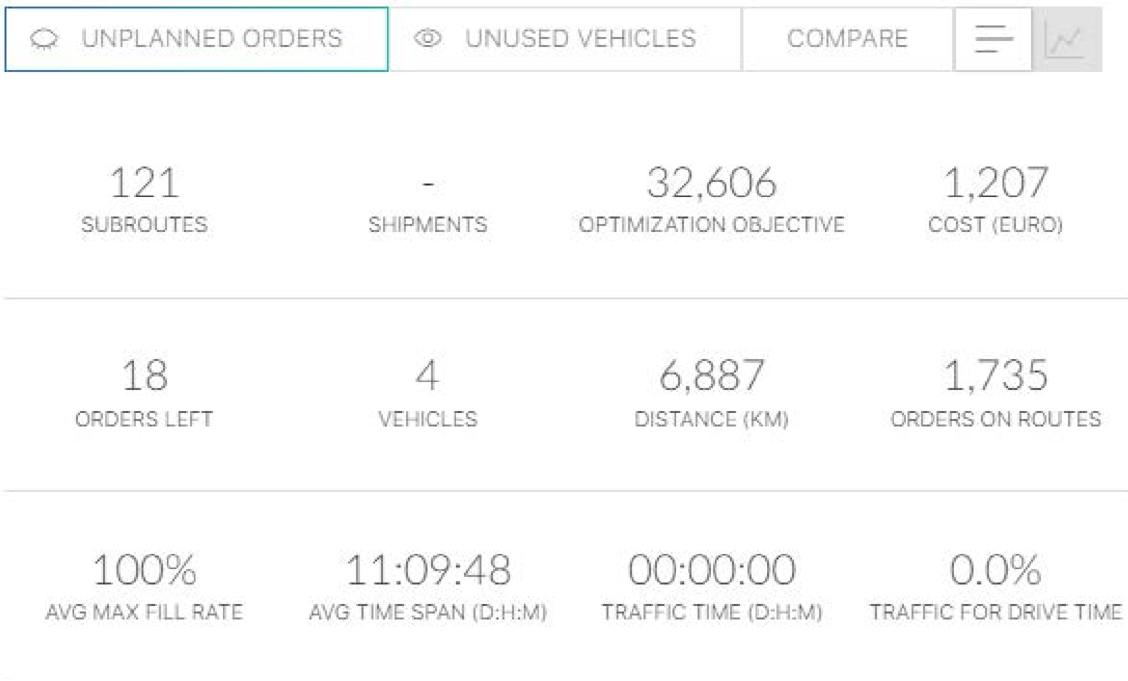

Figure 3.98: Results for Ghent scenario 2.2.1

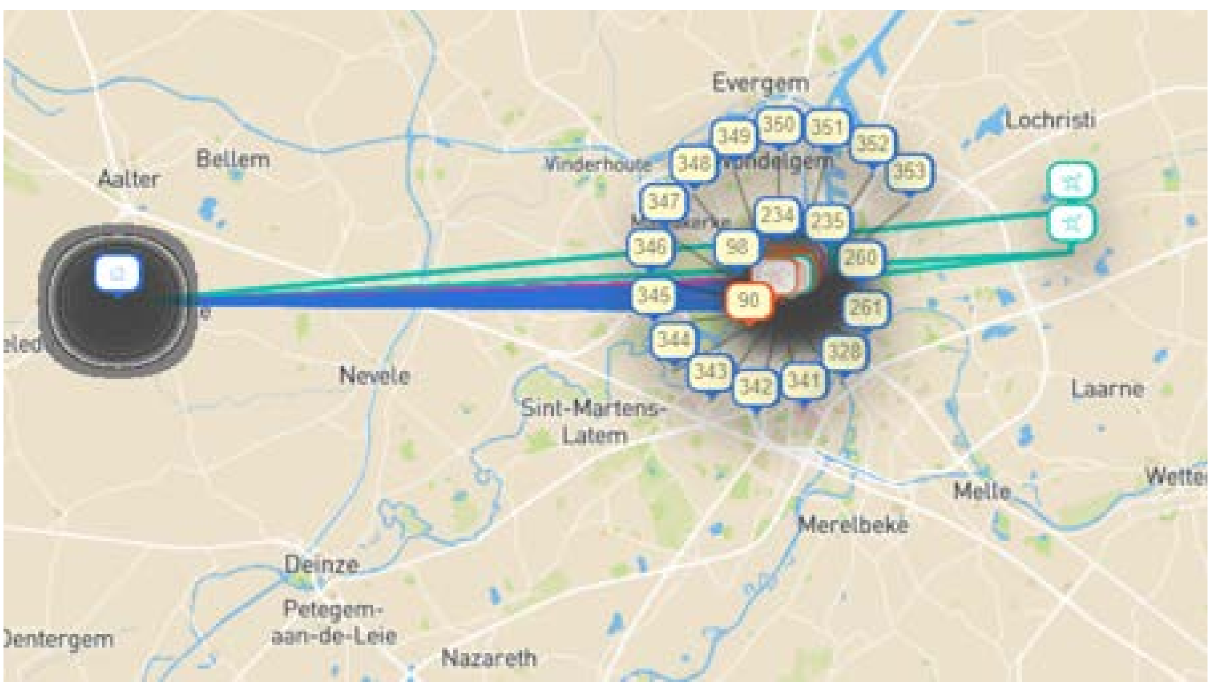

Figure 3.99: Possible routes for Ghent scenario 2.2.1

Scenario 2.2.2 is for Zone South, with results in Figures 3.100 and 3/101. There are 46 companies' waste that do not fit on any vehicle because the vehicle's capacity (10.7m3) is less than the amount of the company's waste.

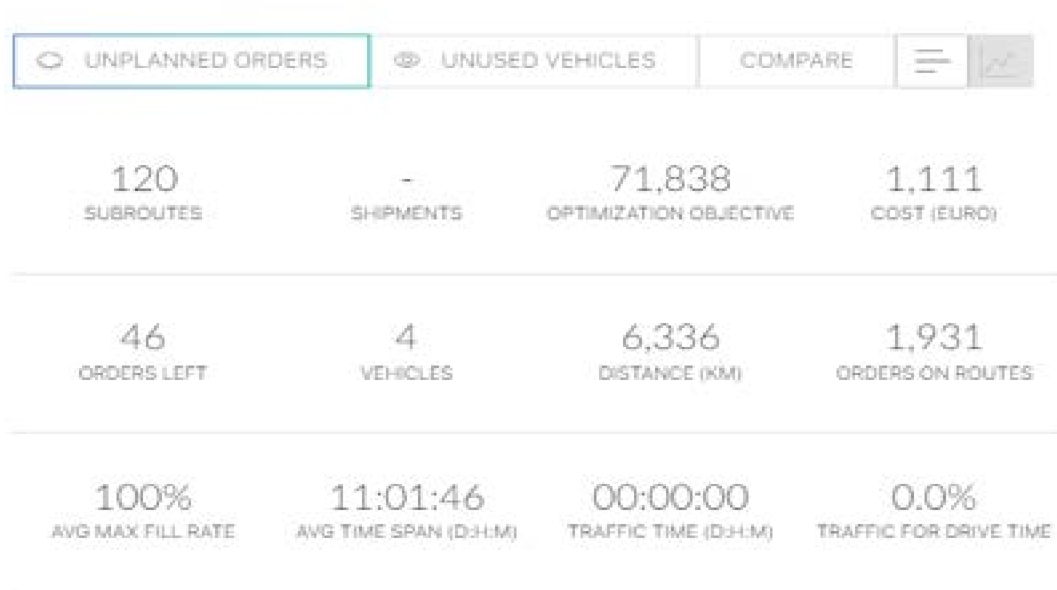

Figure 3.100: Results for Ghent scenario 2.2.2

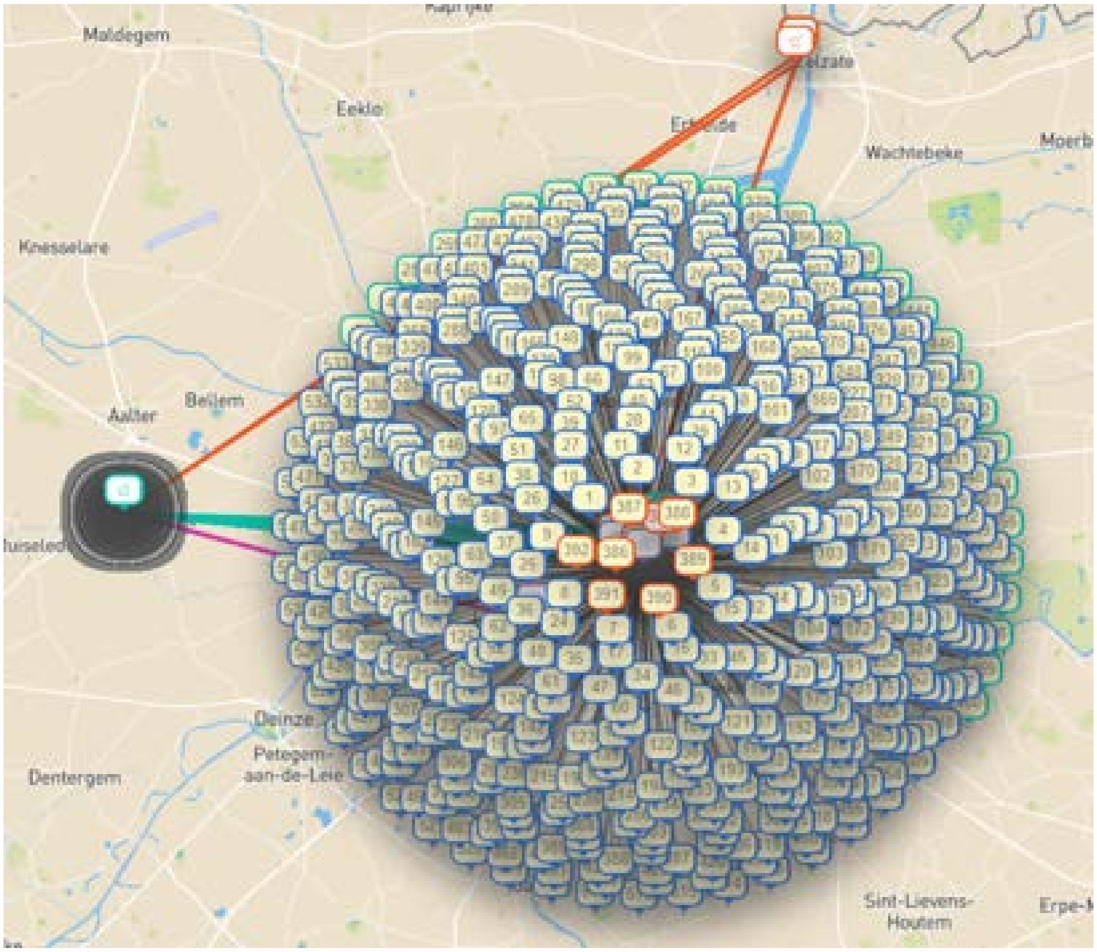

Figure 3.101: Possible routes for Ghent scenario 2.2.2

Scenario 2.2.3 is for Zone East, with results in Figures 3.102 and 3.103. There are 23 companies' waste that do not fit on any vehicle because the vehicle's capacity (10.7m3) is less than the amount of the company's waste.

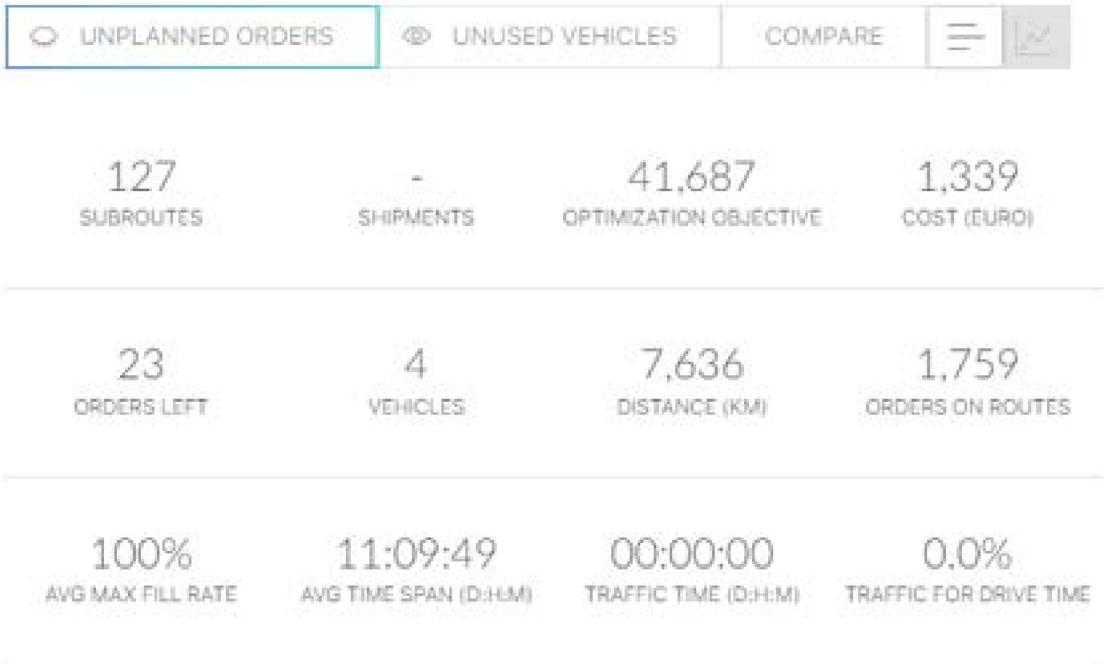

Figure 3.102I: Results for Ghent scenario 2.2.3

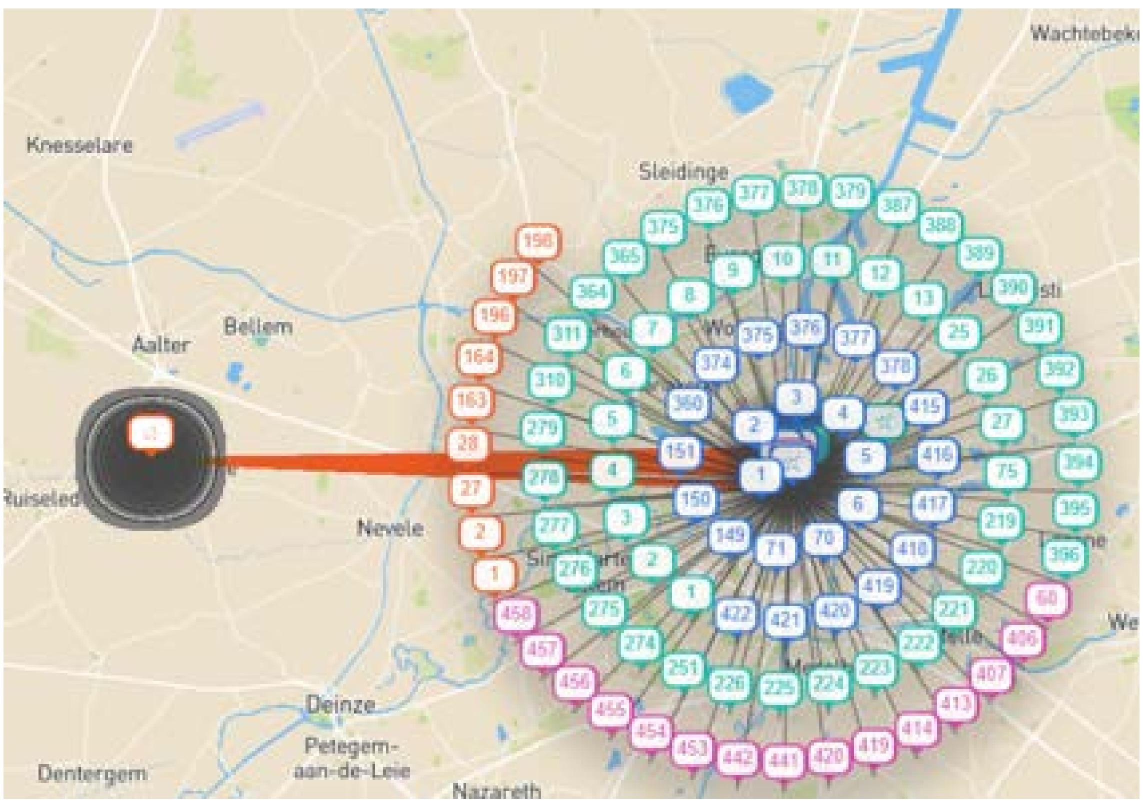

Figure 3.103: Possible routes for Ghent scenario 2.2.3

Scenario 2.3.1 is for Zone Centre, with results in Figures 3.104 and 3.105. There are 51 companies' waste that do not fit on any vehicle because the vehicle's capacity (10.7m3) is less than the amount of the company's waste.

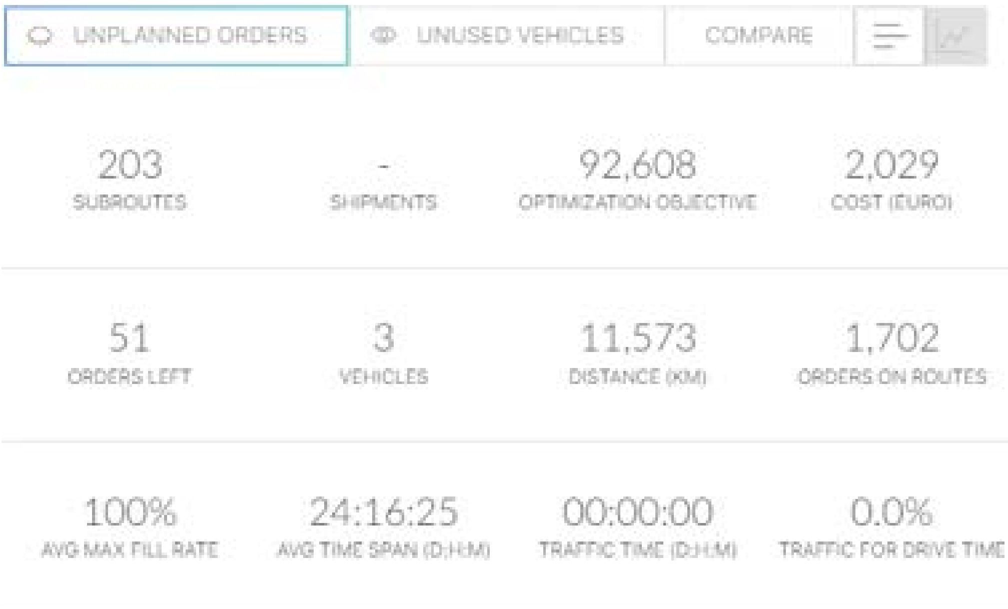

Figure 3.104: Results for Ghent scenario 2.3.1

Figure 3.105: Possible routes for Ghent scenario 2.3.1

Scenario 2.3.2 is for Zone South, with results in Figures 3.106 and 3.107. There are 99 companies' waste that do not fit on any vehicle because the vehicle's capacity (10.7m3) is less than the amount of the company's waste.

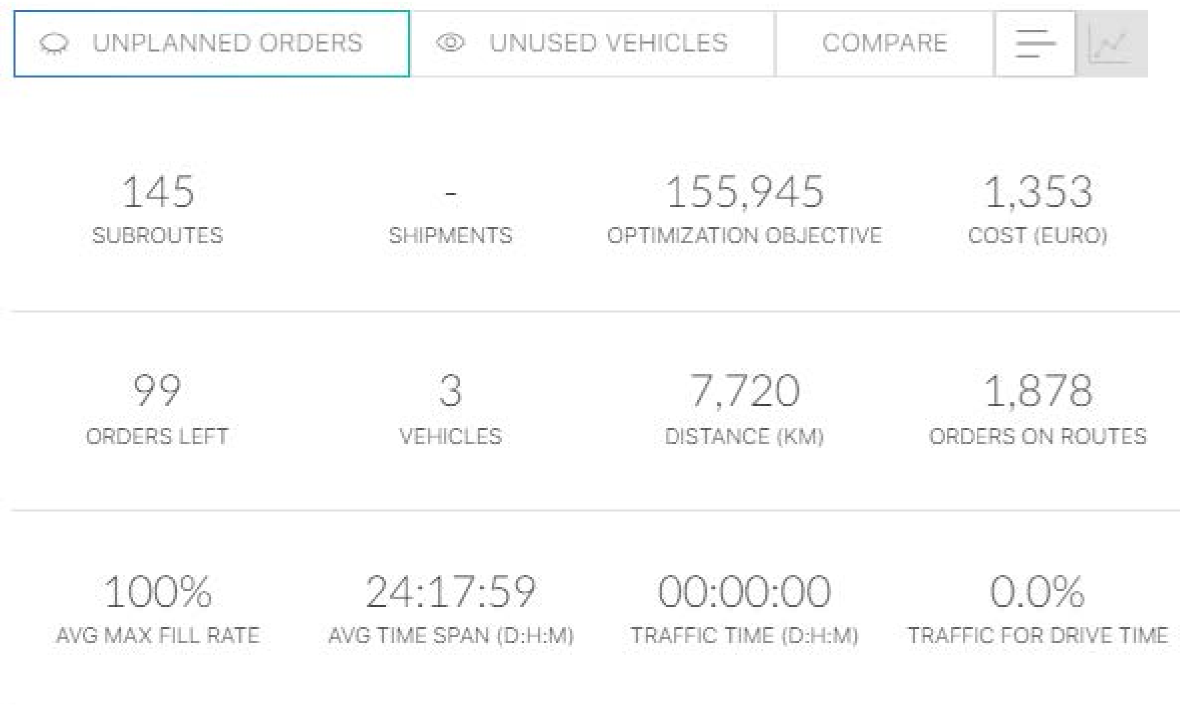

Figure 3.106: Results for Ghent scenario 2.3.2

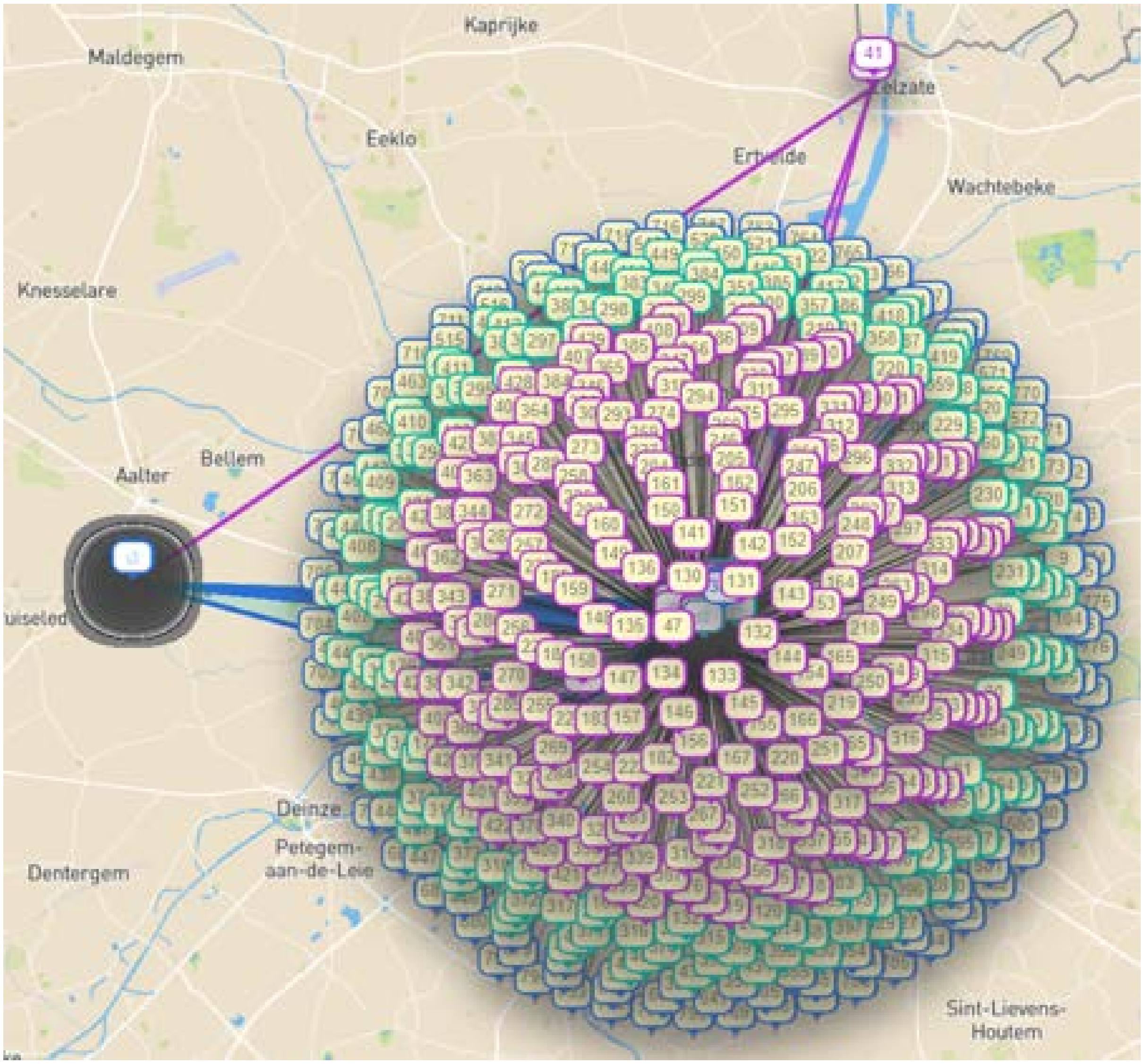

Figure 3.107: Possible routes for Ghent scenario 2.3.2

Scenario 2.3.3 is for Zone East, with results in Figures 3.108 and 3.109. There are 49 companies' waste that do not fit on any vehicle because the vehicle's capacity (10.7m3) is less than the amount of the company's waste.

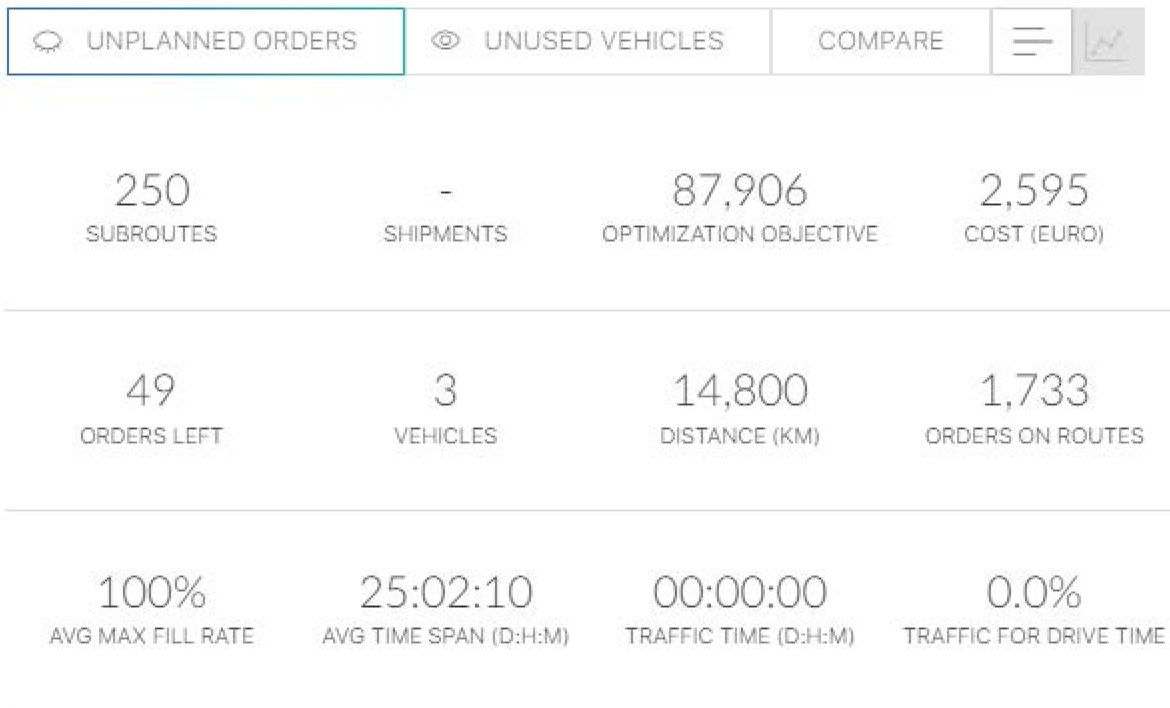

Figure 3.108r: Results for Ghent scenario 2.3.3

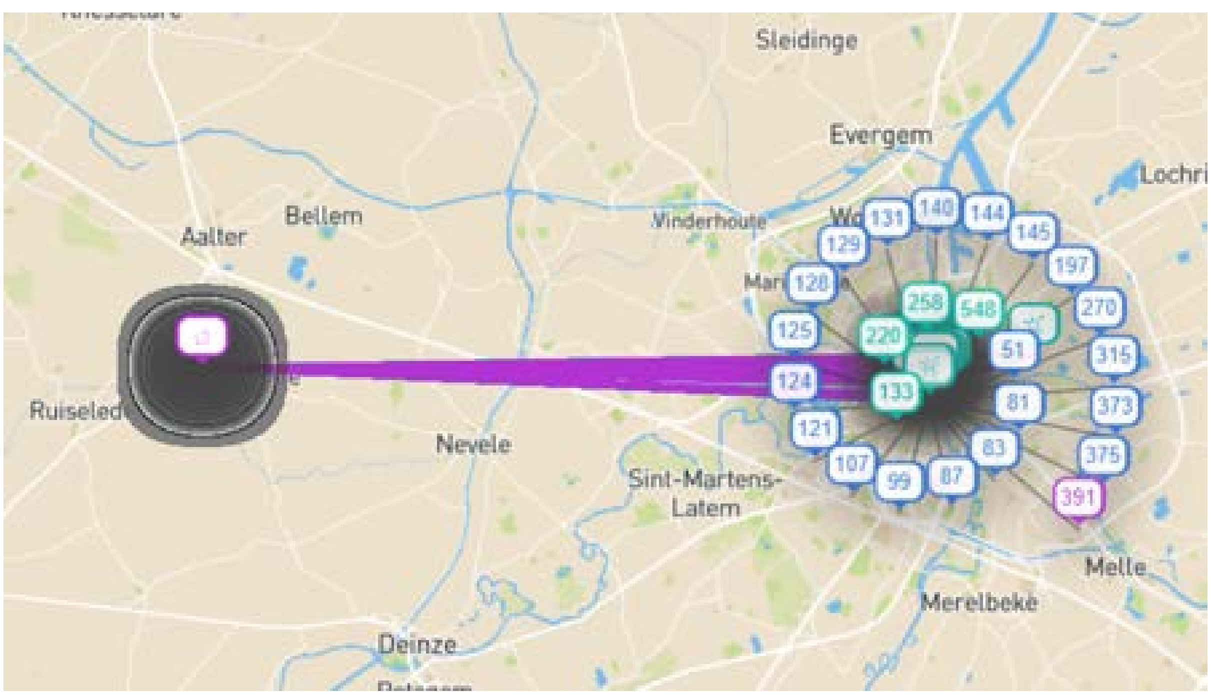

Figure 3.109: Possible routes for Ghent scenario 2.3.3

Comparison of zones in Scenario 2

As shown in Tables 3.31-3.33-6, in Scenario 2, scenarios 2.1.1, 2.1.2, and 2.1.3 are the most expensive for each zone. Scenarios 2.3.1, 2.3.2, and 2.3.3 are the most recommended scenarios (3 electric vans), which collect waste monthly with the lowest cost and shortest routes.

Table 3.31: Weekly collections for Ghent scenario 2

Collect weekly	**Zone Centre**	**Zone South**	**Zone East**
Scenario	**2.1.1**	**2.1.2**	**2.1.3**
Total number of stops	1,753	1,977	1,782
Number of collections per year	52	52	52
Number of vehicles	7	7	7
Cost per km (operational cost)	€ 744	€ 909	€ 915
Cost per hour (labour cost)	€ 19.5	€ 19.5	€ 19.5
Working hours required per week	50	46	50
Utilisation rate	100%	92%	100%
Cost per week	€ 7,569	€ 7,188	€ 7,740
Cost year	€ 393,588	€ 373,776	€ 402,480
Total distance per week	4,241 km	5,186 km	5,216 km
Total distance per year	220,532 km	269,672 km	271,232 km

Table 3.32: Fortnightly collections for Ghent scenario 2

Collect per fortnight	**Zone Centre**	**Zone South**	**Zone East**
Scenario	**S2.2.1**	**S2.2.2.**	**S.2.2.3**
Total number of stops	1,753	1,977	1,782
Number of collections per year	26	26	26
Number of vehicles	4	4	4
Cost per km (operational cost)	€ 1,207	€ 1,111	€ 1,339
Cost per hour (labour cost)	€ 19.5	€ 19.5	€ 19.5
Working hours required per fortnight	100	92	100
Utilisation rate	100%	92%	100%
Cost per fortnight	€ 9,007	€ 8,287	€ 9,139
Cost per year	€ 234,182	€ 215,462	€ 237,614
Total distance per fortnight	6,887 km	6,336 km	7,636 km
Total distance per year	179,062 km	164,736 km	198,536 km
The number of companies' waste cannot fit on any vehicle	18	46	23
Average stops per hour for four vehicles	(1753-18)/100 =17.35	(1977-46)/92 =20.99	(1782-23)/100 =17.95
Average stops per hour for each vehicle	4.34	5.25	4.49

Table 3.33: Monthly collections for Ghent scenario 2

Collect Monthly	Zone Centre	Zone South	Zone East
Scenario	**2.3.1**	**2.3.2**	**2.3.3**
Total number of stops	1,753	1,977	1,782
Number of collections per year	12	12	12
Number of vehicles	3	3	3
Cost per km (operational cost)	€ 2,029	€ 1,353	€ 2,595
Cost per hour (labour cost)	€ 19.5	€ 19.5	€ 19.5
Working hours required per month	190	190	193
Utilisation rate	86%	86%	88%
Cost per month	€ 13,144	€ 12,468	€ 13,886
Cost per year	€ 157,728	€ 149,616	€ 166,626
Total distance per month	11,573 km	7,720 km	14,800 km
Total distance per year	138,876 km	92,640 km	177,600 km
The number of companies' waste cannot fit on any vehicle	51	99	49
Average stops per hour for each vehicle	4.48	4.94	4.49

The fact that the (assumed) waste quantities cannot fit into the smaller vehicles at once needs to be discussed when deploying them. Possible solutions are:

- Call for a larger vehicle, especially in case of large items
- Revisit this business
- Collect more frequently
- Increase the loading volume of the CargoBike, potentially by adding a trailer
- Encourage the business to be a mini-hub where a larger container can be placed, hence also serving the neighbouring businesses

Scenario 3

This is an innercity milk-run by CargoBike to the respective mini-hub for each zone, suitable for onward transport by road or tramway. In Scenario 2.1, Zones Centre and South have 7 vehicles each to collect waste weekly (Monday to Friday), whereas zone East has 8. In scenario 3.2, there are 3 vehicles in each zone, and in Scenario 3.3, there are 2 each. The waste from zones Centre and East are taken to the mini-hub at Korenmarkt, whereas the plastics from zone South go to Sint Pietersstation.

Scenario 3.1.1 is for Zone Centre, with results in Figures 3.110 and 3.111. There are 130 companies' waste that do not fit on any vehicle because the vehicle's capacity (1.5 m3) is less than the amount of the company's waste.

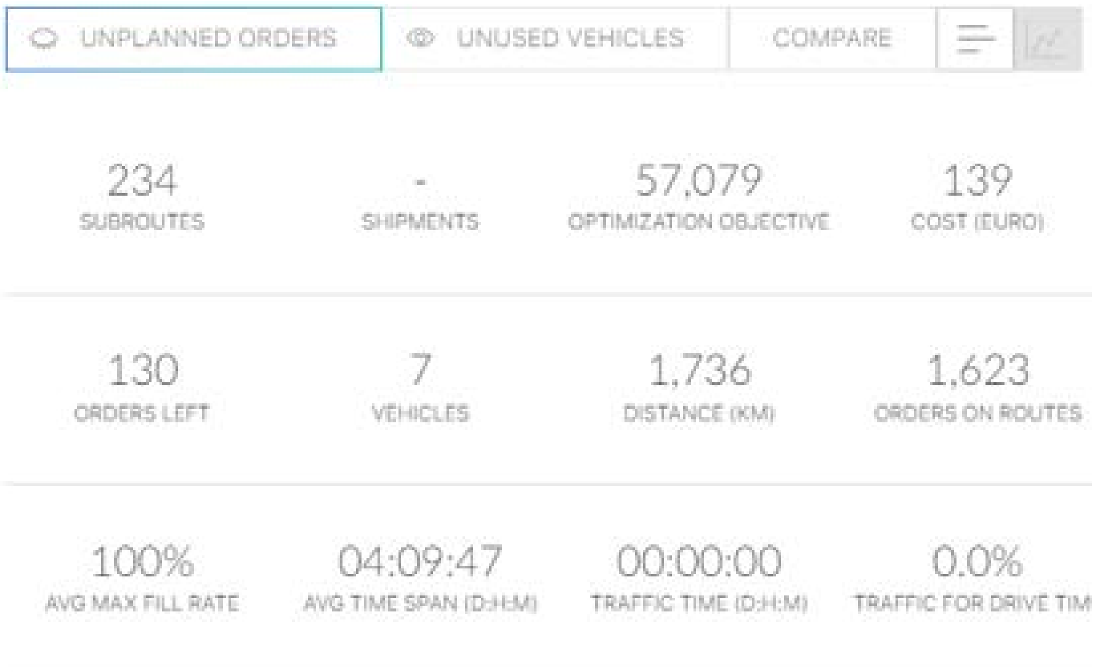

Figure 3.110: Results for Ghent scenario 3.1.1

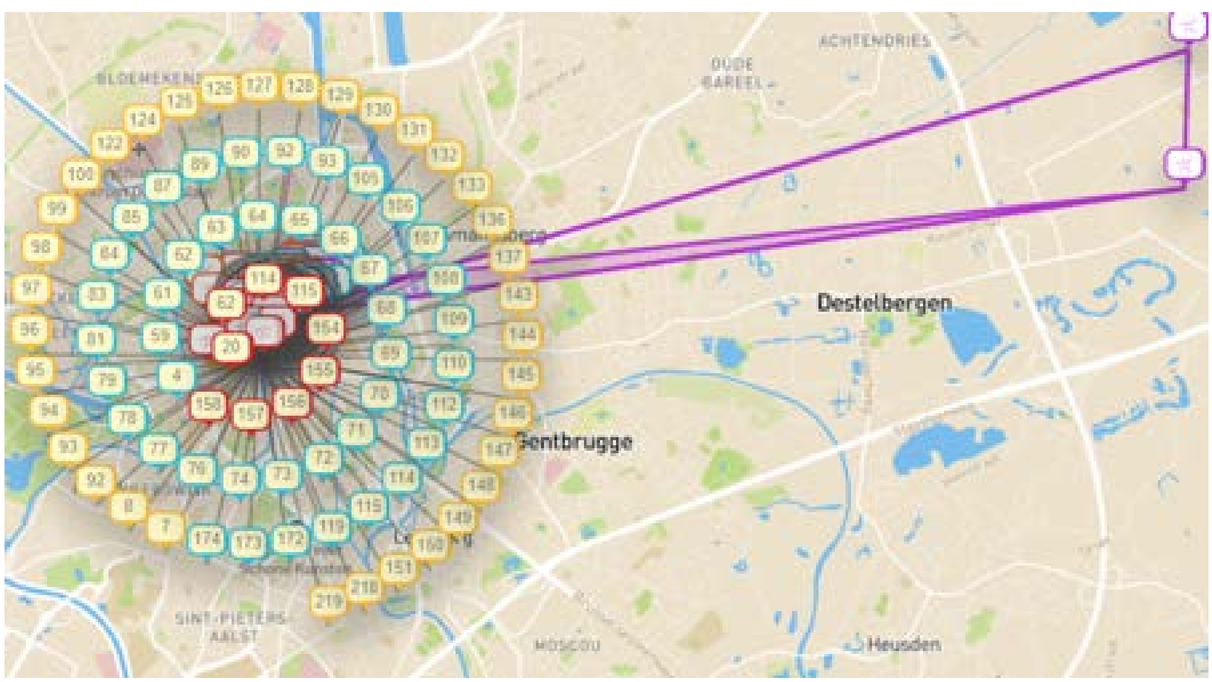

Figure 3.111: Possible routes for Ghent scenario 3.1.1

Scenario 3.1.2 is for Zone South, with results in Figures 3.112 and 3.113. There are 155 companies' waste that do not fit on any vehicle because the vehicle's capacity (1.5 m3) is less than the amount of the company's waste.

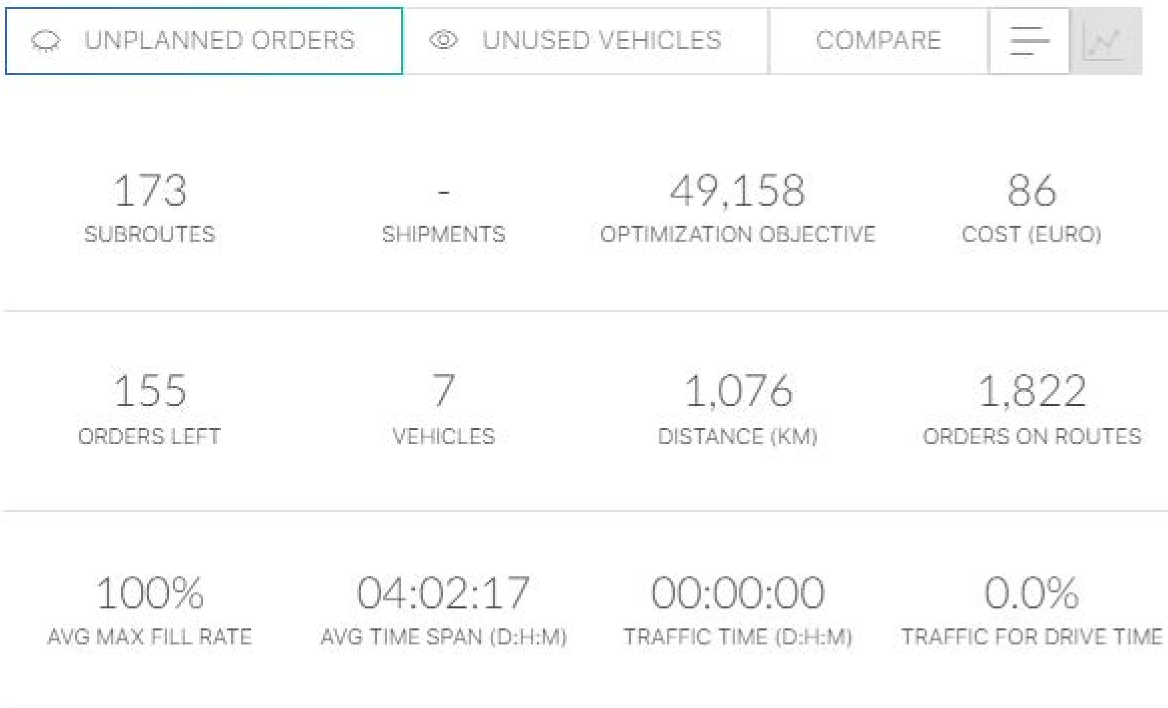

Figure 3.112: Results for Ghent scenario 3.1.2

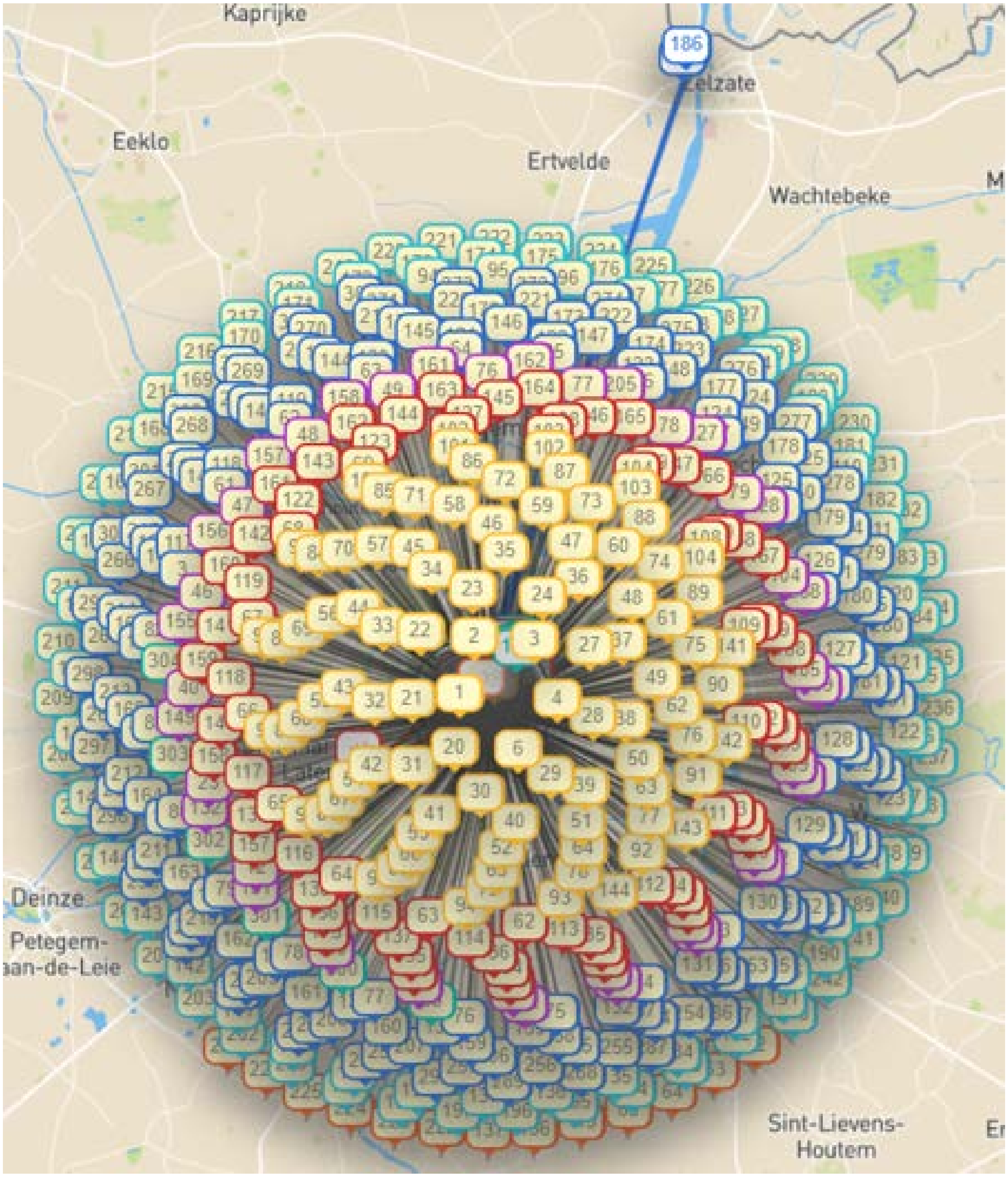

Figure 3.113: Possible routes for Ghent scenario 3.1.2

Scenario 3.1.3 is for Zone East, with results in Figures 3.114 and 3.115 There are 141 companies' waste that do not fit on any vehicle because the vehicle's capacity (1.5 m3) is less than the amount of the company's waste.

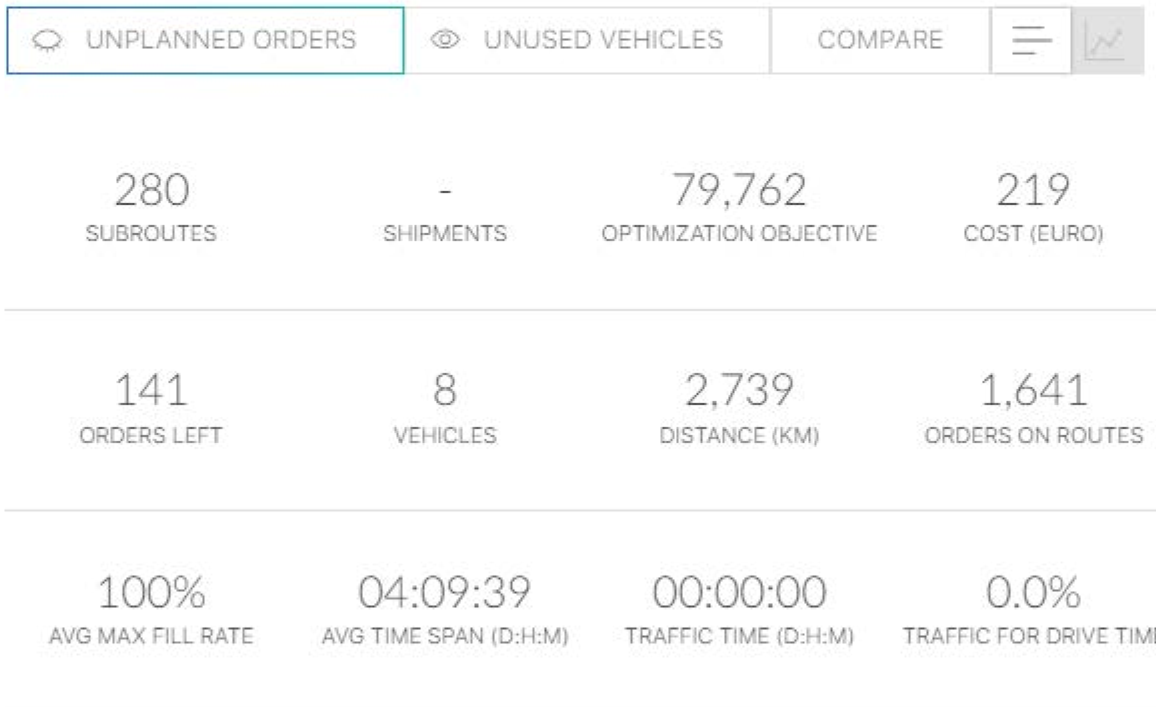

Figure 3.114: Results for Ghent scenario 3.1.3

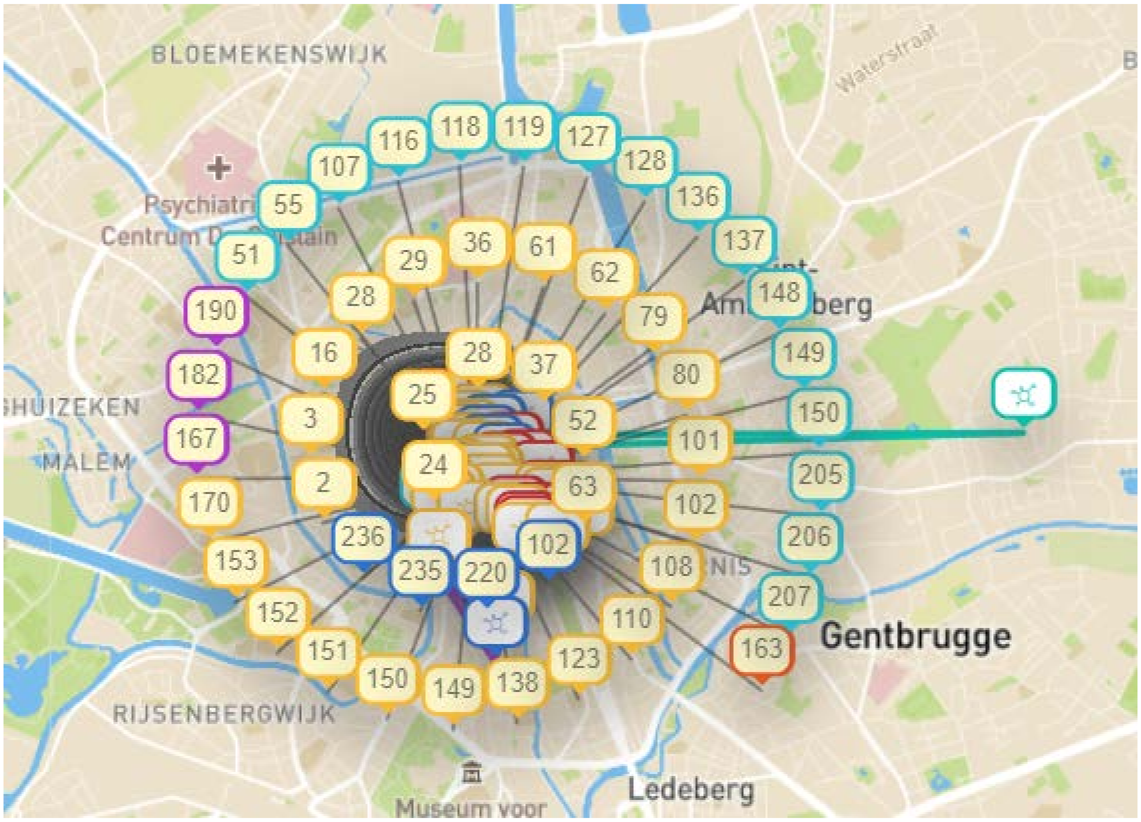

Figure 3.115: Possible routes for Ghent scenario 3.1.3

Scenario 3.2.1 is for Zone Centre, with results in Figures 3.116 and 3.117. There are 340 companies' waste that do not fit on any vehicle because the vehicle's capacity (1.5 m3) is less than the amount of the company's waste.

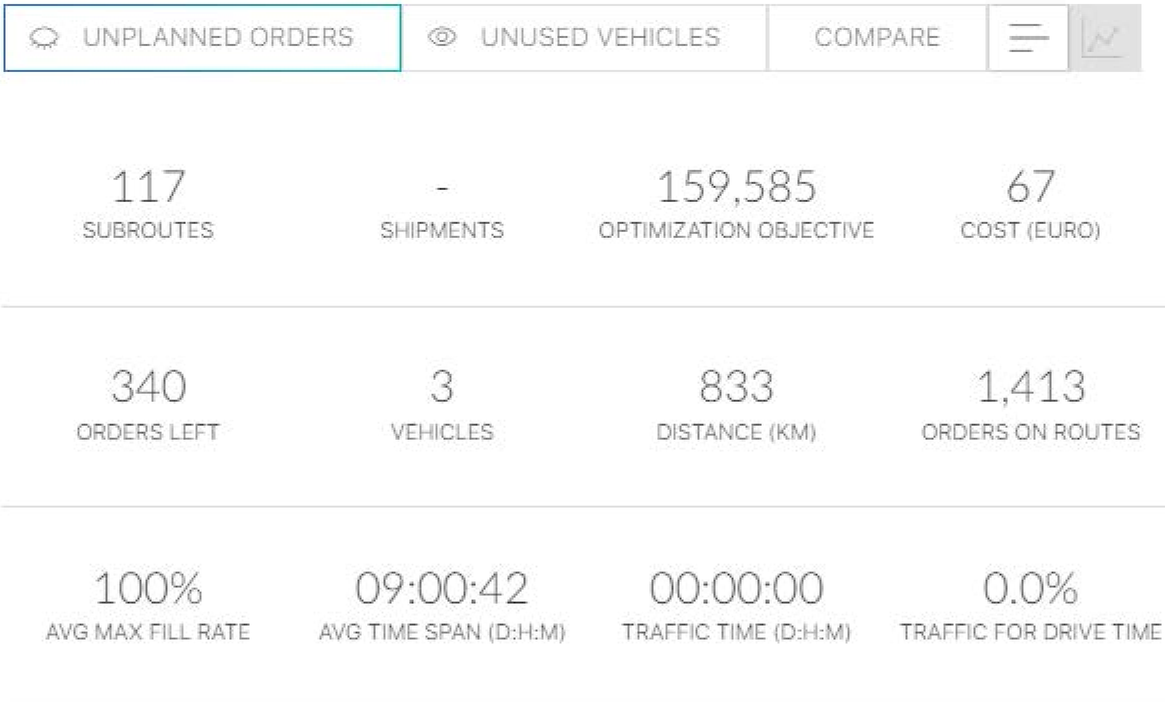

Figure 3.116: Results for Ghent scenario 3.2.1

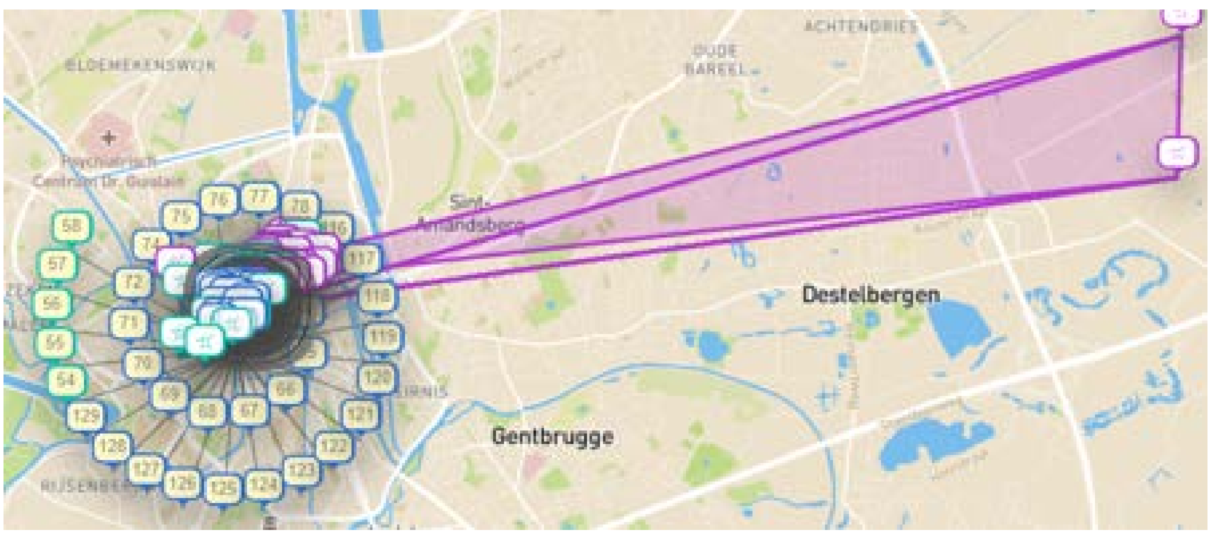

Figure 3.117: Possible routes for Ghent scenario 3.2.1

Scenario 3.2.2 is for Zone South, with results in Figures 3.118 and 3.119. There are 298 companies' waste that do not fit on any vehicle because the vehicle's capacity (1.5 m3) is less than the amount of the company's waste.

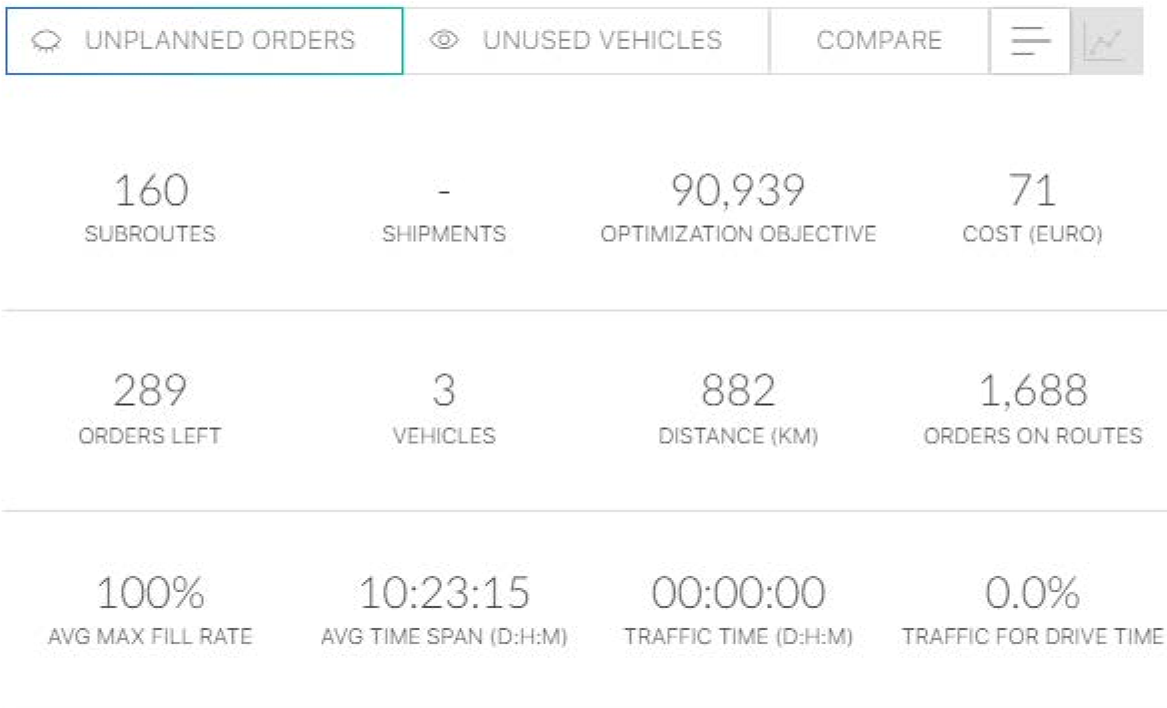

Figure 3.118: Results for Ghent scenario 3.2.2

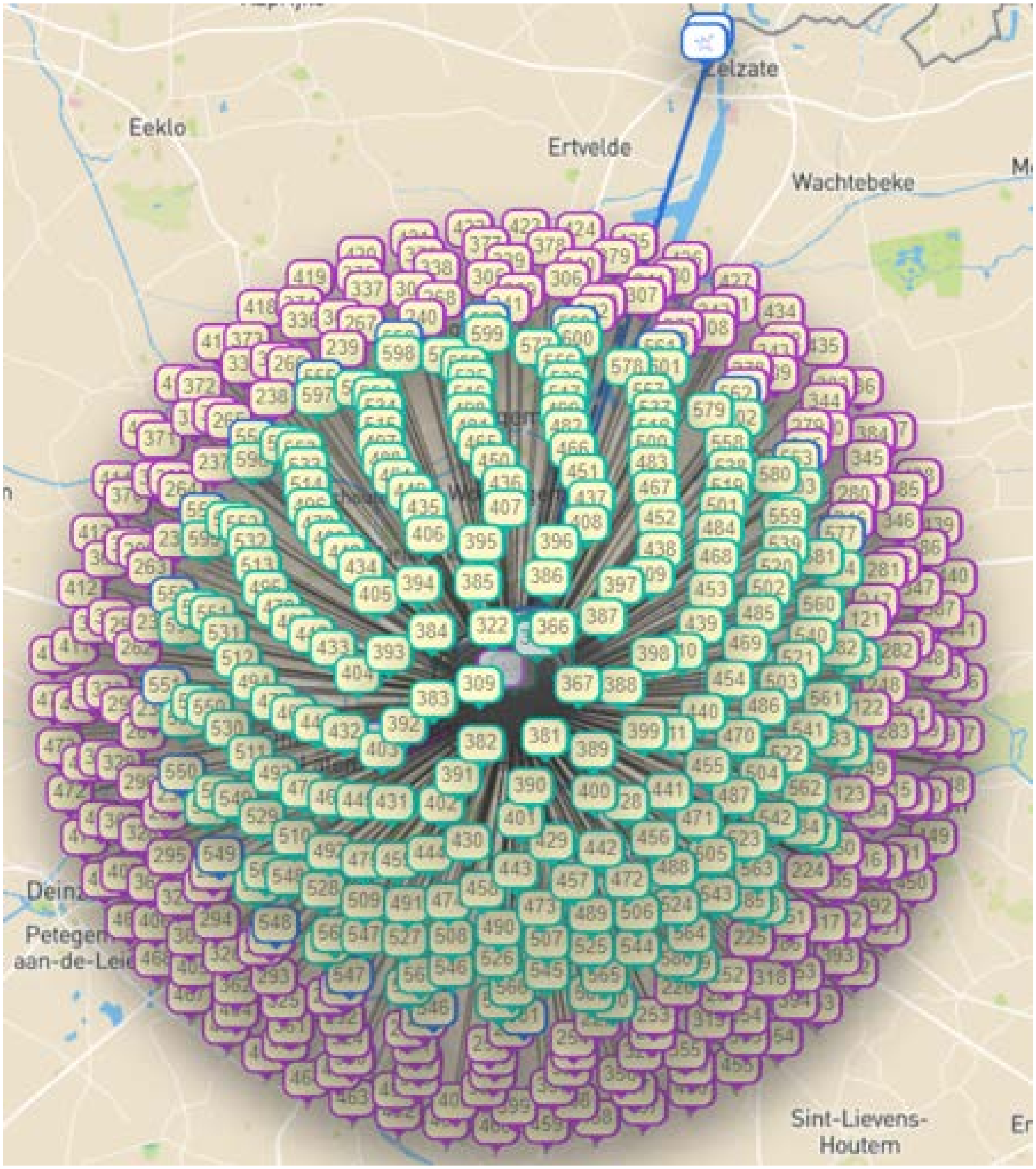

Figure 3.119: Possible routes for Ghent scenario 3.2.2

Scenario 3.2.3 is for Zone East, with results in Figures 3.120 and 3.121. There are 404 companies' waste that do not fit on any vehicle because the vehicle's capacity (1.5 m3) is less than the amount of the company's waste.

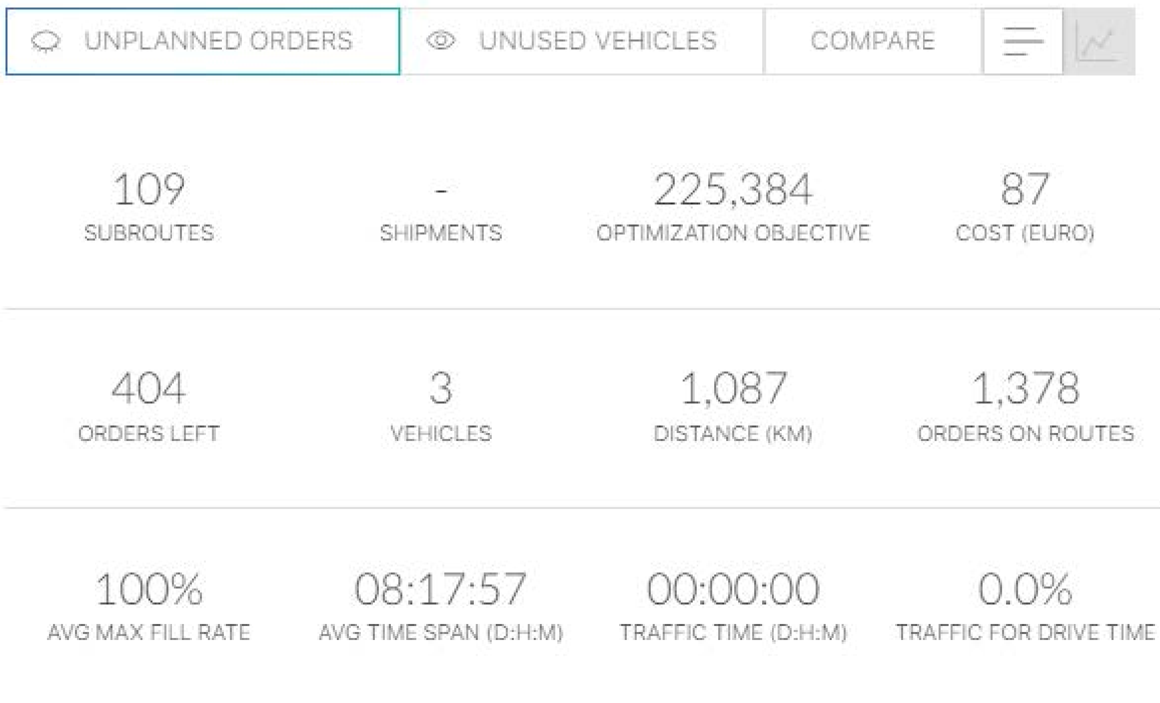

Figure 3.120: Results for Ghent scenario 3.2.3

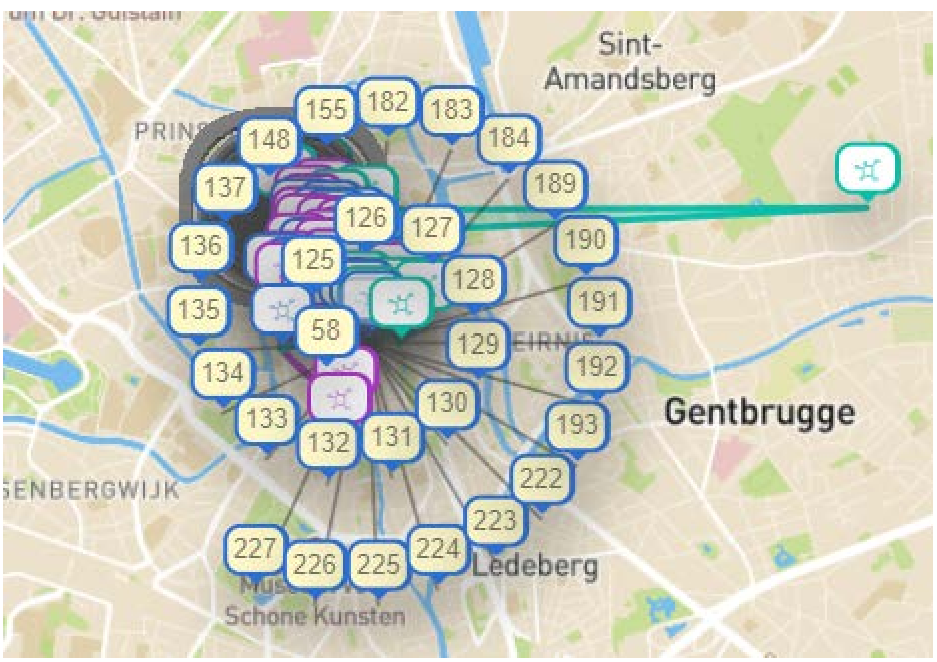

Figure 3.121: Possible routes for Ghent scenario 3.2.3

Scenario 3.3.1 is for Zone Centre, with results in Figures 3.122 and 3.123. There are 383 companies' waste that do not fit on any vehicle because the vehicle's capacity (1.5 m3) is less than the amount of the company's waste.

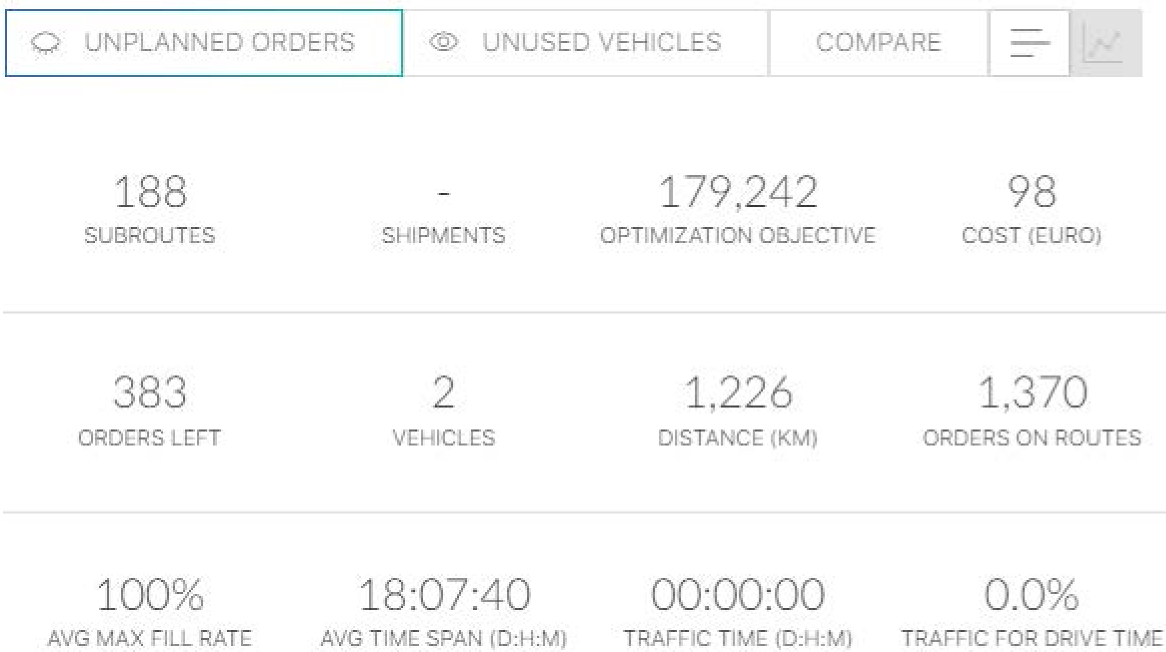

Figure 3.122: Results for Ghent scenario 3.3.1

Figure 3.123: Possible routes for Ghent scenario 3.3.1

Scenario 3.3.2 is for Zone South, with results in Figures 3.124 and 3.125. There are 378 companies' waste that do not fit on any vehicle because the vehicle's capacity (1.5 m3) is less than the amount of the company's waste.

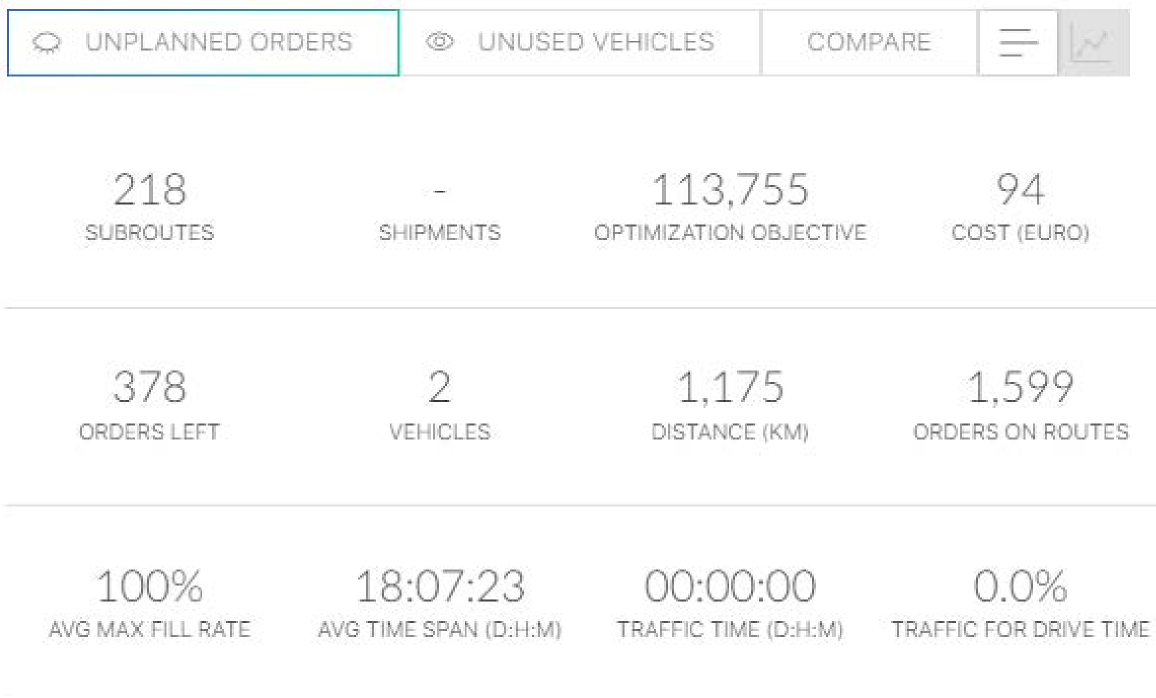

Figure 3.124: Results for Ghent scenario 3.3.2

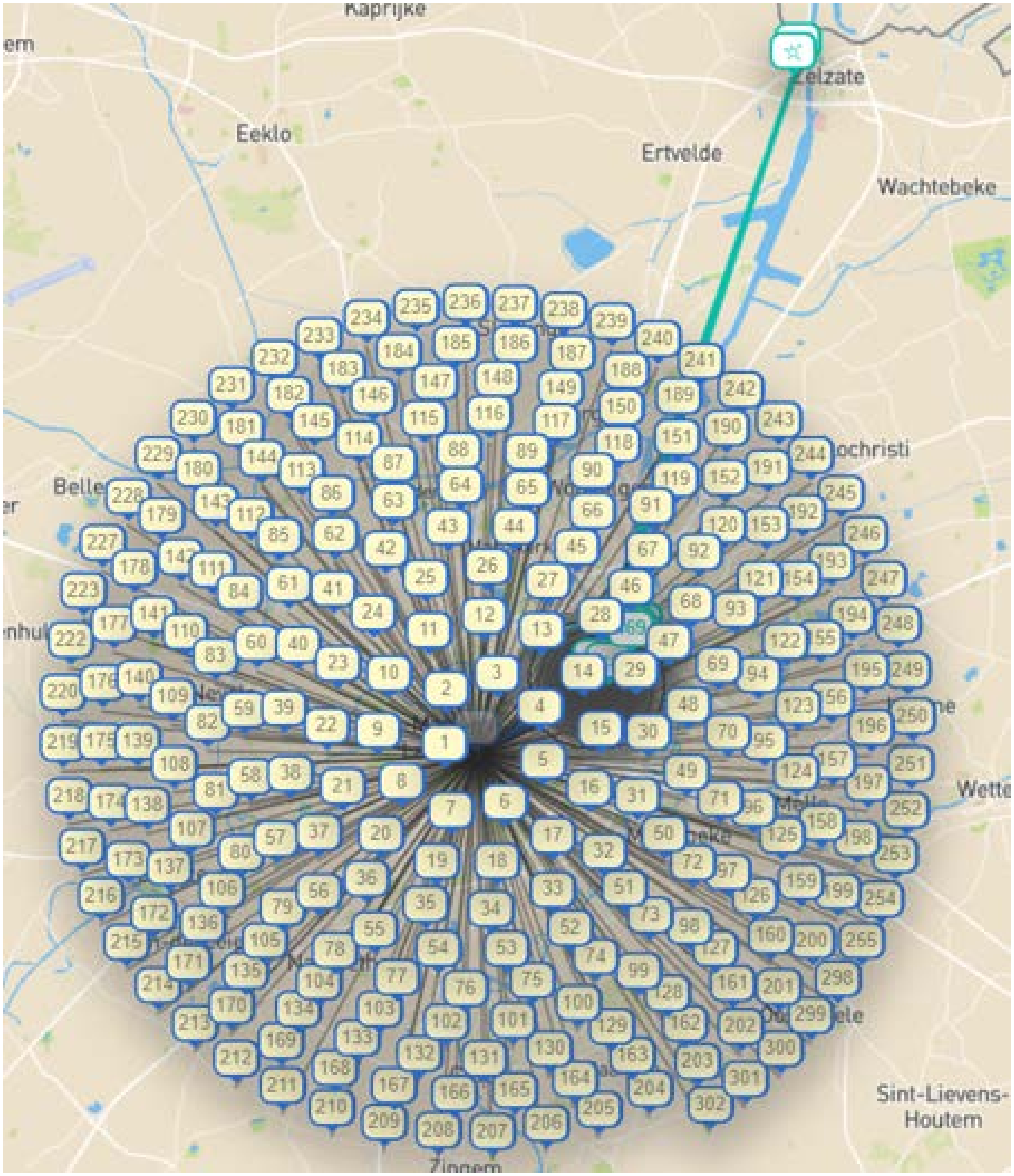

Figure 3.125: Possible routes for Ghent scenario 3.3.2

Scenario 3.3.3 is for Zone East, with results in Figures 3.126 and 3.127. There are 450 companies' waste that do not fit on any vehicle because the vehicle's capacity (1.5 m3) is less than the amount of the company's waste.

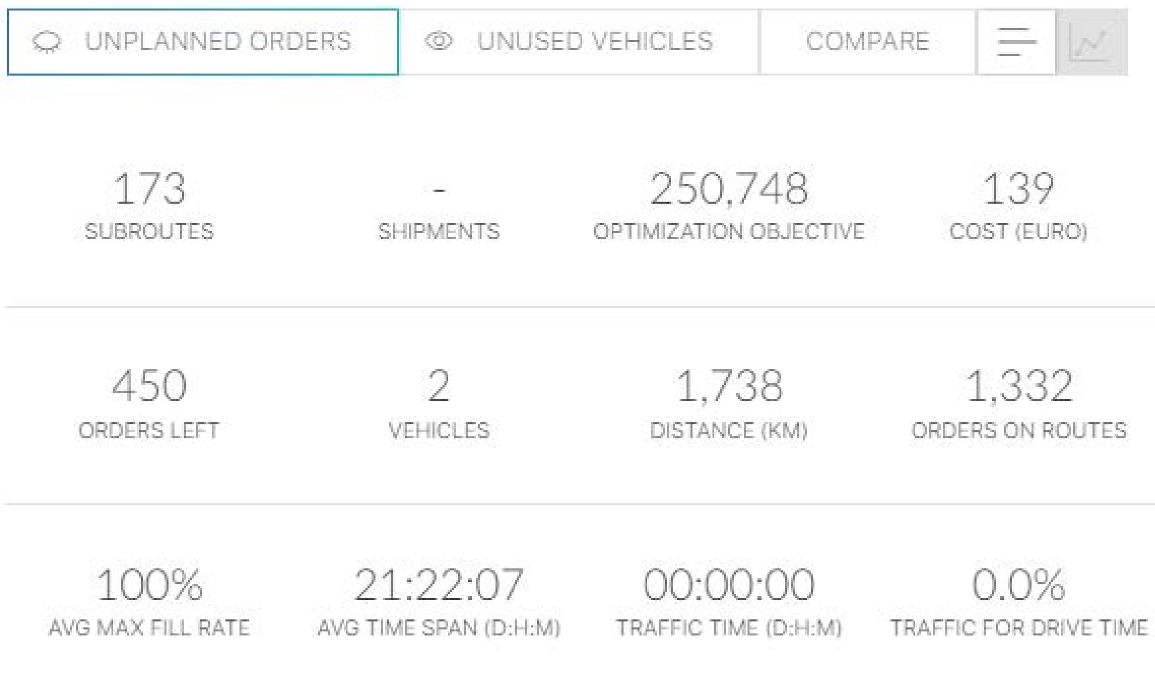

Figure 3.126: Results for Ghent scenario 3.3.3

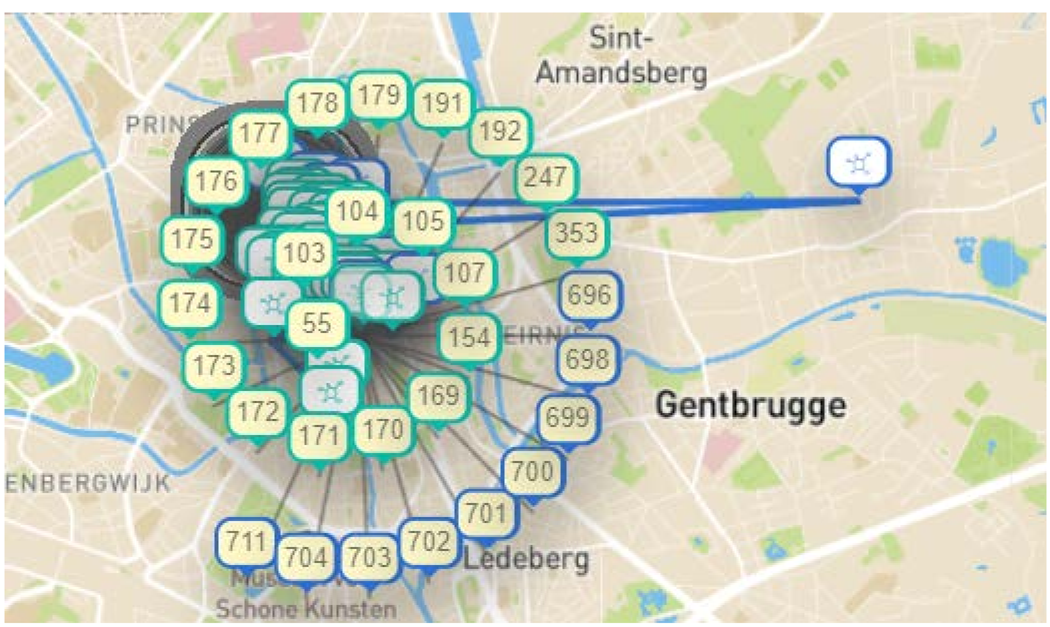

Figure 3.127: Possible routes for Ghent scenario 3.3.3

Comparison of zones in Scenario 3

In scenario 3, all the scenarios cannot collect all companies' plastic waste due to the CargoBike's capacity, as illustrated in Tables 3.34-3.36. So these scenarios are not recommended. Instead, we suggest using multiple types of vehicles (CargoBike and lorry or van) to collect the waste. CargoBikes would drop waste off at mini-hubs, whereas the other vehicles would drop the larger quantities directly at Farmanstraat.

Table 3.34: Weekly collections for Ghent scenario 3

Collect weekly	Zone Centre	Zone South	Zone East
Scenario	3.1.1	3.1.2	3.1.3
Total number of stops	1,753	1,977	1,782
Number of collections per year	52	52	52
Number of vehicles	7	7	8
Cost per km (operational cost)	€ 139	€ 86	€ 219
Cost per hour (labour cost)	€ 26	€ 26	€ 26
Working hours required per week	50	43	50
Utilisation rate	100%	86%	100%
Cost per week	€ 9,239	€ 7,912	€ 10,619
Cost per year	€ 480,428	€ 411,424	€ 552,188
Total distance per week	1,623 km	1,076 km	2,739 km
Total distance per year	84,396 km	55,952 km	142,428 km
The number of companies' waste cannot fit on any vehicle	130	155	141

Table 3.35: Fortnightly collections for Ghent scenario 3

Collect fortnightly	Zone Centre	Zone South	Zone East
Scenario	3.2.1	3.2.2	3.2.3
Total number of stops	1,753	1,977	1,782
Number of collections per year	26	26	26
Number of vehicles	3	3	3
Cost per km (operational cost)	€ 67	€ 71	€ 89
Cost per hour (labour cost)	€ 26	€ 26	€ 26
Working hours required per week	71	90	70
Utilisation rate	71%	90%	70%
Cost per fortnight	€ 5,605	€ 7,091	€ 5,549
Cost per year	€ 145,730	€ 184,366	€ 144,274
Total distance per fortnight	833	882	1,087
Total distance per year	21,658	22,932	28,262
The number of companies' waste cannot fit on any vehicle	340	289	404

Table 3.36: Monthly collections for Ghent scenario 3

Collect Monthly	**Zone Centre**	**Zone South**	**Zone East**
Scenario	**3.3.1**	**3.3.2**	**3.3.3**
Total number of stops	1,753	1,977	1,782
Number of collections per year	12	12	12
Number of vehicles	2	2	2
Cost per km (operational cost)	€ 98	€ 94	€ 139
Cost per hour (labour cost)	€ 26	€ 26	€ 26
Working hours required per week	168	148	180
Utilisation rate	76%	67%	82%
Cost per week	€ 8,834	€ 7,790	€ 9,499
Cost per year	€ 106,008	€ 93,480	€ 113,988
Total distance per week	1,226	1,175	1,738
Total distance per year	14,712	14,100	20,856
The number of companies' waste that cannot fit on any vehicle	**383**	**378**	**450**

Scenario 5

This is a mini-hub service to Farmanstraat by lorry (diesel or CNG) to empty the mini-hubs where waste was accumulated from milk-runs or by people dropping off their own waste. The service is executed weekly (Scenario 5.1), fortnightly (Scenario 5.2) or monthly (Scenario 5.3). We assume that the total waste of two min-hubs (Sint Pietersstation and Korenmarkt) is equal to the waste of three zones (Zone Centre, Zone South, and Zone East), as detailed in Table 3.37. Again, the working week is assumed to be Monday to Friday. First, collections are simulated with one lorry and then with two.

Table 3.37: The waste assumed to accumulated at the mini-hubs and the number of full 40m3 containers this generates

The volume of waste [m3] (and the number of containers)			
Mini-hubs	Weekly	Fortnightly	Monthly
Sint Pietersstation	959.9 (24)	1919.7 (48)	4159.4 (104)
Korenmarkt	1548.7 (39)	3097.3 (78)	6710.9 (168)
Total waste	2508.5 (63)	5017.0 (126)	10870.3 (272)

To fit the lorry capacity (40m3), we suggest collecting the waste once mini-hub's waste reaches 40m3, that is, when the container is full.

Scenario 5.1.1 is for weekly collections with one lorry. Results are shown in Figures 3.128 and 3.129.

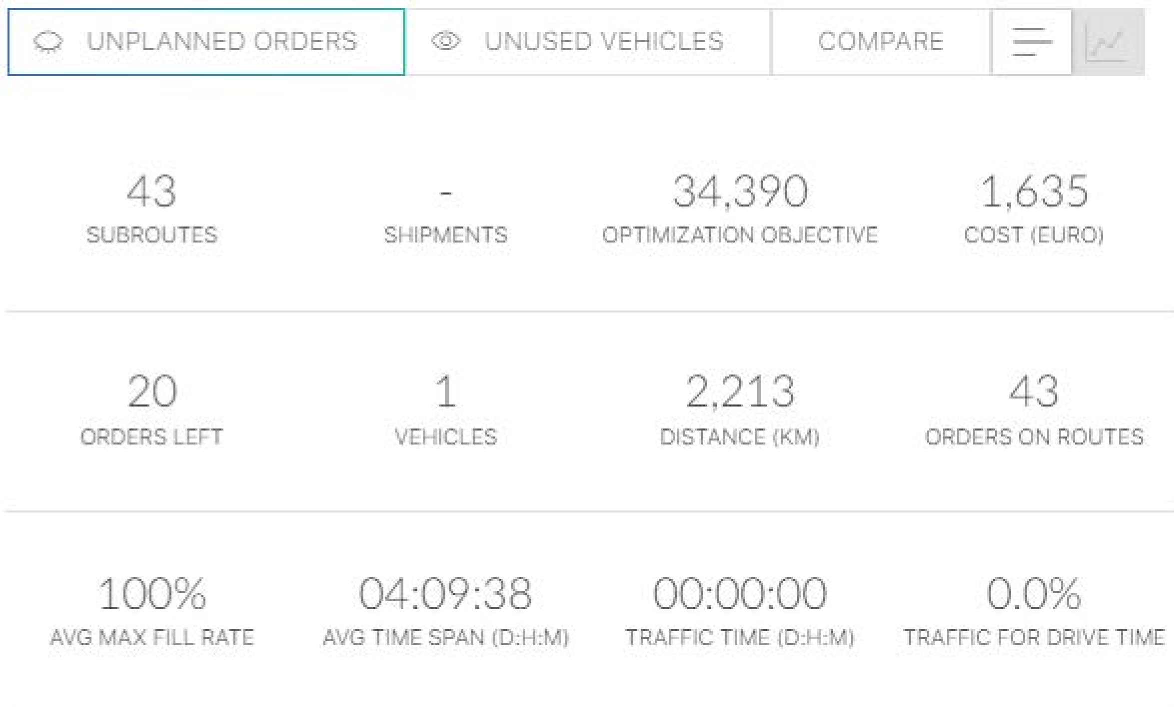

Figure 3.128: Results for Ghent scenario 5.1.1

Figure 3.129: Possible routes for Ghent scenario 5.1.1

Scenario 5.1.2 is for weekly collections with two lorries. Results are shown in Figures 3.130 and 3.131.

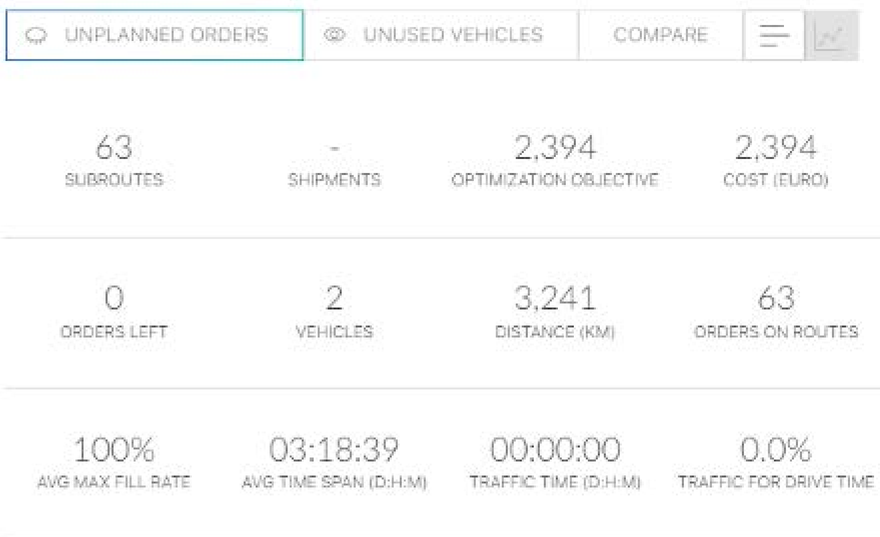

Figure 3.1230: Results for Ghent scenario 5.1.2

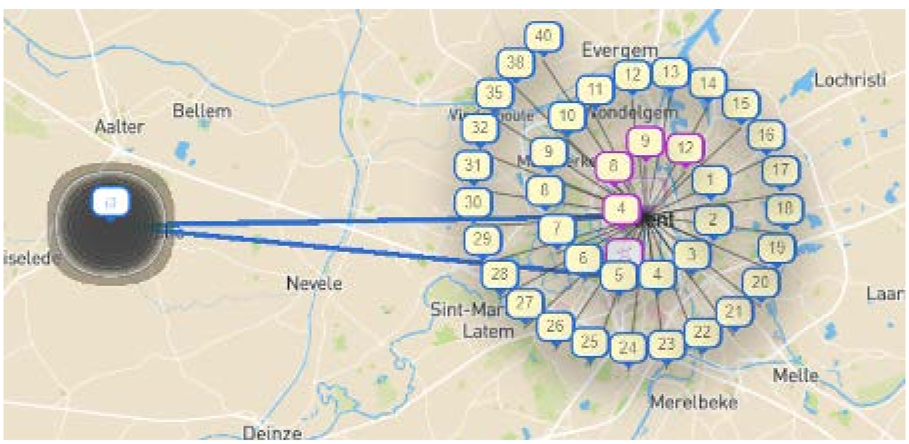

Figure 3.1231: Possible routes for Ghent scenario 5.1.2

Scenario 5.2.1 is for fortnightly collection using one vehicle, with results in Figures 3.132 and 3.133.

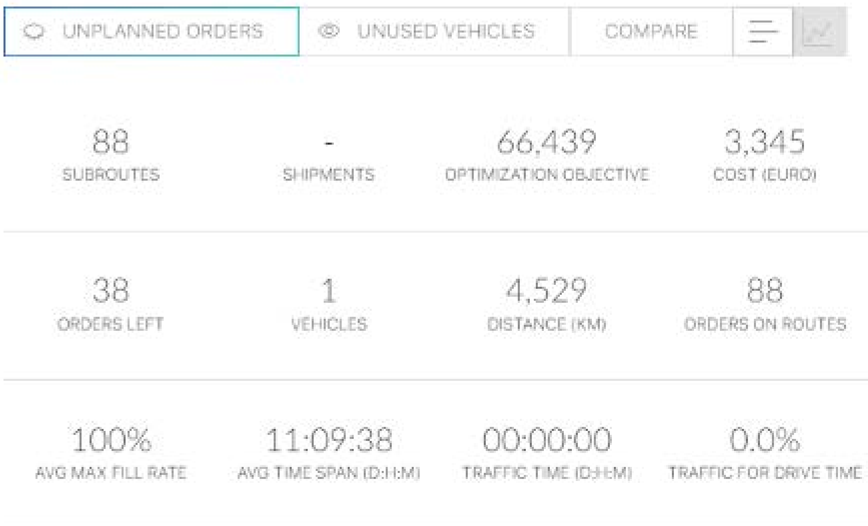

Figure 3.132: Results for Ghent scenario 5.2.1

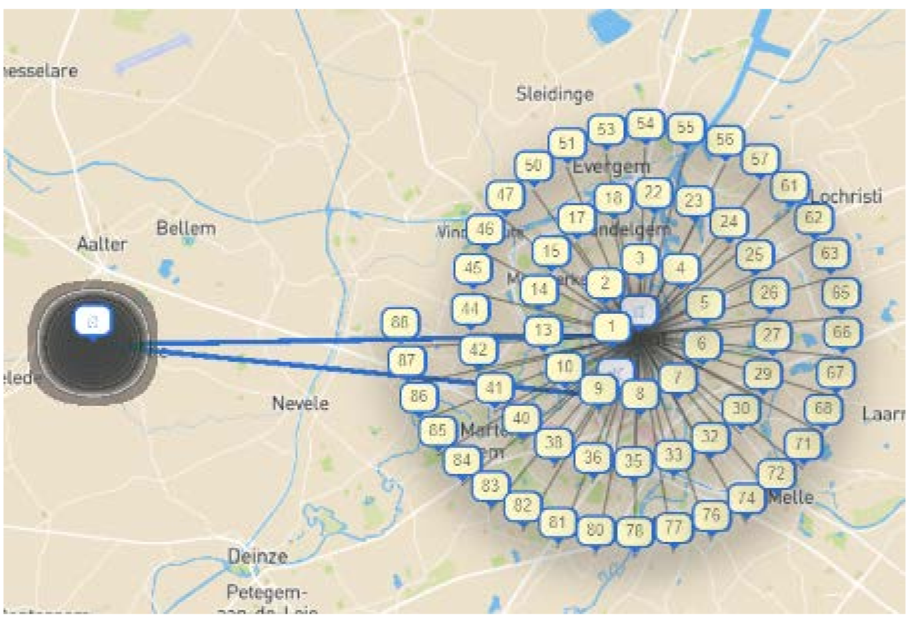

Figure 3.133: Possible routes for Ghent scenario 5.2.1

Scenario 5.2.2 is for fortnightly collections with two lorries. Results are shown in Figures 3.134 and 3.135.

126 SUBROUTES	- SHIPMENTS	4,788 OPTIMIZATION OBJECTIVE	4,788 COST (EURO)
0 ORDERS LEFT	2 VEHICLES	6,483 DISTANCE (KM)	126 ORDERS ON ROUTES
100% AVG MAX FILL RATE	09:16:55 AVG TIME SPAN (D:H:M)	00:00:00 TRAFFIC TIME (D:H:M)	0.0% TRAFFIC FOR DRIVE TIME

Figure 3.134: Results for Ghent scenario 5.2.2

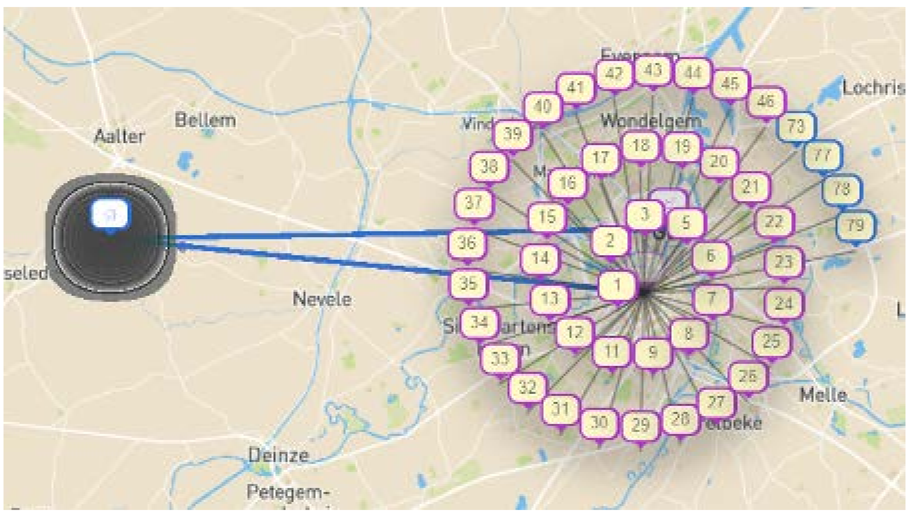

Figure 3.135: Possible routes for Ghent scenario 5.2.2

Scenario 5.3.1 is for monthly collection using one lorry, with results in Figures 3.136 and 3.137.

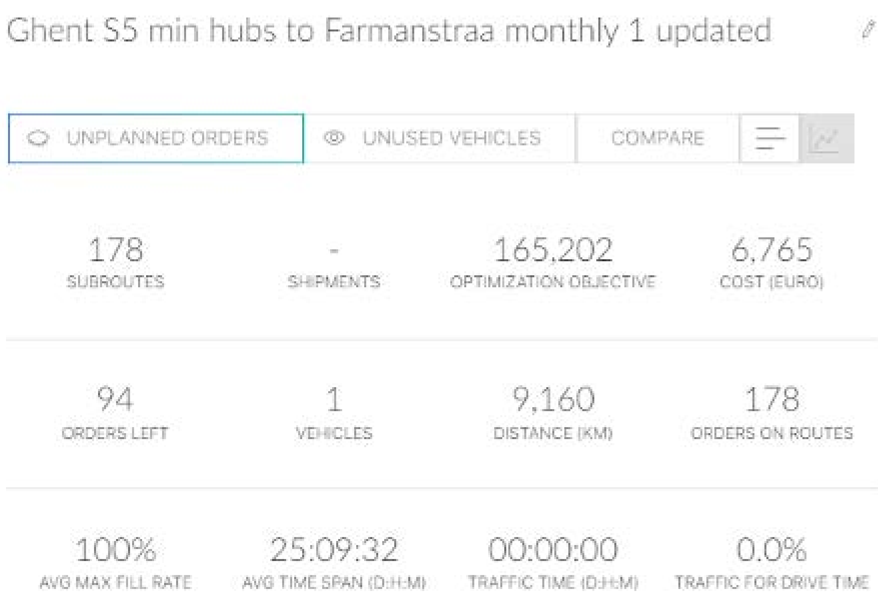

Figure 3.136: Results for Ghent scenario 5.3.1

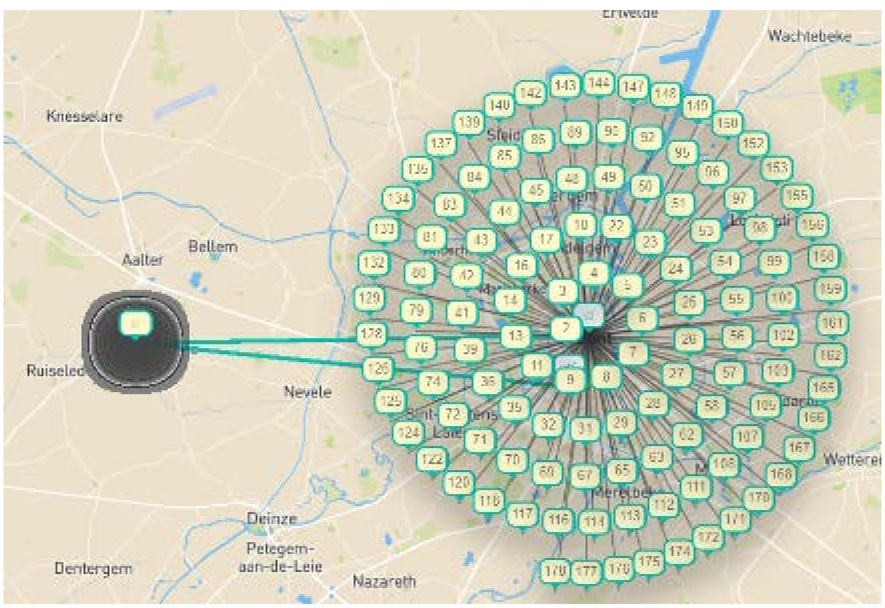

Figure 3.137: Possible routes for Ghent scenario 5.3.1

Scenario 5.3.2 is for monthly collection using one lorry, with results in Figures 3.138 and 3.139.

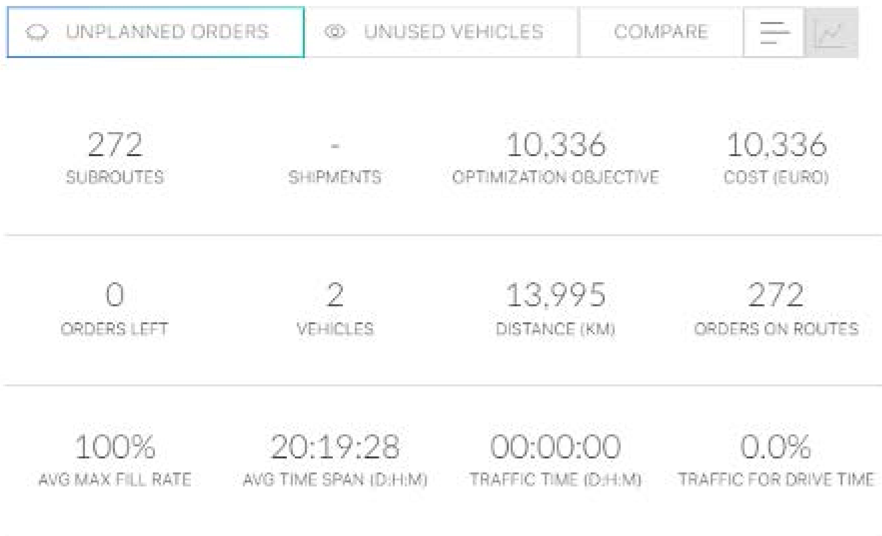

Figure 3.138: Results for Ghent scenario 5.3.2

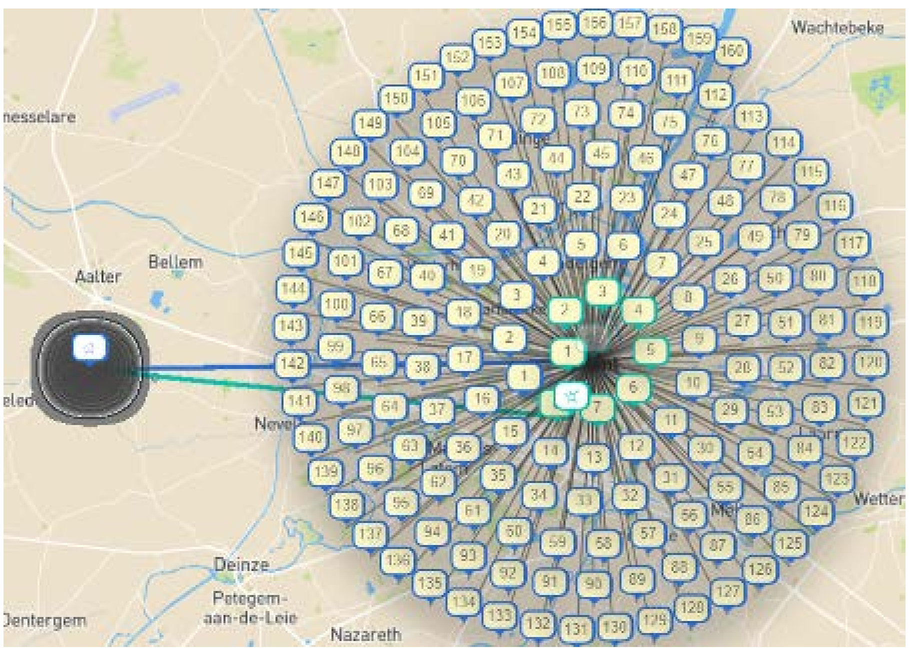

Figure 3.139: Possible routes for Ghent scenario 5.3.2

Comparison of options in Scenario 5

As shown in Table 3.38, the annual costs and distance travelled for all collection options that complete the task are comparable, with monthly collections being slightly less expensive and requiring slightly less travelling (Scenario 5.3.2).

Table 3.38: Comparisons of Scenario 5 collection modes

Scenario	5.1.1	5.1.2	5.2.1	5.2.2	5.3.1	5.3.2
Total number of collections from the 2 mini-hubs	63	63	126		272	
Collection mode	Weekly	Weekly	Fortnightly	Fortnightly	Monthly	Monthly
Number of weeks/year	52	52	26	26	12	12
Number of vehicles	1	2	1	2	1	2
Cost per km (operational cost)	€ 1,635	€ 2,394	€ 3,078	€ 4,788	€ 6,765	€ 10,336
Cost per hour (labour cost)	€ 60	€ 60	€ 60	€ 60	€ 60	€ 60
Working hours required per collection period	50 of 50	40	99 of 100	80	200	170
Cost per collection period	€ 4,635	€ 7,194	€ 9,078	€ 14,388	€ 18,765	€ 30,736
Cost per year	€241,020	€ 374,088	€ 236,028	€ 374,088	€ 225,180	€ 368,832
Total distance per collection period	2,213	3,241	4,168	6,483	9,160	13,995
Total distance per year	115,076	168,532	108,368	168,558	109,920	167,940
The number of companies' waste has not been collected	20	0	38	0	94	0

4 A generic methodology for developing case specific solutions

The full definition of reverse logistics[51], as according to The Council of Logistics Management (UK), is the process of implementing, controlling, and planning the cost-effective flow of finished goods, raw materials, and in-process inventory. The flow is from the point of consumption (i.e. the customer) to the point of origin (i.e. the

[51] Note that this is the wider definition of reverse logistics, where third parties may be organising the reverse flows in a separate operation. A narrower understanding of the concept refers to companies using their own forward logistics for taking packaging, crates, trolleys and damaged or returned products back to the distribution centre.

manufacturer), to properly dispose of these or to recapture value. (...) Recycling and disposal of end-of-life goods is included in reverse logistics, as well as returns, reuse and remanufacturing which, while are not on the scope of the simulations, can also benefit from insights abouts operational costs of transport, etc

Drawing from our experience in setting up and conducting these simulations for plastic waste collection, we have developed the insights about collection modes, vehicles and routes needed to suggest a methodology for developing case specific reverse logistic solutions in other cities. It consists of the following steps, some of which may be iterative:

1) Assess the current situation including any location-specific constraints, including legislation on waste transportation and processing.
2) Consult stakeholders regarding their interests, views, ideas and projects.
3) Check what data is available or can be collected within a useful timeframe.
4) Check what software is available or can be acquired with the available budget.
5) Set realistic objectives for the simulations and communicate them to the stakeholders, managing expectations.
6) Define the exact simulation scenarios and data required by writing a detailed simulation plan for each city. Critical in these scenarios is the location of sites that would act as hubs for reverse logistics, that is the places where plastic waste would be taken to be recycled and from where products made with the plastic could be collected back to be distributed to plastic owners. These hubs act as the start and end point for collection trips, and provide the start point for reverse trips.
7) Acquire the necessary data.
8) Conduct the simulations, taking note of the results.
9) Analyse the results to generate findings and recommendations.
10) Present the findings and recommendations to the stakeholders, usually as a report and presentation.

The subsequent sections discuss aspects of plastic waste collection logistics in detail.

4.1 Separate collection or mixed collection

It is always easier to separate recyclables at source and collect them separately, therefore reducing contamination and removing the separating/sorting work step. However, this requires the discipline to separate consistently and occupies more space at the waste producer’s location (several containers instead of just one). In terms of the collection, it may not make a major difference, unless a business is far away from all others. Mixed plastics mean larger quantities and hence the vehicle needs to drop off at the depot more often; separated collection means smaller quantities, less frequent drop-off but repeat visits for other materials. This is an inconvenience that reduces efficiency when accessing the location takes a lot of time. The strategy explored in Ghent, whereby materials are sorted into colour-coded bags that are then collected together is the best solution, as it combines both advantages: sorting at source and efficient collection. It also makes it easier to monitor the amount of recyclable waste generated at each source. This means that flows of plastics entering the hubs as waste and leaving the hubs as products can be better tracked for improving reverse logistics strategies.

4.2 Modes of transport

The most common mode of transport is clearly the road, and in most cases roads will provide the most convenient solution with the least investment required. Reasons to search for other solutions may include:

- Congestion in town centres or along major traffic axes
- Availability of alternative infrastructure already in place
- Wish to improve a town's sustainability image

Tramways often intersect with roads, so they may also be affected by congestion. Where separate offline rails are available, trams can be a good way to offer a mobile collection point for businesses to drop off their waste locally (e.g. once a week) without the need for occupying space permanently (e.g. for a local recycling collection centre). Another advantage is that the collection facility is at the same time the transport vehicle, so one handling / loading step is eliminated.

Waterways, such as canals leading through cities offer similar advantages as tramways described above. They can either be used in the same way, or just as a mode of transport out of the city centre where road congestion is severe, requiring that additional step of loading which requires infrastructure like a cargo crane at the harbour / anchoring point. Boats used for this purpose may be operated by diesel or electricity, with the same reasoning as for road vehicles.

The most adventurous mode of transport is the air. Whilst interesting, drones are likely most suitable for transporting important, valuable, small items. Plastic waste unfortunately does not fit these criteria.

However, there are possible applications for autonomous vehicles in the other three modes; whether on roads (especially pedestrian zones), water or tramways, it may be possible to remove the human driver in favour of an autonomous vehicle with a

preplanned route, where businesses come to drop off their waste and interact with the autonomous vehicle to signal when the loading has finished the the vehicle can continue. This would likely reduce collection costs, as driver salaries represent a significant part of it.
A major barrier for exploring these alternatives is the scarcity of data about the routes and logistics tools available to make realistic simulations, particularly hybrid tools combining use of roads with waterways or airways. Thus, cities with extensive waterways and/or trainway networks should start collecting data and developing partnerships with logistic companies to develop logistic simulations tools that better capture what the city has to offer in addition to roads and develop a long term hybrid transport strategy for reverse logistics. Optimised road-based reverse logistic strategies should be considered transitional solutions for the short and medium term.

4.3 Different types of vehicles and fuel

Lorries are typically powered by diesel, although there are alternative developments and pilot projects as discussed in Chapter 2. Trucks and vans are more often found with alternative fuel types, as their weight is lower.

It is clear that there is a need to reduce harmful emissions. However, most alternative fuel types only move the emissions away from the vehicle location, unless the energy was produced by renewable sources. There is currently not enough renewable / clean energy available, so intermediate solutions like “blue hydrogen” are produced[52]. It will be a while until we have enough “green hydrogen” available[53].

An additional problem with electrical vehicles is what happens to the batteries once they need to be replaced. Whilst theoretically possible, battery recycling is complicated and expensive; another unsolved problem, with pilot projects running. Also, the whole life cycle of vehicle batteries should be taken into account; the amount of energy required to manufacture the batteries and to mine the materials (as well as the conditions under which this happens).

Using alternative fuel currently makes the most sense in town centres or close to schools where emissions (and noise) need to be reduced locally. Elsewhere, the benefit of alternative fuel is not as clear-cut. Town centres, especially old towns with pedestrian areas and narrow streets, are the locations where the use of a CargoBike makes the

[52] https://theconversation.com/blue-hydrogen-what-is-it-and-should-it-replace-natural-gas-166053
[53] https://www.metabolic.nl/projects/hydrogen-analysis-of-the-current-state-and-outlook-of-technologies-for-production

most sense, anyway. It is also where most people will observe the collection vehicle, and produce the best results in terms of town image.

We have obtained some feedback from four waste collection companies regarding their views on alternative waste collection vehicles or strategies:

Company 1 carried out a test with an electrically powered household waste collection lorry (26t). Since 2018, they have also been operating a small dump truck for small collection tours in the city centre. However, vehicles are still very expensive to purchase as well as to operate. There is no question of generalising these tests yet. The most operational alternative is the use of compressed natural gas. This makes it possible to reduce polluting discharges of fine particles.

Company 2 is mainly active in the placement and emptying of (semi-)underground containers. They have investigated the possibility of using electric trucks, but have come up against the following limitations:

- The purchase price is twice as expensive as a diesel-powered truck.
- The weight is considerably higher, so that the loading capacity is compromised.
- The range is limited (200 - 250 km), which may be sufficient for local collection, but not for their activities.
- The range does not take into account cranes or other parts on the vehicle to empty containers, which will further limit it.

At present, they do use small electric vehicles for emptying, maintaining and cleaning street bins. For this, this propulsion system is very suitable. The use of hydrogen as a propulsion system was not investigated, as the technology is currently too young in their view.

Another option that they see is the use of a 'company-neutral' truck to, for example, empty wheelie bins from various collection companies together. This ensures that, in urban areas for example, different trucks do not have to drive through the same street to collect the same waste. The most important condition that has to be fulfilled for this idea to be implemented with confidence is that the collection is done by a company that only carries out logistical activities, but no waste management.

There is also the possibility to work with compartmentalised containers of, for example, 30 or 40 m^3, equipped with a mobile partition. This means that 2 types of waste can be collected together and then unloaded separately. The problem here is that the waste cannot be compressed and therefore smaller waste quantities can be loaded. This is primarily a problem for low density materials like plastic packaging.

Company 2 also uses 300 litre bags for the collection of EPS, paper and cardboard and plastic films in mainly urban or high-density areas. These are then collected together.

Company 3 is mainly active in collecting, sorting and processing waste materials from construction and demolition activities, hence dealing with mostly high density materials.

In the context of logistical optimisation, they have focused mainly on making maximum use of water transport. Many of the material flows they sort or process are transported by ship. Examples are wood, rubble and sand. This can be done both to local destinations (within Flanders) and abroad (the Netherlands, Germany and Scandinavia). They are also trying to transport more and more waste by ship to their own sites. This is currently done by transporting the waste in bulk. There are also a number of projects in Flanders to transport containers by water, but this does not appear to be profitable at the moment.

In addition to ships, they also use push barges. The advantage of this is that they can remain moored for a long time without incurring high costs. So in this case, one has more time to collect waste materials and the containers can be used as temporary storage places.

The use of electric trucks has not been investigated so far. The reason is the expensive purchase price and the uncertainty as to whether this drive is suitable for heavier work.

Company 4 carried out a test with an electrically powered household refuse dump truck with a maximum GVWR of 26 tonnes. Since 2018, they have also been operating a small dump truck for small collection tours in the city centre. However, vehicles are still very expensive to purchase as well as to operate. There is no question of generalising these tests yet. The most operational alternative is the use of compressed natural gas. This makes it possible to reduce polluting discharges of fine particles.

Drawing on our simulations, we have found that the higher the number of collection sites, the lower the difference in terms of operational costs between electric vehicles and diesel vehicles, due to economies of scale in routing. Following on these, we suggest that cities opting for centralising reverse logistic in hubs should at the same time provide subsidies or competitive loans for the purchase of larger capacity electric trucks, while vehicle manufactures need to improve the provision of evidence regarding the suitability of these vehicles for heavier work.

4.4 Zones and concepts

Collection areas can be organised on the basis of various concepts. Distance from a centre point (e.g. the city centre) can be considered, like in the simulations for The Hague, or collection can be organised based on shopping districts, industrial zones or political structures.

It matters less for the transportation of whole containers, where a lorry can only carry one at a time (two with a trailer), as there is not much routing to be planned. The most efficient configuration is to use the nearest waste treatment facility.

However, for milk-run collections (with any type of vehicle), routing is important and depends on the zone to be covered, the road network configuration and the locations of businesses to be served. Different business types may have different needs and are often located in different zones. For instance:

- In the old town, there are often many small, independent businesses who typically produce smaller amounts of plastic waste. They may not have much space available for accumulating and storing waste, and hence frequent collection of small quantities by a small vehicle such as the CargoBike may be most suitable.
- In high streets, one will often find chain stores of medium size. They may produce more waste and may have some space available for storing plastics. Medium sized vehicles (vans, small trucks) may be most efficient to serve these businesses, unless they send back their waste via reverse logistics.
- In shopping malls, whilst there are often also chain stores, it may make more sense to collectively organise waste sorting, accumulation and collection for all businesses in the mall due to access reasons. There is usually space available for a mini-hub, and containers can be collected by a lorry with a trailer.
- The same idea also applies for more modern, planned cities where space can be arranged for mini-hubs for each zone, and companies will drop off their own waste.
- In industrial areas as well as big box shopping areas, there is usually enough space for companies to have big containers to sort and accumulate waste. They may even receive waste from their branch locations via reverse logistics (using its narrower definition), accumulate it, and then have it collected by lorries with trailers.

Overall, we suggest that companies producing plastic waste should be responsible for managing their recycling flows, and that legislation needs to incentivise them to reuse recycled plastics.

5 Discussions, conclusions and recommendations

Each city needs to make individual decisions.

How companies handle their waste depends on many factors, including whether they are individual locations or part of a chain. For instance, one chain of electronics equipment with many shops in the Netherlands, Belgium, Germany and Luxembourg stated that they separate their recyclables (paper, cardboard and plastic) locally and then take them to the main location for proper disposal. It is possible that the reason behind this strategy is that they need to pay for their recyclables to be collected, and it is cheaper to do this in one location, only, even if it requires company-internal transportation. It may make sense from an environmental perspective as well if the company can benefit from reverse logistics, that is, for the forward distribution to take the recyclables back.

Large companies often use reverse logistics in this way. Some even include the customers in the chain, by asking them to return certain items or materials to the store. For instance, the British supermarket chain Tesco collects post-consumer soft plastics (plastic films of any type) for chemical recycling[54], as councils in the UK currently do not collect these materials and they would end up in landfill / incineration otherwise.

5.1 Recommendations for each PlastiCity city

The scenario considered for Douai is very simple, and the conclusion from it is equally clear: to reduce emissions and costs in the long run, lorries picking up large containers should run with trailers. It would be interesting to explore further possibilities for this town, considering also companies that do not host their own 40m3 container, and using a milk-run approach for collecting their waste. This could be an interesting project for an MSc student, for instance. In addition, policy makers in Douai should actively encourage the use of electric vehicles. The positive impact of EV in emissions reductions depends on each country's energy mix. France's energy mix is heavily dependent on nuclear and renewable energies, and results in the lowest emissions per KW of electricity generated in Europe. In such conditions, the use of EV could result in 60-70% less emissions of

[54] https://www.tescoplc.com/blog/soft-plastic-collection

reverse logistics than diesel lorries and 80% less than gasoline lorries. Our cost analysis in the other cities suggest that the costs of using electric vehicles in Douia will not be substantially higher than current alternatives. However, acquisition costs are steep and would need policy intervention, for instance with subsidies.

For Southend, it is difficult to make a qualified recommendation due to the complete lack of waste quantity data when the simulations were run. However, their idea of creating mini-hubs for accumulating plastics locally certainly makes sense, especially in areas with many small businesses like in high streets, shopping malls and industrial areas with many small and medium sized companies. This idea has been adopted by Ghent. However, the use of a CargoBike with a very small loading capacity is not useful. For the collection service to reach a sensible level of efficiency, it is essential to have the largest loading capacity possible and to have a press on-board. In terms of emissions, the UK energy generation mix is still heavily dependant on fossil fuels, resulting in some of europe's higher emissions per KW. As a result, the environmental advantages of using EV are minimal.

The simulations conducted for The Hague taught us that "distance from the centre" is not necessarily a useful criterion to organise logistics as streets and neighbourhoods are usually not organised in a concentric way. Most importantly, the waste drop-off location is essential especially when using vehicles with small loading capacities. While the use of cargo bikes seems intuitively appropriate for old areas of the city, cargo bikes will always need to be combined with other means of transport with larger carrying capacity, in what could be called a two step strategy. A combination of bikes and electric vans will result in lower running costs, but increase acquisition costs. Environmentally, since The Netherlands has one of the most polluting energy mix of Europe, the use of electric vans is not advisable. The use of cargo bikes may still have benefits but positive effects are more likely to derive from reductions in congestion . A detailed well to wheel analysis of cargo-bikes emissions in The Netherlands is recommended. . n ,

For the Ghent simulations, many of the above-mentioned lessons were taken into account. Collections were arranged by shopping areas, with milk-run drop-off at local mini-hubs which were optimised for the further transportation mode (next to a tramway or river / canal if this modus is considered to empty the mini-hub). The loading volume of the CargoBike used here is larger and it is equipped with a press. However, given that some small companies have waste quantities that still exceed the loading volume, the use of a trailer should be considered. As in the case of France, Belgium has a relatively clean energy mix, where low carbon emitting sources dominate. As a result, the use of electric cargo bikes and larger electric vehicles is definitely advisable from an environmental point of view. Policy incentives should be provided to drive the electrification of waste and reverse logistic companies afloat.

It would make sense for all cities (and rural areas as well) to move away from each waste management company to organise their own logistics. Currently, some streets get visited by 5 recyclables collection vehicles, plus several more for other types of waste. Whilst potentially difficult to negotiate, the use of a joint collection service would reduce emissions, noise and traffic, improving quality of life.

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