A Mixed Integer Linear Programming model for CO_2 emissions minimization in a waste transfer Facility Location Problem

Giulia Caselli
School of Doctorate E4E, University of Modena and Reggio Emilia, Italy
giulia.caselli@unimore.it

Giomaria Columbu
School of Doctorate E4E, University of Modena and Reggio Emilia, Italy
Iren Ambiente S.p.A., Reggio Emilia, Italy
giomaria.columbu@unimore.it

Manuel Iori
Department of Sciences and Methods for Engineering, University of Modena and Reggio Emilia, Italy
manuel.iori@unimore.it

Carlo Alberto Magni
School of Doctorate E4E, University of Modena and Reggio Emilia, Italy
magni@unimore.it

ABSTRACT

In this work, we solve a real-world facility location problem by means of a mixed integer linear programming model. The problem is faced by an Italian multi-utility company operating in the sector of waste management. The company works in several Italian regions to collect and treat the urban waste through a network of facilities. In this problem, a set of demand points is given with a predicted quantity of waste to be collected and a fixed number of visits required over a predetermined time horizon. The flow of different classes of recyclable waste must be optimized by deciding whether and where to open additional intermediate transfer facilities among a set of dedicated points. The aim is to minimize the CO_2 emissions involved in the process, including emissions from the use of additional facilities and the transport of waste across the network. We provide a mathematical formulation for the problem, and use it to solve a real-world case study. An optimal solution is obtained with a significant reduction in CO_2 emissions and a well-structured network, proving the efficacy of the model.

1 INTRODUCTION

Waste management is a general term referring to the set of activities related to collection, transport, treatment and disposal of waste, and, in addition, control and prevention actions across the whole process. The increasing amount and complexity of waste generated by modern societies has indeed raised major sustainability-related concern around governments, firms, and individuals. As a consequence, waste management has been recently connected to environmental issues, as stated, for example, by Tolaymat et al. [27], who referred to waste management as the link between all the subjects involved in the waste production network and the societal entities taking care of environmental goals. The significant environmental impact of the waste industry is well known and reduction measures have been already introduced in many systems (e.g., ReVelle [24]) to cut the amount of greenhouse gas emissions along the process (e.g., products' recycling and salvage, collection routing optimization).

Many strategic and operational problems related to each phase of the waste management process have been studied in the literature for decades, confirming a high interest of both researchers and practitioners in this field. Operational problems refer to short-term optimization decisions like routing and scheduling problems. In this Operations Research context, the literature on the classical Vehicle Routing Problem (VRP) applied to waste collection contexts is huge (e.g., Golden et al. [13]). Strategic problems refer, instead, to medium- and long-term design and management decisions to optimize the waste collection and treatment network, including the location of different facilities (e.g., collection points, intermediate transfer facilities, final treatment facilities, and landfills). The Operations Research area of Facility Location Problems (FLPs) is addressed in this context (e.g., Van Engeland et al. [29]).

This work deals with a specific FLP in the context of urban waste collection, that is, the collection of urban waste from multiple sources and its transport to the treatment or disposal plants. The activity is typically managed by municipal services or by public or private corporations. In this work, we study the strategic problem of transfer facility location to minimize CO_2 emissions, by considering the transfer phase of urban plastics and paper waste carried out by Iren Ambiente S.p.A., an Italian multi-utility private company.

Iren Ambiente is a division of Iren Group, an industrial holding company operating in the Italian market of multi-utilities. Iren Ambiente manages the operations of waste collection, treatment and disposal, designs waste treatment and disposal systems, and controls renewable energy systems in several areas of Italian regions (mainly Emilia Romagna, Piemonte, Liguria, Lombardia, and Sardegna). Our case study refers to the region of Emilia Romagna.

The specific problem studied in this work only considers the transfer of waste, excluding downstream and upstream processes of waste production and treatment or disposal (and the related CO_2 emissions), even tough the entire waste management process is managed by the company in its assigned areas.

The problem is a particular Capacitated Facility Location Problem (CFLP) (i.e., a FLP where facilities have limited capacity), which we solve by means of a Mixed Integer Linear Programming (MILP) model. The goal is to determine the optimal network in real-world scenarios, evaluating how many intermediate transfer locations must be opened and where they must be located to minimize the total CO_2 emissions produced during the process (i.e., facilities' and vehicles' emissions) over a fixed time horizon.

The rest of the paper is organized as follows. A summary of the related literature is given in Section 2. In Section 3, we provide a detailed description of the problem and present our mathematical model. Section 4 reports the results obtained by the proposed solution method on our real-world case study. Concluding remarks are provided in Section 5.

2 LITERATURE REVIEW

Reverse logistics commonly refers to the set of activities and processes related to the flow of raw material, inventory, and finished goods other than waste from the point of consumption back to the origin point. Back in 1998, Carter and Ellram [3] already referred to reverse logistics as the practice whereby firms can become more environmentally efficient by, for example, recovering material and recycling products. A review on reverse logistics is given by Govindan et al. [15]. A restricted field of study on environment-related reverse logistics problems is labelled in the literature as "green logistics". A review on green logistics and related combinatorial optimization problems is given by Sbihi and Eglese [25].

Waste management is the reverse logistic sub-field of study focusing only on waste, and more commonly on solid waste (e.g., Beliën et al. [2]). In their recent survey, Van Engeland et al. [29] reviewed the literature of the so-called waste reverse supply chain, identified as the overlapping subject between waste management and the broader reverse logistic. Collection, transportation, recovery, and disposal of waste are included in the waste reverse supply chain, where several problems are solved with the aim of creating value at three different levels of management decisions: (i) long-term strategic decisions of waste network design; (ii) medium-term decisions (e.g., waste quantities and capacity allocation), and (iii) short-term operational decisions like routing and scheduling. In our work, we are interested only in the first decision level.

Focusing on the area of long-term strategic network design problems, Van Engeland et al. [29] surveyed the extensive literature of the period 1995-2020, providing a classification of strategic network design problems and their combinatorial optimization solution methods based on several characteristics: single- or multi-period decisions, single- or multi-product problems, single- or multi-objective optimization, with specific constraints and different objective functions. They found that 60% of collected works dealt with single-objective functions, representing cost minimization or profit maximization in around 95% of the cases. Only one out of 133 articles surveyed in this work was categorized as a carbon emissions-related single-objective model. In this regard, our work is an attempt to extend this branch of the literature. In multi-objective models, instead, environmental goals are often included and balanced with economic ones, such as the minimization of CO_2 emissions or energy use. Talaei et al. [26] solved a bi-objective cost-emissions minimization facility location-allocation problem for a closed-loop supply chain. They developed an ϵ-constrained method where the higher priority cost function was used as the objective function, and the CO_2 emissions function formed the ϵ-based constraints. Sometimes, the social impact is also included in multi-objective problems. For example, Govindan et al. [14] proposed a multi-objective MILP model for the closed-loop supply chain network of a generic product recovery system, including in the objective function the minimization of carbon emissions and social impact, together with the maximization of revenues. Mirdar Harijani et al. [21] developed a multi-objective model for sustainable recycling of municipal solid waste with similar economic, environmental, and social goals.

In the Operations Research literature, the strategic problems defined above are classified under the broad category of FLPs; they have been of great interest since the 1960s. In their book, Farahani and Hekmatfar [9] defined FLP as the problem of locating a set of facilities (resources) to minimize the cost of satisfying some set of demands (of the customers) with respect to some set of constraints. The authors surveyed different FLP families and related discrete and continuous optimization algorithms, along with case studies from private and public firms.

As reported by Verter [30], the classical FLP has been extended in a number of ways by, for example: (i) increasing the number of products, from single- to multi-commodity FLPs (see, e.g., Liu et al. [19], who studied a complex multi-commodity CFLP involving sustainability concerns); (ii) increasing the number of facility echelons, that is, the types of facility to locate (e.g., Gendron and Semet [11]); (iii) increasing the number of time periods included in the model, defining dynamic FLPs where the facility location is determined at each period so as to minimize the total cost over time (e.g., Nickel and Saldanha-da Gama [23]); and (iv) incorporating possible scale and scope economies in the cost function (e.g., Wu et al. [31]) and uncertainties (e.g., Correia and Saldanha-da Gama [4]).

For what concerns FLPs in the waste management industry, Adeleke and Olukanni [1] surveyed important models and solution algorithms, published between 2006 and 2020 and adapted to deal with several optimization problems. These problems are usually formulated by MILP models, but then solved in practice by means of heuristic algorithms able to find near-optimal solutions in a limited time. In the following, we mention some case studies in the urban waste management contexts. Ghiani et al. [12] studied a bin allocation problem in Italy where the aim is to minimize the total number of activated waste collection sites. The problem was solved by means of a MILP model and a constructive heuristic. Lee et al. [18] proposed several mathematical models for the waste management system of Hong Kong, in which they minimize the total cost for the municipal solid waste management system (i.e., daily waste management costs, transportation costs, net of the revenues from incinerators). Dimitrijević et al. [6] applied a bi-objective optimization model to a landfills' location problem belonging to the class of so-called Undesired FLPs, where the economic objective asks for minimizing total costs (i.e., costs generated by establishing new facilities and satisfying the demand) while the social objective concerns the total number of end users undesirably influenced by new landfills. Gambella et al. [10] studied a facility location and waste flow allocation problem. They developed a stochastic programming model that was applied to solve a real-world Italian case study.

A relevant part of the current literature on waste transfer FLPs includes environmental concerns in the problem statement and in the model formulation. A summary of the main concepts and models for the so-called Green FLP was included in 2017 by Martínez and Fransoo [20]. The focus of their work is on the transportation performance of firms in terms of both costs and emissions, which is strongly determined by the design of the network. In the models under review, the main sources of CO_2 emissions associated with the location of facilities derive from both mobile sources (transportation) and stationary sources (production, storage, and handling). In 2002, environmental qualitative and quantitative evaluations have been combined with a MILP model and multi-criteria methods by Vaillancourt and Waaub [28] to solve waste facility location problems similar to our problem. Valuable results have been obtained on a case study of the city of Montreal, Canada. Some more recent real-world examples of green FLPs are the works by Mohsenizadeh et al. [22], who solved a bi-objective cost-pollution transfer stations location problem in Ankara, by Kudela et al. [17] who addressed a case study for the Czech Republic, and by Eiselt and Marianov [8], who minimized a bi-objective cost-pollution function in a real-world Chilean landfills' location problem.

As stressed by Martínez and Fransoo [20], not many companies have implemented in practice facility locations strategies to reduce their environmental impact, especially as primary goal, although a considerable amount of theoretical work is already available in the literature. In this respect, our work is an attempt to provide an example of application of green FLPs in practice and contribute to the relevant literature.

3 PROBLEM DESCRIPTION AND MATHEMATICAL MODEL

In this section, we describe the CFLP addressed by Iren Ambiente, introduce the mathematical notation, and present the proposed MILP model that we developed.

With the aim of optimizing the waste transfer logistics in a specific area, the number of demand points to be visited (i.e., locations, number of visits, and types and quantities of waste) is assumed to be known and fixed over a limited time horizon (one year) as estimated from past data and budgets. The number of intermediate transfer locations and final treatment locations to open and the flow across the network are the decisions to be made in the problem. Representing a real-world scenario, we assume that some facilities are already open and must stay open even in the optimized scenario. One or more locations are given as candidate locations where a facility can be opened (e.g., areas already owned by the company and activated in the past). The goal is to find the optimal waste transfer network (i.e., locations and flow) that minimizes the total CO_2 emissions involved in the overall process of collection, transfer, and delivery of waste to final treatment plants.

A set I of customers to be visited (i.e., demand points where waste must be collected) is given over a limited time horizon. The total estimated amount of waste produced by each customer over the considered time period must be collected and delivered to final treatment facilities, either directly or passing by one or more intermediate transfer facilities. We call J the set of all candidate facility locations, and J_e the subset of locations where a facility already exists and is open. In addition, we call J_1 the subset of intermediate candidate facility locations. We denote by H the set of recyclable waste types, such as paper, plastics, and glass (i.e., we deal with a multi-commodity CFLP).

Let q_{ih} indicate the total estimated quantity of waste type h to be collected from customer i over the considered time period, and let n_{ih} represent the corresponding required number of trips. The value of n_{ih} is predetermined by the municipality (e.g., paper waste is collected once or twice per week). For each facility location j, we define Q_j as the overall waste capacity and Q_{jh} as the capacity for waste type h, where $Q_j \leq \sum_{h\in H} Q_{jh}$. For example, if a location j has $Q_j = 100$ tons and $Q_{jh} = [70, 60]$ tons for $h = 2$, then we can dedicate half capacity to each waste (i.e., $[50, 50]$ tons), or we can accept an unbalanced solution without exceeding the Q_{jh} values (e.g., $[70, 30]$ tons).

For CO_2 emissions minimization, we introduce the parameters e_{ijh}, for $i \in I, j \in J, h \in H$, and e'_{jkh}, for $j \in J_1, k \in J, h \in H$. The former estimates transport emissions for waste type h from customer i to facility j, while the latter from intermediate facility j to facility k. Parameters e_{ijh} consider, for each customer i, the type of vehicle that serves it, the time required by the vehicle to go from customer i to facility j, its fuel consumption, the conversion factor, and the number n_{ih} of required trips over the selected time horizon (i.e., $[\frac{kgCO_2}{year}]$). Parameters e'_{jkh} consider the capacity of the loading vehicle in use at each facility j, its time to move from facility j to facility k, and its fuel consumption to compute the carbon emissions for a single tripe from j to k (i.e., $[\frac{kgCO_2}{ton}]$).

In addition, let p_{jh} and F_j represent, respectively, variable and fixed components of emissions generated by opening a new facility $j \in J$. For each facility we estimate a different percentage of emissions for fixed and variable components, depending on the energy consumption of the operating machines in the facility, i.e., the equipment used for loading, unloading, and moving waste. The greater the amount of waste collected by a single facility, the greater the environmental benefit from opening that facility.

To formulate our MILP model, we introduce a set of three-index variables x_{ijh} that indicate the fraction of waste of type h collected at customer $i \in I$ and transferred to location $j \in J$ in the overall considered period. The variable is continuous, implying that each customer demand can be fulfilled by one or more facilities. An additional set of non-negative continuous variables f_{jkh} represents the flow of waste transferred from intermediate location $j \in J_1$ to intermediate/final location $k \in J, j \neq k$. Then, binary variables y_j take the value 1 if location $j \in J$ is open, and 0 otherwise.

The problem is modelled as follows:

$$\min \sum_{i\in I}\sum_{j\in J}\sum_{h\in H} e_{ijh}x_{ijh} + \sum_{j\in J_1}\sum_{\substack{k\in J\\ j\neq k}}\sum_{h\in H} e'_{jkh}f_{jkh} + \sum_{k\in J}\sum_{h\in H} p_{kh}\Big(\sum_{i\in I} q_{ih}x_{ikh} + \sum_{\substack{j\in J_1\\ j\neq k}} f_{jkh}\Big) + \sum_{j\in J} F_j y_j \tag{1}$$

$$\text{s.t.} \quad \sum_{j\in J} x_{ijh} = 1 \qquad i \in I, h \in H \tag{2}$$

$$\sum_{i\in I} q_{ih}x_{ikh} + \sum_{\substack{j\in J_1\\ j\neq k}} f_{jkh} \leq Q_{kh}y_k \qquad k \in J, h \in H \tag{3}$$

$$\sum_{i\in I}\sum_{h\in H} q_{ih}x_{ikh} + \sum_{\substack{j\in J_1\\ j\neq k}}\sum_{h\in H} f_{jkh} \leq Q_k y_k \qquad k \in J \tag{4}$$

$$\sum_{i \in I} q_{ih} x_{ikh} + \sum_{\substack{j \in J_1 \\ j \neq k}} f_{jkh} - \sum_{\substack{l \in J \\ l \neq k}} f_{klh} = 0 \qquad k \in J_1, h \in H \quad (5)$$

$$y_j = 1 \qquad j \in J_e \quad (6)$$

$$0 \leq x_{ijh} \leq 1 \qquad i \in I, j \in J, h \in H \quad (7)$$

$$f_{jkh} \geq 0 \qquad j \in J_1, k \in J, j \neq k, h \in H \quad (8)$$

$$y_j \in \{0, 1\} \qquad j \in J \quad (9)$$

The objective function (1) minimizes the total amount of CO_2 emissions involved in the process in one year: the first two terms count the emissions from vehicles' travels for customer-facility and facility-facility trips respectively, while the third and fourth terms consider the emissions generated by the working facilities, addressing variable and fixed components of CO_2 emissions respectively. Constraint (2) ensures that each waste demand is fulfilled by one or more facilities sharing its entire demand over the considered period. Constraints (3) and (4) represent the overall and waste-specific capacity constraints for each facility j. Constraint (5) guarantees the conservation of flow for each intermediate facility (i.e., the total incoming flow from customers and other intermediate facilities is equal to the flow going out to other facilities). Constraint (6) imposes that existing facilities are kept open by the model solution. Constraints (7)-(9) give the domain of the variables.

4 CASE STUDY

In this section, we study the performance of model (1)-(9) on a realistic instance from Iren Ambiente. Our model has been coded in the Mosel language and solved with FICO Xpress Solver 64bit v8.9.0 on an Intel Core i7, 1.80 GHz, with 16 GB of RAM memory, running under Windows 10 64 bits.

The company collects the waste of 34 municipalities serving approximately 460,000 inhabitants in the province of Reggio Emilia, for a total quantity of nearly 330,000 tons of urban waste per year. Such activity consists in moving vehicles from the depots, collecting waste from the municipalities and transporting them to the final treatment or disposal plants, and bringing back the vehicles to the original depots. This does not exclude the possibility of including intermediate transfer facilities, so as to allow waste flows from municipalities to intermediate points, between intermediate points, and from intermediate points to final plants. The company is currently building a new final treatment facility close to the Reggio Emilia district, where the entire volume of plastic and paper urban waste from the entire area of the district could be possibly conferred. The company wants to optimize the future waste collection network, also evaluating whether and where it could be convenient to open additional intermediate waste transfer facilities.

In this strategic decision, the company has been moved, first and foremost, by environmental issues rather than economic concern, under the increasing pressure of the European Union and other international entities for providing more environmentally efficient waste management solutions (see, e.g., [7] and [16]).

In our case study, we use the data on paper and plastic waste collected in the province of Reggio Emilia over a one-year time period (i.e., from October 2019 to October 2020), which is also the time horizon adopted for our model. A preliminary analysis has confirmed that the emergency situation due to Covid-19 pandemics did not affect the urban waste industry significantly, nor was Iren Ambiente's business specifically impacted. In Reggio Emilia district, there are several waste collection points distributed over 34 municipalities. As requested by the company, we aggregate points to find stable solutions by merging similar weekly repetitive patterns of waste collection services. Municipalities are clustered based on several characteristics (e.g., distance, number of inhabitants, balanced number of units per cluster, business constraints). From the clustering, we obtain 18 clusters.

Each cluster represents a service to be fulfilled over the considered time period; it is characterized by: (i) a total predicted quantity of waste to be collected for paper and plastic, respectively; and (ii) a required number of visits and a type of serving vehicle (assumed to serve at full capacity for the sake of simplicity), which, in our analysis, is significant only for the overall impact on CO_2 emissions. The total demand for waste collection from the 18 clusters in a year is equal to 27,532 tons of paper and 16,098 tons of plastic.

The overall capacity of the one final treatment location under construction is equal to 50,000 tons, distributed as 32,000 and 18,000 tons for paper and plastic, respectively. Two candidate locations for intermediate transfer facilities are considered following the strategic guidelines of the company and the clustering logic. For each possible location, 16 different options for its paper and plastic capacities are considered. Total capacities of intermediate candidate facilities range between 540 and 32,000 tons of waste.

In the computation of CO_2 emissions, we consider fuel consumption and gross weight of the different diesel Euro 6 vehicles (ranging between 3 and 15 liters per hour, and 3.5 and 38 tons, respectively). Fuel consumption is converted in CO_2 emissions with the conversion factor (2.63 kg CO_2 per l) taken by (DEFRA) [5]. The number of visits for each cluster is computed over the entire period starting from given weekly requirements (e.g., one or two visits per week for plastic). For emissions generated by building and opening a new facility, we consider some estimations of consumption and productivity done by the company, and a different percentage addressed to the fixed and variable components for each candidate location (e.g., 14% and 86%, respectively).

Our model was able to find an optimal solution in 0.83 seconds of CPU time. We compare two optimal solutions: the one generated by the model assuming additional intermediate transfer locations and the one generated by the model in the absence of intermediate facilities (i.e., the final treatment facility collects the whole waste flow of Reggio Emilia district). The networks resulting from the two solutions are represented in Figures 1 and 2. Red points indicate facilities, with names in black color for final treatment facilities and in purple color for intermediate transfer facilities. Green points indicate the centroids of the municipalities. Waste flows are represented by dashed lines and numbers (tons of waste), where plastic waste flows are in red and paper waste flows are in blue.

Figure 1 represents the optimal solution on the reduced instance with the only final treatment facility (i.e., "C1 RE") open. This first network connects all the clusters to the final treatment plant, with an overall amount of 1,407.7 tons of CO_2 emissions. The solution has been obtained by the model in 0.15 seconds of CPU time.

Figure 2 represents the optimal flow on the complete instance. The model opens two intermediate locations both for paper and

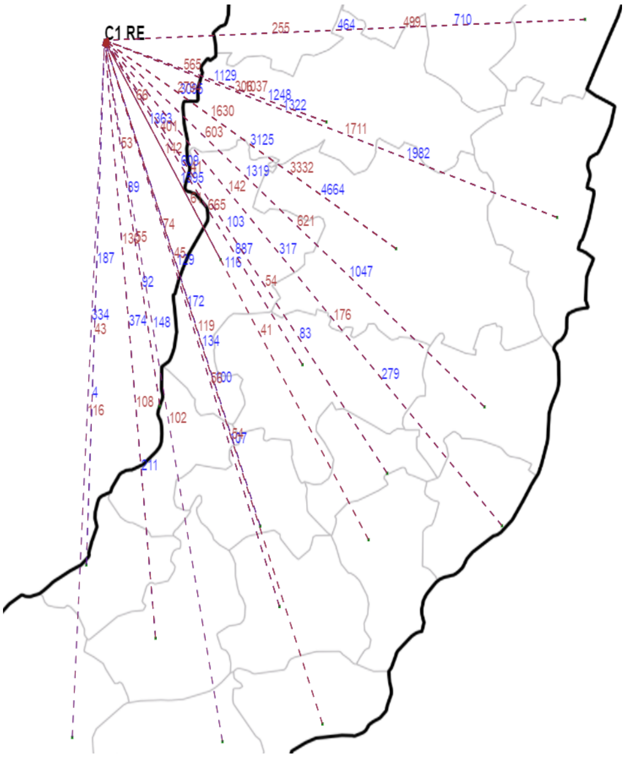

Figure 1: Solution without intermediate facilities

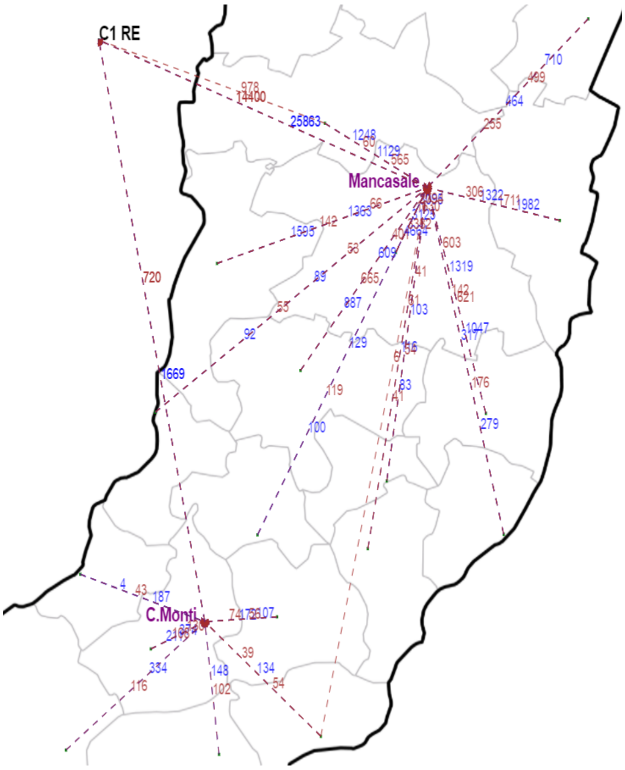

Figure 2: Solution with intermediate facilities

Table 1: Summary of case study results on plastic waste

	Plastic waste		
Facility	C [ton]	F^a [ton]	Sat.
Final *"C1 RE"*	18,000	16,098	89%
Intermediate *"Mancasale"*	14,400	14,400	100%
Intermediate *"C. Monti"*	720	720	100%

[a] Total incoming flow from collection points and intermediate facilities

Table 2: Summary of case study results on paper waste

	Paper waste		
Facility	C [ton]	F^a [ton]	Sat.
Final *"C1 RE"*	32,000	27,532	86%
Intermediate *"Mancasale"*	28,800	25,863	90%
Intermediate *"C. Monti"*	1,920	1,669	87%

[a] Total incoming flow from collection points and intermediate facilities

plastic waste in the two different candidate locations (i.e., "Mancasale" and "C. Monti"). In this extended network, we obtain a 25% reduction in the total amount of CO_2 emissions with respect to the value of the previous solution, and an efficient flow of waste. Almost all the waste flow is delivered to intermediate facilities, apart from a fraction generated by one cluster , which is the nearest one to the final plant in the north-west area of the district. The southern intermediate facility in "C. Monti" has lower capacities, in accordance to the lower quantities of waste produced by the clusters in the south of the district (mainly upland) with respect to the north area (which concentrates the waste produced by the main city of the district, Reggio Emilia, and other urban areas).

Tables 1-2 report the results obtained by the model on the case study in terms of overall capacity (C) and incoming flow (F) for each open intermediate location, expressed in tons of waste for plastic and paper, respectively. For the sake of clarity, results for the final treatment facility are also included, although its capacity was predetermined by the model input data. Plants' saturation (Sat.) is also reported, proving the efficiency of the solution with all facilities' capacity almost saturated. Indeed, they are all greater than 85%, and equal to 100% in the case of intermediate facilities for plastic waste. Note that saturation of travels between facilities is important because waste from different travels converge to intermediate facilities before being transported to the final one. The more the intermediate facilities are saturated, the more the second-level trips (i.e., from intermediate to final facility) can be aggregated.

5 CONCLUSIONS AND FUTURE RESEARCH

In this work, we have studied a real-world capacitated facility location problem occurring in an Italian multi-utility company. The goal is to define the optimal network of final treatment and intermediate transfer facilities in the district of Reggio Emilia (Italy) for plastic and paper waste collection to minimize CO_2 emissions generated by the on-road transfer of waste with heavy vehicles and by the opening of new facilities.

We have modelled the problem by means of a mixed integer linear programming formulation, where binary variables define which facility should be open among a set of candidate facility locations and which capacity should be employed, and continuous variables define the flow between customers and facilities and between different facilities. The model enables dividing the waste demand of each customer among one or more facilities, ensuring that the total and waste-specific capacity constraints for each facility are satisfied.

The model is general, so as to be applied to different case studies of waste collection that appears in the literature and in different real-world contexts. On the other hand, the model considers environmental issues as the single objective. While not so common in the literature, it is nonetheless very important, considering the current situation of the increasing waste industry and the corresponding governments' attention to this topic.

We have solved a real-world case study of our industrial partner by means of the proposed mathematical model, obtaining significant results on an aggregated one-year instance. The model has provided an optimal solution in less than 1 second of computation, with a 25% reduction in CO_2 emissions with respect to the case in which only one final facility (currently under construction) is open. The resulting flow and saturation of new facilities are well-structured. To further test our model, it would be interesting also to solve each daily instance of the considered year, and then sum the results over the total number of days. That could provide more insight on the solution obtained for the single aggregated instance.

In view of the good results, we plan to further work on this problem. First, we plan to study a bi-objective formulation for the problem in order to consider economic as well as environmental goals. The idea is to investigate the investment in new facilities and measure the economic value created (as expressed by the project Net Present Value) also performing a sensitivity analysis for detecting the parameters that have the greatest impact on the objective function.

Moreover, we plan to provide a more extensive computational evaluation of our model, testing it on other real-world scenarios and on more complex random instances, to better evaluate the performance and scalability of the proposed model.

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