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Research Paper

Transporting household waste over water can reduce costs and emissions: A case study in the Netherlands

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ABSTRACT

Inland waterways can be an attractive under-utilized alternative to road transport. In the current situation, heavy trucks transport residual household waste from municipalities to incineration plants around the Netherlands. Logistics research groups have suggested using barge pushing ships for household waste transport to reduce emissions and costs. We analyze this suggestion for a case study involving the residual household waste of 55 municipalities across three provinces in the Netherlands. A Mixed Integer Linear Programming formulation is used to find the optimal combination of trucks and barge pushing ships in this waste network. The results demonstrate that adopting electric pusher ships can achieve significant reductions in costs (19%), emissions (41%), and waste carrying truck traffic (48%), compared to truck-only solutions. Diesel cargo ships are also shown to outperform truck-only approaches but are less effective than electric alternatives in most metrics. Sensitivity analysis shows that the solutions are fairly robust to parameter variations.

1. Introduction

In this paper, we study a multi-modal waste network where residual household waste is transported using ships and trucks. We model this network using a Mixed Integer Linear Programming formulation. This formulation is applied to a large case-study in the Netherlands, involving the waste of 55 municipalities.

This paper is motivated by the fact that in urbanized societies, the processing of residual household waste is a continuous problem that governments have to handle. Most residual household waste in the Netherlands is burned, approximately 66%, while the other 34% is composted (Ministerie van Infrastructuur en Waterstaat, 2025). This is done after separation and possibly recycling, at incineration plants around the country, generating energy (Werkgroep Afvalregistratie, 2018). Waste is generally transported from residential clusters to incineration plants by trucks (Van Rhijn et al., 2023). These heavy diesel trucks cause extensive damage to road networks and emit a large number of pollutants (Van Rhijn et al., 2023).

A large number of infrastructure objects in the Netherlands are approaching the end of their safe lifespan (Ministerie van Infrastructuur en Waterstaat, 2024a). These bridges, viaducts, tunnels, and other structures were all built during the 1950s and 1960s (Ministerie van Infrastructuur en Waterstaat, 2024a). Over half of all reinforced concrete has corrosion damage after 70 years (TNO, 2025), resulting in these structures from the 1950s and 1960s all requiring extensive renovation around the same time. Such renovations cause significant disruptions to road traffic in the Netherlands, especially affecting trucks, as these structures are generally more sensitive to heavy vehicles. For example, during the renovation of the A7 highway trucks were not allowed to cross the bridge at the city of Purmerend (Ministerie van Infrastructuur en Waterstaat, 2024b).

These factors have led policymakers to look to alternative transport modes for several logistic flows. Water is relatively underused for local transport in the Netherlands, despite the nation's strong naval tradition. In addition, recent developments regarding electrically powered cargo ships have increased the possibilities for low-emission transport over water. In this research, we study an electrically powered pusher ship, with separate cargo barges.

Waste transport is particularly suitable for transport over water due to a number of reasons. Most importantly, waste is relatively non-perishable. While waste should be processed quicker than, e.g., building materials, it is acceptable for the waste to be stored at a depot for

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several days. This is in contrast with consumer goods, like perishable food products, which need to be transported to stores as quickly as possible. In addition, household waste is separable into smaller quantities, and thus doesn't need to be transported whole or in containers.

In this paper, we look at several possible modes of transportation for residual household waste, using a case study in the Netherlands where the processing plants are located near water. We study (1) a system using trucks, (2) a system using a combination of trucks and cargo ships powered by fossil fuels, and (3) a system using a combination of trucks and electrically powered cargo ships. An overview of the suggested system is shown in Fig. 1.

The major research questions of this study are as follows:

1. Would transporting residual household waste using waterways in the Netherlands, compared to the standard practice of truck transport, results in a reduction of system operating costs?
2. In addition to Question 1, would a modal shift to ships result in non-financial benefits, such as a reduction in CO_2 emissions or waste-related truck traffic?

The contributions of this paper are threefold. First, we present an Integer Program which models a multi-modal waste network with ships and trucks. Second, we apply our model to an in-depth case study in the Netherlands, showing the potential for a reduction in costs and emissions by moving residual household waste transport to waterways. Finally, we show that the business case for a modal shift to water transport is advisable even when varying input parameters.

This paper proceeds as follows. In Section 2, we discuss relevant literature. In Section 3, we introduce the mathematical model we use to study the effects of different transport modes. Subsequently, we give a precise formulation for the used Mixed Integer Linear Program~(MILP) in Section 3.1. Next, in Section 4, we give an overview of the data and sources used. In addition, we give a more thorough description of the case study at the end of this section. In Section 5.1 we give the results from applying our model to the case study and in Section 5.2 we test how sensitive our findings are to model input. Finally, we conclude and discuss the results in Section 6.

2. Literature review

Collection and transport of municipal solid waste has several distinct steps which have all received ample attention in literature. Waste is collected at the customer and subsequently shipped to a transfer facility in the municipality (Van Rhijn et al., 2023). We focus on a system where waste is transported directly from the municipality to the incineration plant, i.e., the waste is not processed at a recycling plant before being transported to the incineration plant. The first part of this process is well studied, see the work by Beliën et al. (2014) for an overview, as the local collection process is costly and responsible for emissions in urban centers when using diesel powered trucks. Various venues have been explored to implement alternative methods for collecting waste from consumers. For example, Erdinç et al. (2019) look at electric trucks, and in Amsterdam experiments have been done with small electric barges (Amsterdam Institute For Advanced Metropolitan Solutions, 2020). Other studies aim to improve the usage of diesel powered trucks by optimizing routes, for example the work by Karimipour et al. (2021).

In addition to studying various different transport methods, there is a large body of research aimed at making waste collection more effective by improving algorithms for waste collection routing. The recent survey by Hess et al. (2024) gives an overview of different problems and the computational methods used to solve them. They find that most works are on Vehicle Routing Problems, focusing only on vehicle routing where the underlying networks are fixed. They do however also note a number of papers where network design and vehicle routing is taken into account. A paper by Lavigne et al. (2021) evaluated a bio-waste collection network in Brussels, Belgium, using a Mixed Integer Linear Programming (MILP) model. Yu et al. (2020) also use a MILP for designing a hazardous waste management network in Wuhan, China. The review by Hess et al. (2024) mentions more successful applications of MILP models in waste collection systems. Based on these results we also employ a MILP to model a waste collection network using ships and trucks.

From this facility, the waste is either transported directly to an incineration plant or separation facility, depending on whether the waste is already collected separated from the customer. In this second stage, several aspects change: The vehicles used in this stage only need to transport bulk amounts of solid waste, allowing for a larger variety in possible vehicle types. For long-distance transport, rail is commonly used. For example, in Austria, all waste transported over distances exceeding 200 km must be moved by rail rather than by truck (Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, 2023). For smaller distances, the use of trams has been considered in Prague (Zilka et al., 2021). For long distance cross-border transport, ships are already a common mode of transports for bulk waste. In the Netherlands the transportation of waste over water for medium distance has been suggested, the practical considerations of which are discussed in the work by the Amsterdam Institute For Advanced Metropolitan Solutions, 2020.

Modal shifts and intermodal transport have received ample attention in the literature. Archetti et al. (2022) review optimization in the field of multimodal freight transport. A waste network in Belgium with inland barge transport is studied by Inghels et al. (2016). The problem studied in their research has similarities to the problem studied in this work. Their case study is however smaller and more stylized, containing only

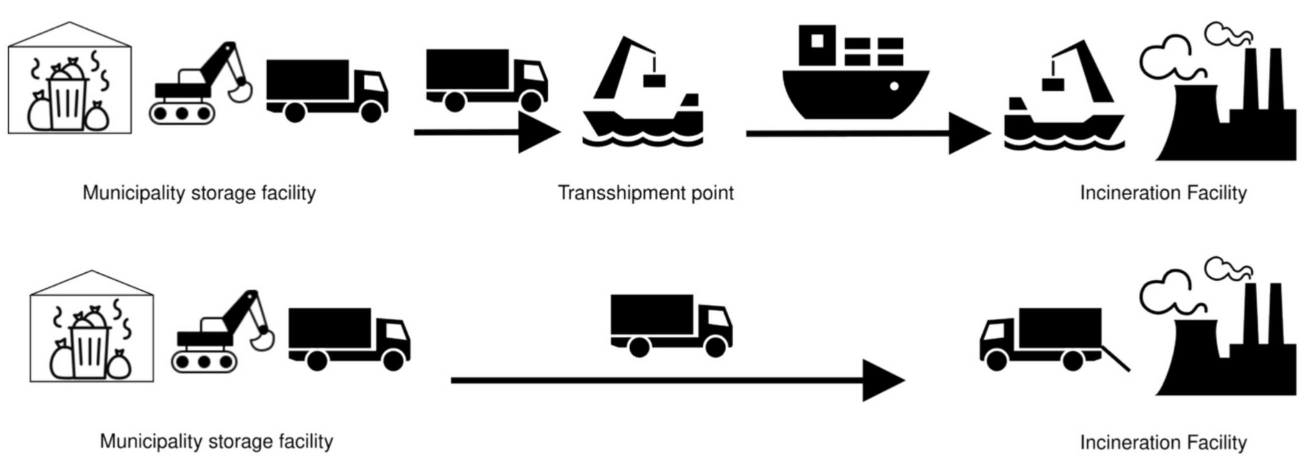


Fig. 1. Schematic overviews of the suggested multi-modal waste network (top) and current practice (bottom).

nine collection centres, rather than the 55 municipalities in the problem studied in this paper. More fundamentally, they only allow a single transshipment point to be used per waste transfer facility, while our model allows the pooling of waste by municipalities at transshipment points. In our results section we find that this can help reduce costs significantly for municipalities. In addition, the use of electric barges is novel.

The problem studied in this paper can be modeled as a Location Routing Problem (LRP). We will use a Split Delivery Vehicle Routing Problem (SDVRP) based formulation, as waste can be seperated into smaller units. The work by Maranzana (1964) is probably the first to discuss the location of facilities in relation to transport costs. This work and further works on the LRP all consider this relation between location and transport costs. Mara et al. (2021) classify recent work in the LRP domain, reviewing 222 papers on the topic. The problem studied in this paper is most similar to the heterogeneous LRP where different vehicle types may be used.

Recent work on heterogeneous LRPs in the context of waste management include the work by Mara et al. (2021). In this work they discuss a case study with various vehicle types in Indonesia. Their study differs from ours in the type of vehicles used as only various types of trucks are considered. In addition, their model is only aimed at reducing costs, and emissions are not take into account in their analysis.

The SDVRP was introduced by Dror and Trudeau (1989) and has received a lot of attention in literature. An overview of problems studied in the context of the SDVRP is given in the review by Archetti et al. (2022). We will use a SDVRP based approach to model the routing part of our problem.

For our problem, it is also required to determine the optimal location for the facilities where waste is transferred from land to water. Such decisions are the core of research on facility location problems. The review by Owen and Daskin (1998) looks at a large number of solution methods for these problems.

The contribution of this paper is tree-fold. First, we present a Mixed Integer Linear Programming approach for modelling multi-modal waste transport with transshipment location selection. Second, an extensive case study is done for 55 municipalities in the Netherlands. Third, we present managerial insights for decision-makers in the area of waste logistics.

3. Problem formulation

We formulate the problem in the following way, Greek letters are used for parameterEach municipality $\mu \in M$ produces ω_m kilotons of waste weekly. This waste must be transported to one of the incineration locations, which is specific to the municipality. Waste can be transported by truck, diesel ship, or electric pusher. The amount of waste transported directly from municipality m to its incineration location is t_{μ}^{direct}. Waste that is transported by barge must first be transported by truck to a transshipment point $\pi \in P$. The amount of waste transported to a transshipment point p from municipality μ is denoted by $t_{\mu,\pi}$. Combining the sums of these amounts for all municipalities and transshipment points gives the total amount of waste transported by truck. Multiplying each value by the distance between municipality and transshipment point/processor we get the amount of waste transported in tonne kilometres which is denoted by t^{total}. Denoted by δ_{μ}^{truck} is the distance between municipality m and its processor. The distance between municipality μ and transshipment point π is $\delta_{\mu,\pi}$.

Ships sail along routes, which are denoted by $\rho \in R$. The length of route ρ is denoted by δ_{ρ}^{ship}. Routes can have an arbitrary number of stops, and start and stop at the incineration plant. However, for practical reasons, we only use shuttle routes in our case study, i.e., routes that go to exactly one transshipment point and back. The reasons for using such shuttle routes are further discussed in Section 5.1.

The number of ships that is used by the final solution is denoted by n_{ship}. We denote the emissions generated by the trucks and ships in the chosen solution by u_{truck} and u_{ship}, respectively. The amount of emissions a truck generates per kilometre are denoted by ϵ_{truck} and the amount generated per km by a ship is ϵ_{ship}. Trucks and ships have a capacity of σ_{truck} and σ_{ship} respectively. We also introduce several decision variables. Let $y_{\rho,\pi}^{i}$ be the amount of waste transported on route ρ from transshipment point p on day $i \in \{1, 2, 3, 4, 5\}$, the weekdays. We also define x_{ρ}^{i} the number of times route ρ is run on day i. Let o_{π} be a boolean variable which denotes whether transshipment point π is opened (one if opened, zero otherwise). The number of transshipment points opened in the final solution is denoted by $n_{transshipment}$.

We denote costs by the letter κ, where the fixed cost of opening a transshipment point is denoted by $\kappa_{transshipment}^{fixed}$. The fixed cost of operating a ship is denoted by κ_{ship}^{fixed}. Similarly, the variable costs of operating a ship (per km) is denoted by κ_{ship}^{km}. The variable costs for running a truck are denoted by κ_{truck}^{tkm}.

For an overview, all notation is also given in the following list:

μ— Municipality.

ω_{μ}— Amount of waste produced by municipality .m

t_{μ}^{direct}— Amount of waste transported directly from m to .l_m

$t_{\mu,\pi}$— Amount of waste transported from m to transshipment point .p

t^{total}— Total amount of waste transported in tonne-kilometers.

δ_{μ}^{truck}— Distance between municipality m and its incineration location .l_m

$\delta_{\mu,\pi}$— Distance between municipality m and transshipment point .p

ρ— Route along which ships sail.

δ_{ρ}^{ship}— Length of ship route .r

n_{ship}— Number of ships used in the final solution

$n_{transshipment}$— Number of transshipments opened in the final solution

$\kappa_{transshipment}^{fixed}$— Fixed cost of opening a transshipment point per week.

κ_{ship}^{fixed}— Fixed cost of operating a ship per week.

κ_{ship}^{km}— Variable cost of operating a ship per km.

κ_{truck}^{tkm}— Variable cost of operating a truck per tkm.

u_{truck}— Emissions generated by trucks in the chosen solution

u_{ship}— Emissions genrated by ships in the chosen solution

ϵ_{truck}— Emissions per kilometre for a truck.

ϵ_{ship}— Emissions per kilometre for a ship.

σ_{truck}— Capacity of a truck in tonnes.

σ_{ship}— Capacity of a ship in tonnes.

$y_{\rho,\pi}^{i}$— Waste transported on route r from p on day .i

x_{ρ}^{i}— number of times route r is run on day .i

o_{π}— Boolean variable, 1 if transshipment point p is open, 0 otherwise.

3.1. Mixed Integer Linear Programming formulation

We calculate the optimal usage of trucks and ships by formulating a Mixed Inter Linear Program (MILP) and solving this program using a solver. We use the following formulation, based on the split vehicle routing problem formulation in the work by Archetti et al. (2008). We extend the formulation by adding constraints related to the usage of transshipments points. Note that this formulation is computationally inefficient (Archetti et al., 2008), but is suitable due to our choice of the set of potential routes R, which will be elaborated upon in Section 5.1.

Minimize $\sum_{\rho \in R} \sum_{i=1}^{5} x_{\rho}^{i} \delta_{\rho}^{ship} \kappa_{ship}^{km}$ (4.1)

$$+ n_{ship} \kappa_{ship}^{fixed} \# \tag{4.2}$$

$$+ \sum_{\mu \in M} t_{\mu,truck}^{total} \kappa_{truck}^{tkm} \tag{4.3}$$

$$+n_{\text{transshipment}}\kappa^{\text{fixed}}_{\text{transshipment}}\cdot\# \tag{4.4}$$

Subject to:

$$\sum_{\pi\in P} y^{i}_{\rho,p} \le \sigma_{\text{ship}} x^{i}_{\rho}, \forall\rho \in R, \forall i \in \{1,\cdots,5\}, \tag{4.5}$$

$$n_{\text{transshipment}} = \sum_{\pi\in P} o_p, \tag{4.6}$$

$$\sum_{\pi\in P} t_{\mu,p} + t^{\text{direct}}_{\mu} = \omega_m, \forall\mu \in M, \tag{4.7}$$

$$t_{\mu,p} \le Mo_p, \forall\mu \in M, \forall\pi \in P, \tag{4.8}$$

$$\sum_{\rho\in R}\sum_{i=1}^{5} y^{i}_{\rho,p} = \sum_{\mu\in M} t_{\mu,p}, \forall\pi \in P, \tag{4.9}$$

$$y^{i}_{\rho,\pi} = 0, \forall r \in R, \forall\pi \in P : \pi \notin r, \forall i \in \{1,\cdots,5\} \tag{4.10}$$

$$t^{\text{direct}}_{\mu}\delta^{\text{truck}}_{\mu} + \sum_{\pi\in P} t_{\mu,\pi} d_{\mu,\pi} = t^{\text{total}}_{\text{truck}}, \forall\mu \in M, \tag{4.11}$$

$$2\epsilon_{\text{truck}} \sum_{\mu\in M} t^{\text{total}}_{\mu,\text{truck}} / \sigma_{\text{truck}} = u_{\text{truck}}, \tag{4.12}$$

$$\epsilon_{\text{ship}} \sum_{\rho\in R}\sum_{i=1}^{5} x^{i}_{\rho}\delta^{\text{ship}}_{\rho} = u_{\text{ship}}, \tag{4.13}$$

$$n_{\text{ship}} \ge \sum_{\rho\in R} x^{i}_{r}, \forall i \in \{1,\cdots,5\}, \tag{4.14}$$

$$x^{i}_{r} = 0, \forall r \in R, \forall i \in \{1,\cdots,5\}. \tag{4.15}$$

With the following variables:

$$y^{i}_{\rho,\pi} \in R^{+}, \forall\pi \in P, \forall\rho \in R, \forall i \in \{1,\cdots,5\} \tag{4.16}$$

$$x^{i}_{\rho} \in Z^{+}, \forall\rho \in R, \forall i \in \{1,\cdots,5\}, \tag{4.17}$$

$$o_{\pi} \in \{0,1\}, \forall\pi \in P, \tag{4.18}$$

$$t_{\mu,\pi} \in R^{+}, \forall\mu \in M, \forall\pi \in P, \tag{4.19}$$

$$t^{\text{direct}}_{\mu} \in R^{+}, \forall\mu \in M, \tag{4.20}$$

$$u_{\text{truck}}, u_{\text{ship}}, t^{\text{total}}_{\text{truck}} \in R^{+}, \tag{4.21}$$

$$n_{\text{ship}}, n_{\text{transshipment}} \in Z^{+}. \tag{4.22}$$

The objective function has four parts: The first part (4.1) contains the variable costs for ships, and the second part (4.2) contains the fixed costs for ships. Following, we have the costs for trucks in part (4.3). Finally, in part (4.4) the cost for opening the transshipment points is calculated.

Constraints (4.5) assure that the amount shipped does not exceed the capacity of the ship. Constraint (4.6) is used to calculate the number of opened transshipment points. Next, we make sure that all waste at each municipality is shipped to either transshipment points or directly to the processor in Constraints (4.7). To force that waste is only brought to opened transshipment points we use Constraints (4.8). In these Constraints (4.8), we use a big-M notation, here M is a sufficiently large value to ensure that waste can be freely shipped to opened transshipment points. In Constraints (4.9) we ensure that all waste at a transshipment point is picked up by a ship. In Constraints (4.10), we make sure that waste is only picked up from transshipment points that are visited by an active route. To calculate the total amount of tkm transported by truck we use Constraints (4.11).The emissions are calculated using Constraints (4.12) and (4.13). Constraints (4.14) determine the number of ships needed for the planning and finally, Constraints (4.15) assures that routes are not longer than the ships can sail in a day. Finally, in Constraints (4.16) through (4.22) we define all decision variables and restrict their domains.

The solver used was IBM CPLEX version 22, running on a personal laptop with 32 GB of RAM and an AMD Ryzen 5 7535HS processor. All solving runs took less than one second. In addition, we ran our model using the open source and freely available HiGHS solver, to test if the model is only usable with commercial solvers which might be prohibitively expensive. We found that solving runs took a few seconds, which is fast considering the strategic nature of this problem.

4. Data

Data for the case study was retrieved from several public and private sources. Information on the amount of residual household waste produced at the municipality level was retrieved from Centraal Bureau voor de Statistiek (2024a). The properties of the electric pusher were retrieved from a ship constructor which builds electric pushers. Fixed costs for the electric pusher are built up as follows. The exact purchase costs are confidential, therefore an overestimation of €4,000,000 (KOTUG International, 'Personal Communications', 2024). This includes the cost of a battery, which has a shorter lifespan than the electric pusher. Costs are split into €3,400,000 for the electric pusher itself, and €600,000 for the battery. These numbers are based on the cost of a battery, estimated using information on large scale battery packs from Energetech (2024) and eigenstroomopslaan.nl, 2024. Assuming an expected lifespan of 25 years for the pusher and 10 years for the battery, this leaves us with a weekly fixed cost of €2,615 for the ship, and €1,154 for the battery (KOTUG International, 'Personal Communications', 2024).

To calculate power costs we use that an electric pusher uses at minimum 120 kW and at maximum 150 kW of power (KOTUG International, 'Personal Communications', 2024). We decide to use the average of the two, arriving at a value of 135 kW, as we were informed by a shipping expert that power usage is mainly dependent on skipper behavior (KOTUG International, 'Personal Communications', 2024). For the price of electricity, we use the wholesale price in the Netherlands, determined August 2024 at €0.071 per kWh (Centraal Bureau voor de Statistiek, 2025). Taking an average speed of 10 km/h (KOTUG International, 'Personal Communications', 2024), we get a price of €0.959 per km. Regarding the cost of a shipper, we use a value of €44.82 per hour. This value is based on cost per hour for inland shipping personnel found in Jonkeren (2023), indexed by 120% based on data from Centraal Bureau voor de Statistiek (2024b). Taking the 10 km/h average again, we get €4.482 personnel costs per km.

While we assume that electric pushers would have to be purchased by municipalities we allow the trucks and diesel powered ships to be chartered as there are many transport companies offering such services. Therefore, we only take the costs per ton kilometre into account (tkm).

For the diesel powered ship, we use numbers from Jonkeren (2023). Specifically, we use the costs from 2020 for a medium-sized cargo ship transporting 'other goods'. We index these costs using data from Centraal Bureau voor de Statistiek (2024d). We get a value of €0.032 per tkm in 2020, which leads to a value of €0.039 per tkm in 2024, using an inflation rate of 23%.

For diesel trucks, we use numbers from the same report (Jonkeren. 2023), again looking at 'other goods'. Here we get a value of €0.159 per tkm resulting in a value of €0.197 per tkm in 2024. As our method requires a distance matrix to compute the solution to our strategic problem we need routing software. For truck routing, a local GraphHopper instance was used with OpenStreetMap data. The routing profile was set to HGV, to account for any closures the trucks might need to take into account due to their heavy load. The used truck routes are the optimized shortest routes, and may not take local constraints into account that are not present in the OpenStreetMap data. Further network optimizations for the truck only system such as pooling of waste by muncipalities to increase truck fill rates are not considered. The truck baseline in our case study therefore represents current practice rather than the most efficient truck-based system. The costs per tkm from the report by Jonkeren

(2023) represent the total costs for a cargo operator and are specifically collected for use in studies like this one. We developed our own routing API for ships, based on the 'Vaarweg Netwerk Data Service – bevaarbaarheid' ('Waterway Network Data Service – Navigability') dataset from Rijkswaterstaat (2024). The electric pushers and diesel cargo ships studied by us are only able to sail on waterways which are at least class III in the CEMT system (International, 2024; Koedijk, 2020). Therefore, we filter out all waterways with lower class. We used these methods to create a distance matrix file containing for all possible required trips and loaded this into the model. We note that such distance matrices are not unique to waterways, an extension to other transportation modes, e.g., rail, would not require a structurally different model.

The location of possible transshipment points is based on the same 'Vaarweg Netwerk Data Service – bevaarbaarheid' dataset as the routing API. The code of this API is publicly available (Nagel, 2025). We use an algorithm which selects points along suitable waterways (Class III and up) at pre-defined intervals. Afterward, the points were manually filtered to remove any obviously infeasible points. Points were removed if they were not in a municipality belonging to the case study, were in areas that are too urban, or obviously infeasible for another reason. Many factors have to be taken into account for every location where opening a transshipment point is possible. We did not do further filtering of points with location specific data, as we believe this would be far too large an undertaking for the current strategic level of research. Instead, policymakers should rerun our analysis when more comprehensive information is available for specific potential locations.

The costs of opening a transshipment point are set to €2,000 per week. This value contains expenses for labor, a crane, storage facilities, construction, etc. Here, we assume there will be loading two times a week at the facility, taking four hours each time. The crane costs €350,000 (POM Oost-Vlaanderen, 2019), which is discounted over 25 years (to maintain consistency with the lifespan of the e-pusher), leading to a weekly cost of €269.23. We assume a weekly operation of four hours, twice a week, to load the barges. The fuel expenses with diesel priced at €1.5264 per L (November 5th, 2024 (FullTank, 2024)) and a diesel flow rate of 28 L/h (POM Oost-Vlaanderen, 2019) are €341.91 per week. The crane also requires maintenance, at €9.00 per running hour (POM Oost-Vlaanderen, 2019) this results in a weekly cost of €76.00. For a crane operator we use the same value per hour as for a ship operator, resulting in €358.56 salary costs per week. We combine these values to get €1,045.70. In order to take other significant expenses into account, such as power usage, storage facilities, taxes, inflation, waste spill prevention measures and other unknown costs, we round up to €2,000 per week. We will vary this value in our sensitivity analysis, since this value requires a number of assumptions.

Emissions will also need to be estimated. For the electric pusher, we assume 0.27 kg CO_2-eq per KWh (CO_2 equivalent), the average emissions generated on the Dutch energy grid (Centraal Bureau voor de Statistiek, 2023). Using, again, an average power demand of 135 kW at a speed of 10 km/h, we get 3.645 kg CO_2-eq per km.

The emissions for a diesel cargo ship are based on figures from the website 'co2emissiefactoren.nl', a cooperation between several environmental organizations and the Dutch government (Milieu Centraal, Stichting Stimular, SKAO. Connekt en Rijksoverheid, 2024). We use that for a small cargo ship (300–600 tonne capacity), the emissions are 0.0416 kg CO_2-eq per km.

For the diesel trucks, we use the same source (Milieu Centraal, Stichting Stimular, SKAO. Connekt en Rijksoverheid, 2024). For a truck with a capacity of 20 tonnes, we get 0.105 kg CO_2-eq per km.

Our case study looks at the waste logistics for 55 municipalities in the Netherlands. A list of these municipalities is given in the online appendix. These municipalities were chosen due to the incineration locations contracted for their waste processing. These incineration locations are HVC Alkmaar (HVC Groep, 2024a), HVC Dordrecht (HVC Groep, 2024b), and AEB Amsterdam (AEB Amsterdam, 2024). We chose these three plants due to their location near water. In addition, each of these incineration plants is owned by their respective customer municipalities in a collective ownership structure. Due to this public ownership structure, data on the processes involving the incineration plant is more readily available than for privately owned incineration plants. In addition, the government has more influence of the operations of these incineration plants than on those that are privately owned. An overview of these municipalities and their incineration locations is given in Fig. 2.

5. Results

5.1. Case study

In this section we analyze the outcomes of our model for the case study, which was presented in Section 1. For our case study we used shuttle routes, i.e., ships sail to one transshipment point and then back to the processing plant. This was done for practical reasons, because using shuttle routes allows us to work on a two-barge principle. When a pusher arrives at the transshipment point, it drops of an empty barge and takes a full barge. The barge can then be loaded while the pusher is sailing with the other barge, allowing for practically no downtime for loading. We tested if more complicated routes increased cost efficiency, but found that there were little, if any, gains for doing so (around 1.5%). This lower cost would most likely be offset by the cost of the added complexity of such a system.

First, we present the results for the standard parameters, these are shown visually in Fig. 3. The shown solutions use electric pusher boats. We find that the optimal solution is to open four transshipment points: two in Noord-Holland, one in Zuid-Holland, and one in Flevoland. No ships are used to service the AEB incineration plant. This might be caused by the relative compactness of the service area, resulting in short truck routes. Furthermore, the distance trucks must drive from the municipality to the transshipment point may be nearly as far as its distance to the processing plant. When routes are short, the cost savings from using efficient ships do not sufficiently compensate for the additional expense of opening transshipment points. Note that some municipalities split their waste between truck transport and ship transport. In Table 1 we show some important attributes of the found solutions. The current situation, using only trucks, has the highest cost and emissions. Using diesel cargo ships, emissions and costs can be reduced significantly. Changing the diesel cargo ships to electric pushers sees a small further reduction in costs and a substantial further reduction in emissions. The lowest number of truck kilometres occurs when using trucks and diesel cargo ships. This is most likely due to the possibility of chartering diesel cargo ships, as the fixed costs cause the electric pusher to be too expensive to use for these truck routes. In Fig. 4 we show a pareto front of solutions for different limits on emissions.

We calculate these values by setting a constraint on the amount of emissions possible in a solution, and systematically lower this amount. The associated costs are than plotted. The figure shows that for diesel cargo ships this curve is quite steep, i.e., a small reduction in emissions comes at high cost. For electric pushers, the curve is rather shallow at first, but then becomes very steep. A manager might therefore choose a solution somewhere on the shallow part of the curve, where a good trade-off between emissions reduction and cost is achieved. For the trucks there is only one solution given as we have no decision variable in our MILP which influences emissions when using only trucks.

5.2. Sensitivity analysis

The model requires a large number of input parameters, some of which must be estimated. Therefore, we study the sensitivity of the model to variation in the given input.

Sensitivity with respect to the amount of waste

We apply a multiplier to the weekly amount of waste at produced in each municipality. This multiplier is varied from 0.1 to 2.0, increasing in

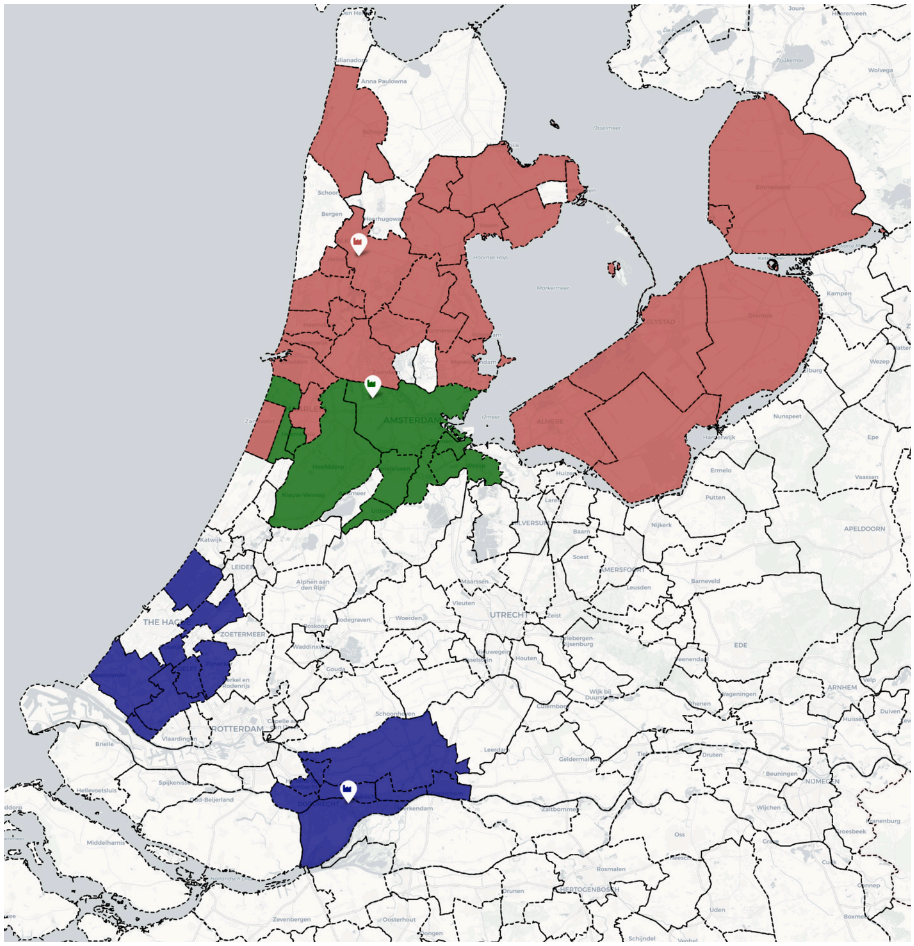


Fig. 2. Overview of incineration locations in our case study and their respective customer municipalities. The red municipalities transport their waste to HVC Alkmaar (which is located at the red icon), the green municipalities to AEB (which is located at the green icon), and the blue municipalities to HVC Dordrecht (which is located at the blue icon). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

steps of 0.1. The reason for measuring the senstivity with respect to the amount of waste is the steady reduction of residual household waste generation in the Netherlands (Centraal Bureau voor de Statistiek, 2024c). We show the outcomes of this analysis in Fig. 5. We find that even for a large reduction in waste generation the same number of electric pushers is used. When waste generation would reduce by 40%, we find that diesel ships are preferred by the model as can be seen in Fig. 5b. This is because diesel ships can be chartered and thus have lower fixed costs than electric pushers. If electric pushers could be chartered we would see similar results for electric pushers. For policymakers our findings are reassuring that waste transport over water will still be beneficial should residual household waste generation keep declining. When waste generation increases, we see that more pushers can be used in the network. This result is as expected, as the same routes can be used with more ships if waste generation increases.

Sensitivity with respect to the electric pusher costs

While the costs for trucks and diesel cargo ships come from rigorous studies, the costs for electric pusher boats are more uncertain due to their relative novelty. As electric pushers are made to order we only have an estimation of cost from the manufacturer (KOTUG International, ‘Personal Communications’, 2024), and thus, the costs of a specific electric pusher might end up significantly higher or lower. In addition, commercial electricity prices in the Netherlands can be volatile (Centraal Bureau voor de Statistiek, 2025)), and may influence the financial viability of using electric pushers. Therefore, we study what happens when we vary both the fixed and variable costs for pushers. We apply a multiplier to these costs and calculate the optimal solution, and then we plot the number of pushers used in the final solution. These results are shown in Fig. 6. When the electric pushers are cheap, we see that three pushers are used in the system. Two pushers are used for multipliers between 0.6 and 2.1. We plot the costs for the optimal solution using diesel ships as well. Here, we find that at a multiplier of 1.2 the diesel ships become the cheapest solution. We believe our estimation for the electric pusher costs to be realistic. Due to the small difference, policymakers should get detailed offers from possible contractors before making final decisions on the choice between electric and diesel. However, when policymakers prefer to reduce emissions, even if this comes at a higher costs, the electric ships are clearly the more sustainable choice.

Sensitivity with respect to the transshipment costs

Our estimation of transshipment costs is based on several sources, but as noted in Section 1 requires some assumptions. Therefore, we apply a multiplier to this parameter to see the effect it has on the final solution. Even for a large increase ($\times$ 3) or decrease ($\times$ 0.5) in transshipment costs we find that two pushers is the optimal solution. Only if we multiply the costs by four do we find that the solution with only trucks is chosen.

Sensitivity with respect to the distance to the transshipment points

The availability of transshipment points is subject to many local variables such as land ownership, environmental protections, accessibility, etc. Therefore, we test what would happen if the trucks would

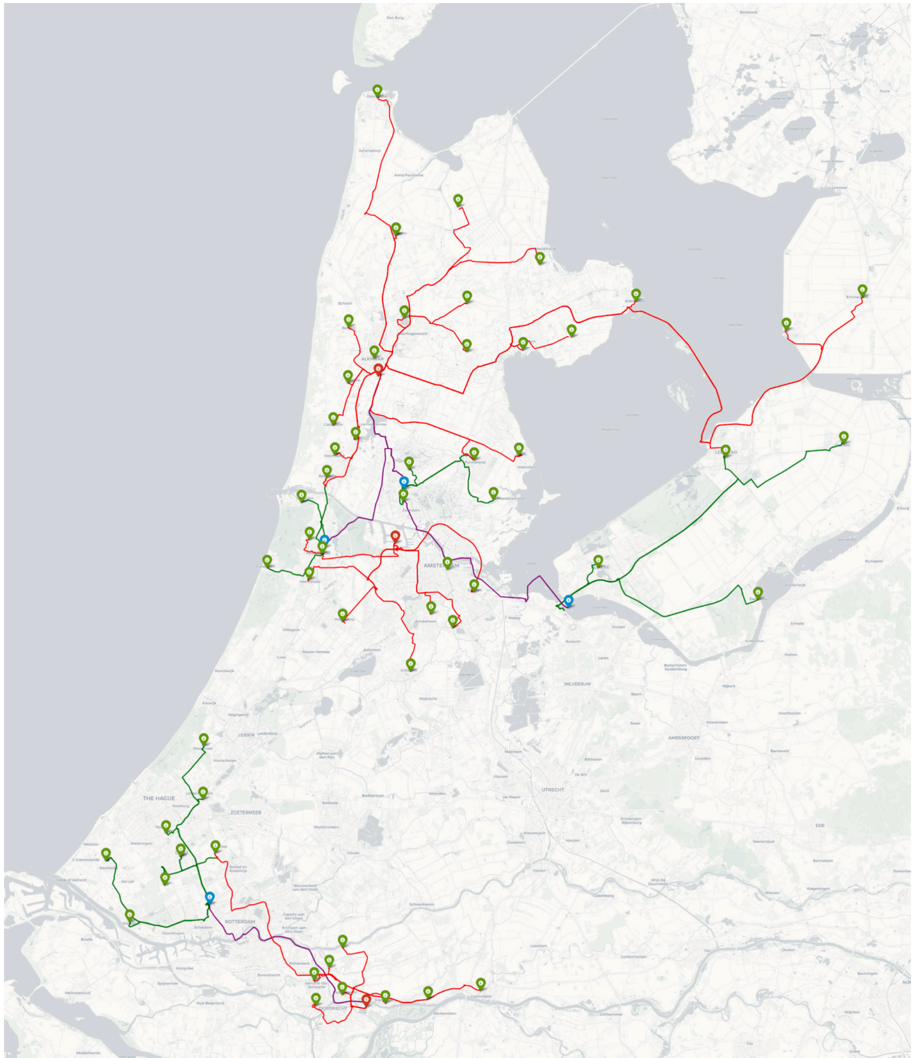


Fig. 3. The results for the case study in the Netherlands. Green lines indicate truck routes to transshipment points, red lines truck routes to processing plants and purple lines ship routes. The green icons indicate source municipalities, red icons processing plants, and blue icons transshipment points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Properties of found solutions for different transport modes.

Transport methods	Cost (€)	kg CO_2-eq	Total truck tkm
Trucks only	68,214	72,716	346,264
Trucks and electric pushers	55,161	42,646	189,197
Trucks and diesel cargo ships	57,025	52,046	176,326

need to travel further to reach the transshipment points. We do this to determine how sensitive the model is to our chosen transshipment point locations. The results of this experiment are shown in Fig. 7. We find that even when trucks would have to drive significantly further, 10 km, the electric pushers are still the preferred option. Only when the distance becomes 20 km do we find that using trucks is optimal. To put this distance into context, the longest distance from a municipality to its transshipment point is 50 km. For most municipalities it is however much lower, around 20 km. An additional 10 km would thus mean an increase of between 20% and 50%, and be quite significant. It seems likely that policymakers can find a suitable transshipment location in such a large area. We should note that we only looked at increasing all distances, rather than increasing the distance to one transshipment point at a time. This is experiment is therefore very much a worst-case

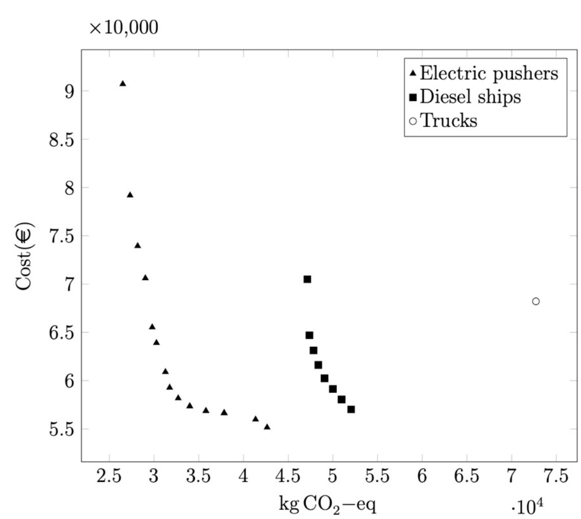
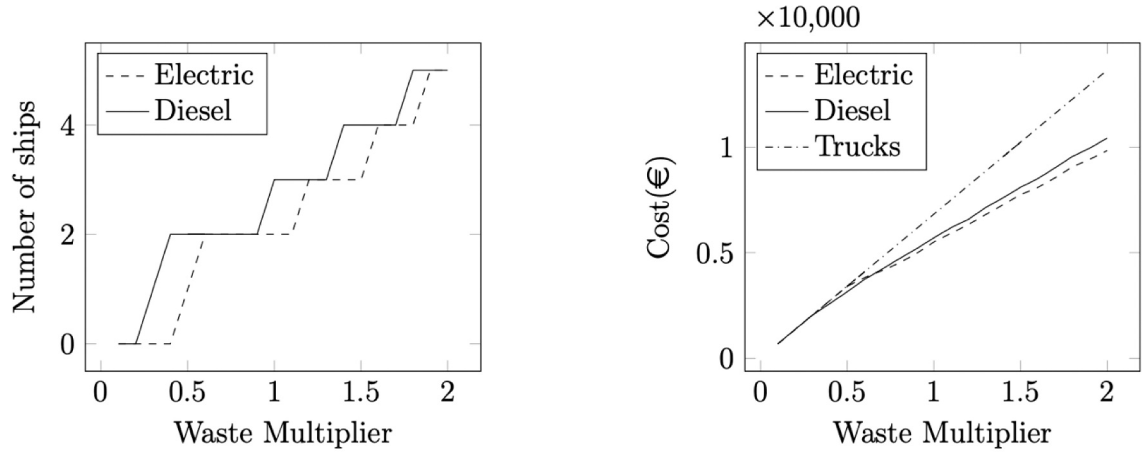


Fig. 4. Pareto front showing the trade-off between emissions and costs.



(a) Number of ships (b) Cost

Fig. 5. Varying the amount of waste produced by the municipalities.

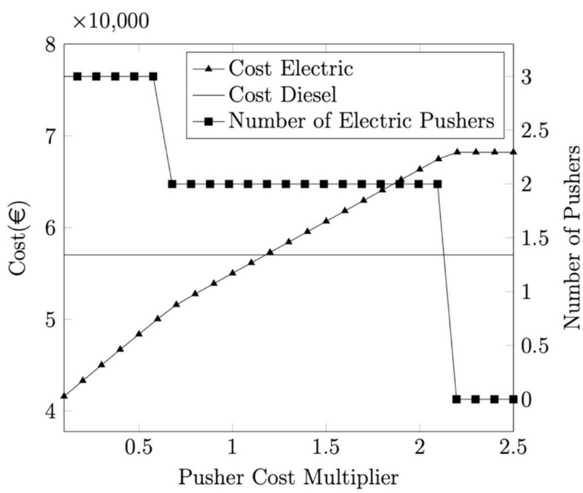


Fig. 6. Comparing the number of electric pushers used and solution costs for a varying pusher costs.

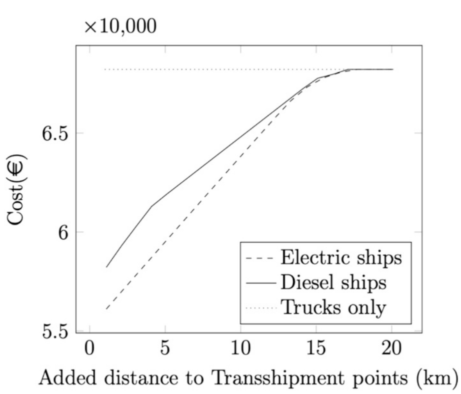


Fig. 7. Adding distance needed to travel to transshipment points.

scenario, and it seems that the solutions are more than sufficiently robust.

Sensitivity with respect to the exclusivity of the transshipment facilities

In this experiment, we look at a system where transshipment facilities are specific to municipalities. We rerun our model, but with a different set of potential transshipment points. For each municipality, we take the closest suitable waterway and allow the construction for a transshipment servicing that municipality only at that location. We find that no pushers are used by the final solution, as both pushers are no longer financially viable. This causes a very significant increase in cost, emissions, and total truck kilometres. Allowing municipalities to cooperate when building facilities would therefore help make inland waterway transport competitive.

6. Discussion and concluding remarks

In this research we studied different modes of transport for residual household waste logistics. A case study covering municipalities in three Dutch provinces was presented and covered in-depth. Data was retrieved from a number of public and private sources to support the case study. We introduced a Mixed Integer Linear Programming formulation to find the optimal combination of inland shipping and truck routes for the case study. We set out to answer the following research questions:

1. Would transporting residual household waste using waterways in the Netherlands, compared to the standard practice of truck transport, results in a reduction of system operating costs?
2. In addition to Question 1, would a modal shift to ships result in non-financial benefits, such as a reduction in CO_2 emissions or waste-related truck traffic?

Our findings provide clear anwers to both research questions. Regarding Question 1, It was found that using electric pusher ships can reduce costs by 19%, and that diesel ships also outperform truck-only solutions, althought to a lesser extent.

For Question 2 we found that a shift to electric pushers reduced emissions on the network by 41%, in addition to reducing the amount of heavy traffic for household residual waste logistics on the road (48%). Diesel cargo ships also outperformed the truck-only solutions on these societal measures, performing worse than the electric pusher ships regarding emissions, but better on the amount of trucks taken of the road. The sensitivity of the solutions was tested by varying a number of parameters, and it was found that the solutions are fairly robust with respect to parameter choice.

The conclusions from this research strengthen the suggestion to use inland waterways for shipping waste in the Netherlands, for which quantitative analysis at this scale was not yet done. Particularly noteworthy is our finding that, in our case study, cooperation between municipalities is essential to ensure the system's financial viability.

There are several potential practical limitations which have not been taken into account in the model. Household waste is generally a pollutant, and transporting such a pollutant over water might increase risk of environmental spills. Van Rhijn et al. (2023) consider several methods of transporting household waste using ships. In this paper we consider loose transport of bulk waste, which would require sufficient measures at the transshipment points to prevent environmental spills (Van Rhijn et al., 2023). Waste could be compacted into bales at the transshipment point and covered with plastic. Such packing material would not reusable and therefore less sustainable. The risk of evironmental spills would however be greatly reduced and this method has been succesfully attempted as part of pilot in the Netherlands (Van Rhijn et al., 2023).

In addition, shifting waste transport from traditional truck routes to waterways might cause aditional strain on waterway networks, resulting in congestion problems. Our discussions with policymakers lead us to believe this is not a significant risk in the studied areas, which the authors of Van Rhijn et al. (2023) also report. When finalizing routes, further research should be done on the impact of this modal shift at specific bottlenecks such as locks, bridges, etc.

Ships might also be more sensitive to extreme weather events, such as low water due to upstream droughts (Waterrecreatie Nederland, 2018) or high winds. A report by Dutch research institute Deltares discusses the sensitivity of different transport networks in the Netherlands (Bles et al., 2021) to climate change and extreme weather. Policy makers should take the sensitivity of shipping networks into account when considering a modal shift.

Regulatory requirements are also not taken into account in our model. In the research by Van Rhijn et al. (2023), the authors note that several permits are required to transport household waste with ships. From experience with pilot projects, they find that the storage and transshipment are subject to the strictest rulesets. They specify that the earlier mentioned plastic wrapped bales were found to satisfy requirements (Van Rhijn et al., 2023). Further investigation should be done into regulatory limitations that might prevent a modal shift for household waste, especially as regulations may be highly localized. Further specific, potentially blocking, legal context such as contracts with truck operators are outside the scope of this research but should be taken into account by policy makers.

In addition to our research, policymakers should examine more specific data on transshipment location availability and conduct a more detailed cost analysis for opening a transshipment point. Such site-specific analyses would take significant resources and are not viable at this stage of research but would be required to make shipping waste over inland waterways a reality. Policymakers in other countries might not find the inland waterway network as extensive as in the Netherlands. Therefore, further research could focus on extending the model to include railways, which in other countries might be more available than inland waterways. According to our government partners, the excess capacity on the Dutch railways is lower than on the inland waterways, leading to our decision to focus on inland waterways. In addition, the case study in this paper could be extended to include more municipalities and incineration plants in the Netherlands to test how general the conclusions of this research are. Given the minimal computation time needed for our case study, extending the analysis relies primarily on gathering additional data rather than improving the proposed computational method.

CRediT authorship contribution statement

Jesse Nagel: Writing – original draft, Visualization, Validation, Software, Conceptualization. **Joris Slootweg:** Writing – review & editing, Validation. **Dede Mehmet Eğirgen:** Software, Methodology, Conceptualization. **Chaima Fathi:** Methodology, Formal analysis, Conceptualization. **Jordan Ratnavelayutham:** Software, Methodology, Conceptualization. **Nicky Trijbits:** Writing – original draft, Methodology, Data curation, Conceptualization. **Ole Vriethoff:** Software, Methodology, Conceptualization. **Janneke Tack:** Supervision, Conceptualization. **Elles de Vries:** . **Rob van der Mei:** .

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2025.115241.

Data availability

Data will be made available on request.

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