Chapter 14
A Sustainable Reverse Logistics System: A Retrofit Case

Abstract This chapter presents a real case study of a recyclable waste collection system aiming at redesigning service areas and associated vehicle collection routes to support a sustainable operation. Not only economic objectives are to be considered, but also one should account for environmental and social aspects. The economic dimension is modeled through traveling distance that directly influences the global cost. The environmental one is modeled throughout the calculations of the CO_2 emissions. Finally, the social aspect is considered by aiming to define a balanced solution regarding working hours among drivers. A multi-objective solution approach based on mixed-integer linear programming models is developed and applied to real data.

Keywords Carbon dioxide emissions · Global cost · Multi-objective programming · Routing problem · Working hours

14.1 Introduction

Waste collection systems usually plan their operations according to administrative territorial boundaries (e.g. municipalities, county, district…). Even when managing two adjacent municipalities, operations are plan independently. The company studied in this chapter is no exception. All operations have been managed under a municipality perspective, i.e., the service areas of each depot and the collection routes have been defined taking into account the municipalities' boundaries. This approach has proved to be very costly and motivated the restructure of the company's tactical and operational planning decisions. Moreover, the company aims to foster the system's sustainability by integrating economic, social, and environmental objectives in the new plan.

This company responsible for the recyclable collection system covering 19 rural municipalities with a total area of 7000 km^2. It involves 1522 glass bins, 1238 paper bins, and 1205 plastic/metal bins spread over 207 sites (see Fig. 14.1). A collection site is assumed to correspond to an area instead of an individual container to reduce the problem size. Due to the proximity of the bins within an urban area (an average distance of 500 m), it is realistic to assume the containers to collect within this site as

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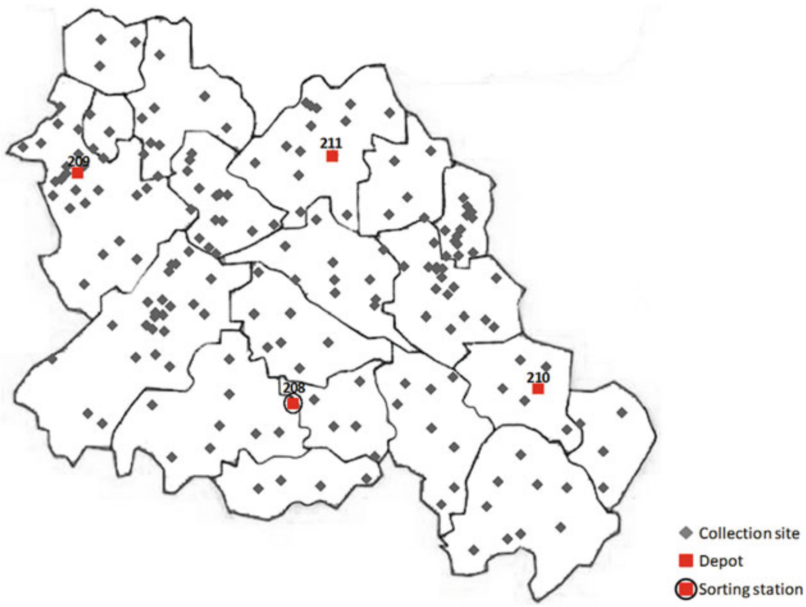


Fig. 14.1 Collection sites and depot locations

a single node. The number of containers at each site is known in advance. The company operates four depots and a vehicle fleet of eight vehicles. One of the depots acts also as a sorting station (depot 208). The remaining three depots are only transfer stations where the recyclable waste is consolidated and afterward transferred to the sorting station.

The company provided a dataset with historical data concerning all routes performed over a year. For each route, this available data contains the day, the collected recyclable material type and the corresponding number of containers, the traveled distance (in kilometers), the route duration, and the total collected weight. To estimate the collected amounts at each site and the corresponding collection frequency, the daily collected weight average per container was estimated. It took into account the time interval between two consecutive collections sites and the average collected amount per container in each route.

The three recyclable materials present different collection frequencies. Glass has to be collected every 6 weeks, plastic/metal every 3 weeks, and paper every 2 weeks. Therefore, a 6-week planning horizon is assumed. The materials are collected in separated routes since the vehicle fleet has no compartments. Taking into account the materials' densities and vehicles' maximum capacities, it was considered that vehicles can load a maximum of 8500 kg of glass, 3000 kg of paper, and 1000 kg of plastic/metal. For the outbound transportation (from the depots to the sorting station), larger vehicles are used, and their weight capacities are, under the same assumption, 12,000 kg for glass, 5000 kg for paper, and 3000 for plastic/metal.

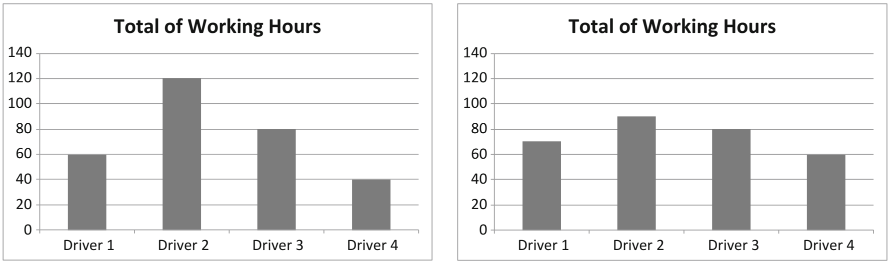
All collection routes start at a depot, visit several sites collecting a single type of material, and return to a depot to unload. Multiple trips per day, as well as inter-depot routes (routes starting and ending at different depots), are allowed. However, by the end of a working day, all vehicles have to return to their depot of origin. Collection is performed 5 days a week, 8 h per day. The new plan should consider a vehicle route planning for a 6-week period that is to be repeated every 6 weeks. To avoid containers' overflow, managers should set a minimal and a maximum interval between two consecutive collections when defining route scheduling for each material.

14.2 Sustainability Objectives

The economic objective accunts, only for the variable costs of the system, since the fixed costs are associated with strategic decisions that have already been taken, (as number of depots, number of vehicles, and number of drivers), and cannot be changed. Hence, the variable costs are mainly related to the distance traveled by vehicles when collecting containers and transporting waste from depots to the sorting station. This includes fuel consumption and maintenance of the vehicle. Such costs depend linearly on the distance traveled, and thus the economic objective function is assessed by the total distance traveled. This includes the inbound distance (from the collection sites to the depots) and the outbound distance (from the depots to the sorting stations), to which adds the possible distance covered by empty vehicles between depots (heavily penalized). Currently, the total distance traveled is about 270,000 km per year.

On the environmental objective, and since transportation is this system's main activity, the greenhouse gas emissions (like CO_2, CH_4, HFCs, NO_x) are generated, in particular CO_2, which negatively impact the environment. The function is defined as the total CO_2 emitted by all vehicles in the system: each collection route performed and the round-trips between depots and the sorting station. Notice that since these last vehicles travel empty when returning to the depots, different CO_2 values are assumed for each direction. It was estimated that a total of 340,000 kg of CO_2 are emitted per year.

Lastly, the social objective promotes equity among human resources, in this case, the drivers. In the current plan, drivers' schedules are imbalanced with some drivers operating larger number of routes than others. From the historical data, a maximum of 220 and a minimum and 100 driving hours, are observed in a 6-week horizon. The company wants to put into practice a new operation scheme which will account for this organizational issue. Hence, the social objective is modeled as the minimization of the maximum working hours among all drivers in the planning horizon. This metric has a twofold contribution toward social sustainability. First, it promotes equity among drivers, enabling balanced workloads since all drivers are assigned to collection activities with similar number of hours (see Fig. 14.2 for an illustrative example). Second, with the minimization of the maximum working hours, drivers may be released to perform tasks other than just collection, as sorting activities, participation in recycling awareness campaigns, or training. This latter activity helps to improve the career development and promotes versatility among the human resources.



Max {60,120,80,40} = 120 hours

Max {70,90,80,60} = 90 hours

Fig. 14.2 Example of the effect of minimizing the maximum working hours

14.3 Modeling and Solution Approach

This case study involves the definition and scheduling of vehicle routes in multiple depot system, where inter-depot routes and multiple trips per vehicle are allowed. It is modeled as a multi-depot periodic vehicle routing problem with inter-depot routes (MDPVRPI). This model allows for the simultaneous selection of a set of visiting days for each client, the definition of the service areas of each depot, and of the multiple routes to be performed in each day of the planning horizon (see Annex A for the full model formulation). The MDPVRPI combines three problems: a multi-depot vehicle routing problem (MDVRP), a periodic vehicle routing problem (PVRP), and a vehicle routing problem with multiple use of vehicles (VRPMU). While the MDVRP considers a planning horizon of a single time unit, the PVRP considers a planning horizon with several time units, since it assumes customers to have different delivery (or collection) patterns. In this problem, a customer specifies a service frequency and a set of allowable delivery patterns, and the company has to decide on which day the delivery will occur. In the VRPMU, a vehicle can perform several routes during a working day and/or the planning horizon. The multiple uses of vehicles appear when the fleet is either small or the working day period is larger than the average route duration (see Petch and Salhi (2003), Oliveira and Vieira (2007), Azi et al. (2010), and Rieck and Zimmermann (2010)).

In the classical MDPVRP, all routes have to start and end in the same depot (closed routes). Whereas, in the MDPVRP with inter-depot routes (MDPVRPI), vehicles can renew their capacity in any depot in order to continue delivering or collecting materials without being forced to return to their home depot before the end of the working day. Hence, routes can start and finish at different depots enabling a vehicle rotation composed by inter-depot routes. The different routes concepts are illustrated at Fig. 14.3. The difference between an open and an inter-depot route is that in the latter a rotation has to be defined in order to get the vehicle back to its home depot. One defines a rotation as a set of inter-depot routes that can be performed consecutively until the home depot is reached.

A solution approach is developed to solve the case study as multi-objective MDPVRPI. Since the problem is modeled with the set partitioning formulation, a set of a large number of feasible routes has to be generated, and then the most

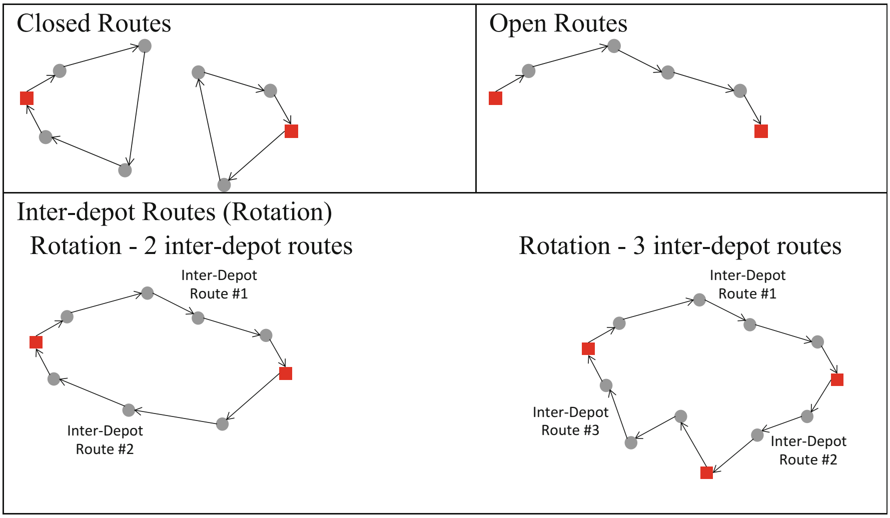


Fig. 14.3 Illustration of closed, open, and inter-depot routes

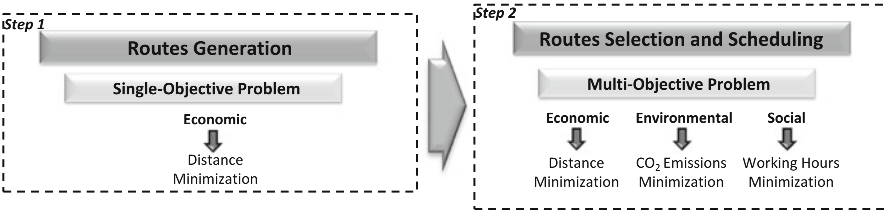


Fig. 14.4 Solution approach overview

adequate ones are selected from that pool. Therefore, the solution approach involves a first step to generate the routes and a second step where the multi-objective problem is solved (see Fig. 14.4). As the goal is to obtain a solution where costs are balanced with environmental and social concerns, the set of routes is defined considering only the economic objective. However, when selecting and scheduling the routes, at step 2, the three objectives are taken into account by solving the multi-objective MDPVRPI with the augmented ε-constraint method (see book Sect. 12.3.4). With such approach, an approximation to the Pareto front is obtained, which can be used by the decision-maker to evaluate trade-offs and to select the most adequate solution to put into practice.

The goal of step 1 is then to build the set of feasible routes required by the multi-objective MDPRVPI formulation. Generating all the feasible routes is however intractable (Laporte 2007), so only a subset will be defined. Accounting for the characteristics of the problem addressed, a diverse set of closed and inter-depot routes are generated representing alternative solutions to collect all sites. To build only closed ones, a MDVRP is solved – procedure 1. To build closed and inter-depot

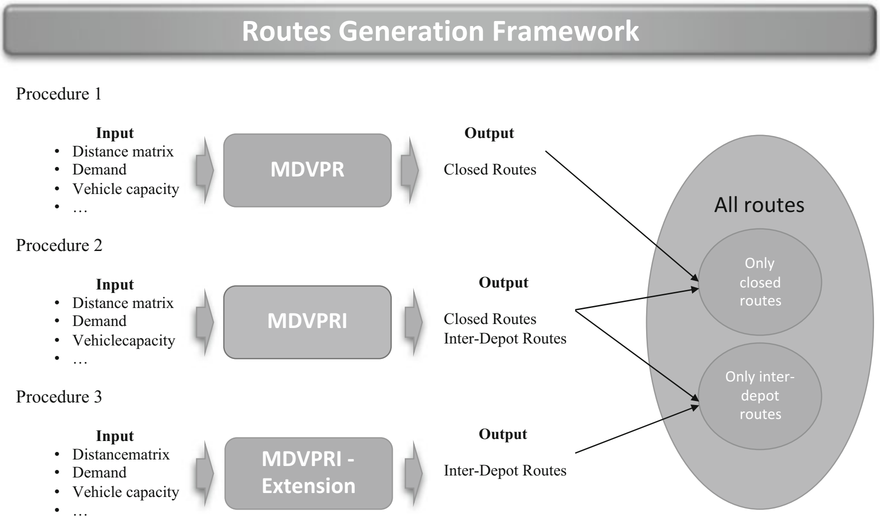


Fig. 14.5 Routes generation procedures

routes, a MDVRPI is solved – procedure 2. To build only inter-depot routes, a MDVRPI Extension is solved – procedure 3 (see Annexes B.1.1, B.1.2, and B.1.3 for all the details). Therefore, the set of all routes is fed by three independent procedures modeling the three alternative solutions to collect waste from all collection sites (see Fig. 14.5).

14.4 Results and Analysis

The solution approach proposed is applied to the described case study in order to define a sustainable plan for the recyclable waste collection in 19 Portuguese municipalities. It was implemented in GAMS 23.7 and solved through the CPLEX Optimizer 12.3.0, on an Intel Xeon CPU X5680 @ 3.33 GHz.

14.4.1 Routes Generation

Three procedures were applied to generate a set of diverse closed and inter-depot collection routes for each of the three recyclable materials. The number of routes provided by each procedure for each material is shown in Table 14.1.

The mixture of plastic and metal, which is assumed as a single material, requires more collection routes than the other two materials. This mixture has a lower density

Table 14.1 Number of routes defined per procedure and recyclable material

	Glass	Paper	Plastic/metal
Procedure 1			
Closed routes	39	42	66
Procedure 2			
Closed routes	37	41	64
Inter-depot routes	9	6	9
Procedure 3			
Inter-depot routes	38	40	62

when compared to the other two materials, and thus the vehicle weight capacity for plastic metal is smaller for the same vehicle volume capacity.

14.4.2 Sustainable Collection System

Step 2 of Figure 14.4 selects routes from set *K* while considering the number of available vehicles (eight in total) and where they are based. It also takes into accounts the planning horizon of 6 weeks (i.e., 30 working days) and observes the interval between collections. Then step 2 the multi-objective problem is solved by applying the augmented ε-constraint method Marieloas (2009) to define an approximation to the Pareto front. The proceedure ends with the application of a compromise solution method to compute a sustainable solution for the case study (see Annex B.2).

The payoff table generated by the lexicographic method (see section 12.4.1) is shown in Table 14.2. When minimizing the total distance (economic objective), a solution with 27,261 km is obtained. This solution emits 34,982 kg of CO_2, and the maximum number of hours among the eight vehicles is 200 h. When minimizing the CO_2 emissions (environmental objective), a solution with 34,747 kg of CO_2 is achieved. It implies less 0.7% of CO_2 emissions and more 0.3% kilometers when compared to the economic solution. The number of working hours remains unaltered. When minimizing the maximum number of working hours in the planning horizon (social objective), a solution with a maximum of 165 h is obtained. This solution implies a total of 30,118 km (about 11% more than in the economic solution) and 38,042 kg of CO_2 (about 10% more than in the environmental solution).

Figure 14.6 shows the total hours each driver has to work (social concern) in the collection activity for each of the three optimal plans: economic, environmental, and social. Both economic and environmental optimal plans are quite unbalanced, with differences between the maximum and minimum working hours of 102 and 120 h, respectively. On the contrary, the social optimal plan presents a totally balanced plan, where all drivers work the same number of hours in collection activities (165 h).

Table 14.2 Payoff table obtained with the lexicographic optimization of the objective functions

		Optimized objective function		
		Economic (km)	Environmental (kg)	Social (h)
Optimal solution of the objective	Economic	27,261	34,982	200
	Environmental	27,337	34,747	200
	Social	30,118	38,042	165

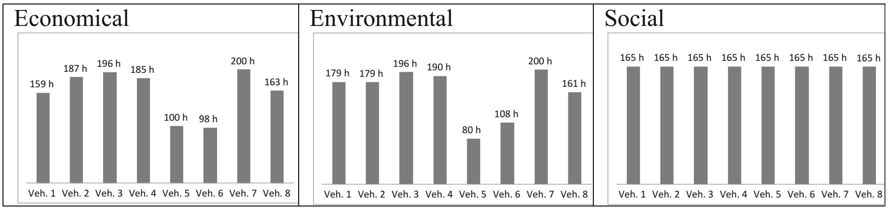


Fig. 14.6 Number of working hours per vehicle in the three solutions

The daily schedule for each vehicle with the assignment of all the routes to be operated in each day is the output of the procedure step 2. Vehicle 7's daily schedule is given in Fig. 14.7. Each day has the number and type of routes to be performed (*Pl* stands for plastic/metal, *Gl* for glass, and *Pa* for paper) and the total duration (in minutes). For example, in day 1 of the economic plan, the vehicle has to perform route #56 to collect plastic/metal and afterward route #250 to collect paper. The total duration (including unloading activities) is 461 min. Route #250 is performed three times during the planning horizon in line with the collection frequency set for the material paper (days 1, 12, and 22). The interval between consecutives visits respects the minimum and maximum interval allowed for this material (9 and 11 days, respectively).

Comparing both schedules (Fig. 14.7a, b), fewer routes are performed by vehicle 7 in the social solution (44 against 52 routes in the economic solution). On the one hand, in the "economic schedule," routes are to be performed every day, while in the "social schedule" there is one day (day 6) where no routes are assigned. In the "social schedule," the driver of vehicle 7 works 165 h in collection activities, while in the "economic schedule," he/she works 200 h. To reduce 35 working hours from vehicle 7, the scheduled hours for the remaining vehicles have to increase. This can be achieved with the reconfiguration of depot service areas. As an illustrative example, the service areas for the material glass for the three solutions are shown in Fig. 14.8. In the social solution, the number of collection sites assigned to depot 208 (114 sites) is the lowest when among the three solutions (128 sites in the economic solution and 136 in the environmental solution). In opposition, the number of sites assigned to depot 209 is the largest (46 sites in the social solution against 32 and 26 in the economic and environmental solutions, respectively). Depot 209 (where vehicles 5 and 6 are based) is the one with less working hours in the economic and

(a) Economical plan
∑ Hours = 200h

1	2	3	4	5
#56 (Pl); #250 (Pa) *461 m*	#54 (Pl); #249 (Pa) *448 m*	#253 (Pa); #254 (Pa) *480 m*	#59 (Pl); #63 (Pl) *467 m*	#251 (Pa) *346 m*
6 #61 (Pl); #62 (Pl) *428 m*	**7** #252 (Pa) *295 m*	**8** #248 (Pa) *299 m*	**9** #255 (Pa); #267 (Pa) *387 m*	**10** #57 (Pl); #58 (Pl) *471 m*
11 #55(Pl);#60 (Pl);#81(Pl) *425 m*	**12** #49 (Pl); #250 (Pa) *478 m*	**13** #249 (Pa); #254 (Pa) *467 m*	**14** #253 (Pa) *295 m*	**15** #397 (Gl) *249 m*
16 #251 (Pa) *346 m*	**17** #56 (Pl); #252 (Pa) *461 m*	**18** #54 (Pl); #248 (Pa) *465 m*	**19** #255 (Pa); #267 (Pa) *387 m*	**20** #59 (Pl); #63 (Pl) *467 m*
21 #61 (Pl) *258 m*	**22** #62 (Pl); #250 (Pa) *465 m*	**23** #249 (Pa) *282 m*	**24** #253 (Pa); #254 (Pa) *480 m*	**25** #57 (Pl); #58 (Pl) *471 m*
26 #55(Pl);#60 (Pl);#81(Pl) *425 m*	**27** #251 (Pa) *346 m*	**28** #49 (Pl); #252 (Pa) *478 m*	**29** #248 (Pa) *299 m*	**30** #255 (Pa); #267 (Pa) *387 m*

(b) Social plan
∑ Hours = 165 h

1	2	3	4	5
#250 (Pa) *295 m*	#249 (Pa); #254 (Pa) *467 m*	#62 (Pl); #253 (Pa) *465 m*	#63 (Pl) *165 m*	#391 (Gl) *292 m*
6	**7** #49 (Pl); #54 (Pl) *349 m*	**8** #248 (Pa); #267 (Pa) *378 m*	**9** #255 (Pa) *308 m*	**10** #56 (Pl); #81 (Pl) *214 m*
11 #413 (Gl) *337 m*	**12** #250 (Pa) *295 m*	**13** #249 (Pa); #254 (Pa) *467 m*	**14** #60 (Pl); #253 (Pa) *370 m*	**15** #397 (Gl) *249 m*
16 #251 (Pa) *346 m*	**17** #252 (Pa) *295 m*	**18** #57 (Pl); #248 (Pa) *468 m*	**19** #55 (Pl); #267 (Pa) *381 m*	**20** #63 (Pl); #255(Pa) *473 m*
21 #61 (Pl) *258 m*	**22** #54 (Pl); #250 (Pa) *461 m*	**23** #49 (Pl); #249 (Pa) *465 m*	**24** #254 (Pa) *185 m*	**25** #56 (Pl); #253 (Pa) *461 m*
26 #81 (Pl) *48 m*	**27** #251 (Pa) *346 m*	**28** #252 (Pa) *295 m*	**29** #60(Pl);#248 (Pa);#267(Pa *453 m*	**30** #255 (Pa) *308 m*

Fig. 14.7 Schedule for vehicle 7 in economical (**a**) and social (**b**) plans

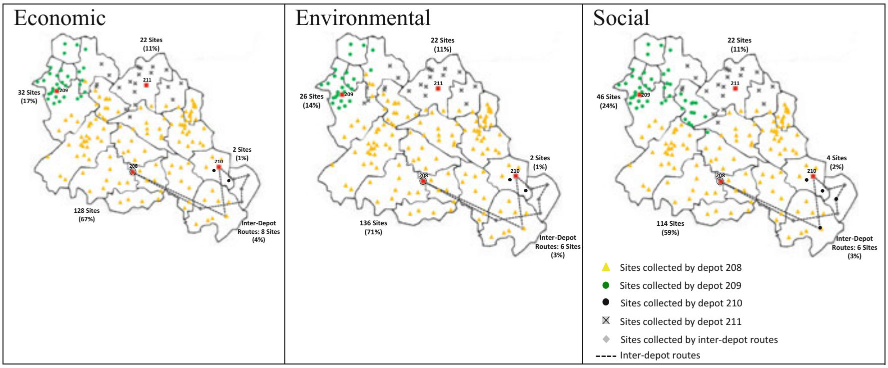


Fig. 14.8 Service areas for glass material for the economic, environmental, and social plans

environmental plans (Fig. 14.6). To balance the number of working hours in the social solution, more sites have to be assigned to this depot.

The environmental solution is the one with the highest number of sites assigned to depot 208 (also acts as the sorting station). The outbound transportation is performed by large vehicles that release more CO_2 than the collection vehicles. Therefore, since the objective is to minimize the CO_2 emissions, more sites are assigned to the sorting station to avoid the outbound transportation. Moreover, the environmental solution selects routes where vehicles travel shorter distances with heavy load given since it minimizes the CO_2 emissions.

Nine different solutions are obtained when applying the augmented ε-constraint method (S1 to S9 in Table 14.3). Such solutions can be visualized in Fig. 14.9 where

Table 14.3 Pareto optimal solutions

	S1	S2	S3	S4	S5	S6	S7	S8	S9
Economic (km)	30,118	28,445	27,676	27,489	27,412	27,345	27,287	27,337	27,261
Environmental (kg)	38,042	36,351	35,580	35,580	35,179	35,100	35,010	34,747	34,982
Social (h)	165	170	175	180	185	190	195	200	200

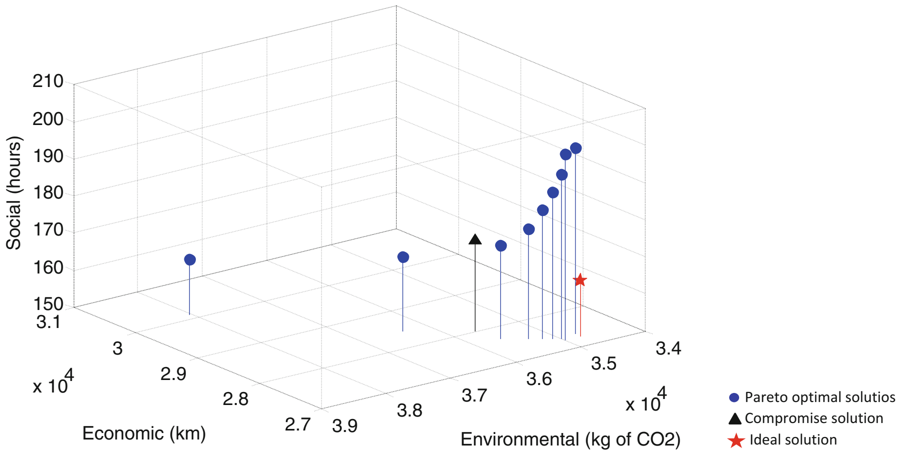


Fig. 14.9 Approximation to Pareto front considering the three objectives with the ideal point and the compromise solution highlighted

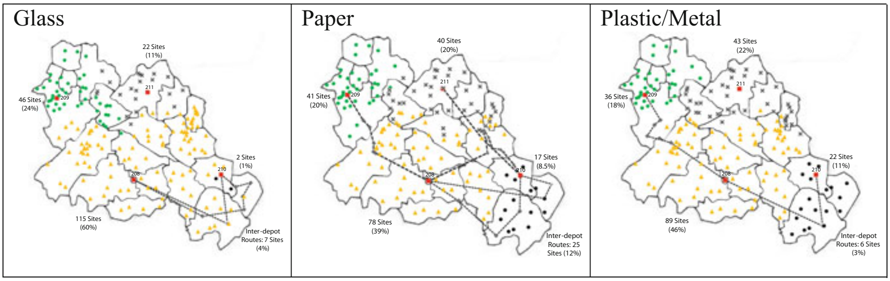


Fig. 14.10 Representation of the compromise solution for the three recyclable materials

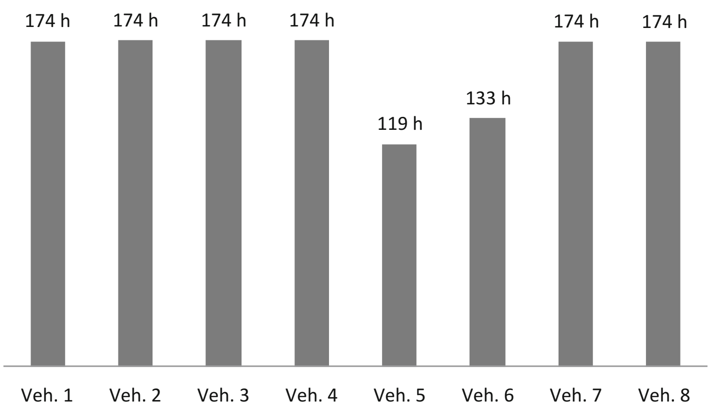


Fig. 14.11 Number of working hours by vehicle in the compromise solution

one can observe that to improve the social objective (reducing the number of maximum working hours), the economic and environmental objectives deteriorate. For instance, to increase the social objective in 17.5%, the economic and the environmental objectives deteriorate 10% and 9.5%, respectively (S1 versus S8). However, the economic objective only deteriorates 1.2% and the environmental 2.4% with an improvement of 12.5% in the social objective (S3 versus S8). Regarding the economic and environmental objectives, the trade-off only exists between S8 and S9. To improve 0.7% in the environmental objective, the economic objective deteriorates 0.3%. In the remaining solutions, these objectives are inversely proportional to the social objective.

Aiming to find a compromise solution between the three objectives to reach a sustainable plan for the logistics network, a compromise solution method is applied. The ideal point (z_I) is defined according to the individual minima of each objective. In this case, ideal point coordinates are $z_I = (27{,}261$ km, $34{,}747$ kg CO_2, 165 h$)$. The nadir point (z_N) is defined according to the individual maxima of each objective, $z_N = (30{,}118$ km, $38{,}138$ kg CO_2, 200 h$)$. Figure 14.9 also depicts the compromise solution and the ideal point. After normalizing the objective functions with the amplitude between the nadir and ideal points, the compromise solution (z_C) is obtained by minimizing the Tchebycheff distance to the ideal point. The compromise solution obtained is $z_C = (28{,}013$ km, $35{,}653$ kg CO_2, 174 h$)$ – all details presented in Annex B.2.

In the compromise solution (depicted in Fig. 14.10), the economic objective deteriorates 2.7%, the environmental 2.6%, and the social 5.5% regarding each corresponding value when a single objective is optimized. For all materials, the number of sites assigned to the sorting station is smaller than the ones obtained for the economic and environmental solutions but higher than the one of social solution. For instance, in the compromise solution for paper, 39% of the sites are assigned to depot 208 (sorting station), while 45% are assigned when the economic and environmental objectives are minimized individually and 38% when considering the social objective. Also, more sites are collected in inter-depot routes. These differences increase the distance traveled and emitted CO_2 but balance the solution regarding workload among depots (Fig. 14.11).

The compromise solution represents a sustainable solution that has been presented to the company. Savings of about 10% in the distance and 9% in CO_2 emissions and a reduction of 21% in the maximum of driving hours are obtained with this sustainable solution, when comparing to the current company operation plan.

14.5 Conclusion

The planning a multi-depot logistics system has been taken into account considering the three dimensions of sustainability. Economic, environmental, and social objective functions have been modeled in a tactical routing and scheduling problem with multiple depots. In particular, this work addresses service areas and routes definition as well as routes scheduling, CO_2 emissions, and human resources working hours.

The solution approach has been applied to a real recyclable waste collection system where the trade-offs between the three objectives were highlighted and a compromise solution proposed. When economic and environmental objectives are minimized, unbalanced solutions are obtained regarding working hours by vehicle (and consequently be driver). On the contrary, when the social objective is minimized, a balanced solution is obtained where all drivers drive the same number of hours. However, this equity solution leads to a significant increase in distance and CO_2 emissions. Between environmental and economic objectives there are only minor trade-offs. An efficient solution taking into account the three objectives is obtained through the compromise solution method, where the distance to the ideal point is minimized.

Annex A: Multi-objective Formulation for the MDPVRPI

The multi-objective MDPVRPI is formulated as a set partitioning problem (Balas and Padberg 1976), where K represents the set of all feasible routes (closed and inter-depot routes) and τ_{ktg} is a binary variable that equals 1 if route k is performed on day t by vehicle g; and 0 otherwise. The mathematical formulation considers the following indices and sets.

Indices

k	Route indices
t	Time period (days) indices
g	Vehicle indices
i, j	Node indices
m	Recyclable material indices

Sets

K	Route set $K = \sum_{m \in M} K_m$, $K = K_{in} \cup K_{cl}$
K_m	Route subset to collect material m
K_{in}	Inter-depot route subset
K_{cl}	Closed route subset
T	Time period set
G	Vehicle set
V	Node set $V = V_c \cup V_d \cup V_s$
V_c	Collection site subset
V_d	Depot subset
V_s	Sorting station subset
M	Recyclable material set

Each route $k \in K$ is characterized by (1) a distance dis_k; (2) a duration dur_k including travel, service, and unloading times; (3) a load Lo_k; and (4) CO_2 emissions Co_k. The collection sites belonging to route k are given by a binary parameter μ_{ik} that equals 1 if collection site i belongs to route k and 0 otherwise. The starting and ending depots for route k are also given by binary parameters St_{ki} and En_{ki}, respectively; St_{ki} equals 1 if route k starts at depot i, and En_{ki} equals 1 if route k ends at depot I and 0 otherwise.

The vehicles are fixed at the depots. If vehicle g belongs to depot i, the binary parameter α_{gi} equals 1 and 0 otherwise.

The collection frequency of each collection site i with recyclable material m is given by fr_{im} representing the number of times a collection site needs to be visited within the planning horizon. The minimum and maximum interval between two consecutive collections for recyclable material m are given by $I\mathrm{min}_m$ and $I\mathrm{max}_m$, respectively.

Three objective functions are addressed in this work to tackle the three sustainability dimensions: the economic objective ($z^1(S)$), the environmental objective ($z^2(S)$), and the social objective ($z^3(S)$). Let S be the vector of decision variables; $z^1(S)$, $z^2(S)$, and $z^3(S)$ the three objective functions; and Ω the feasible region; the multi-objective problem can be written in the following form:

$$\begin{array}{ll} \min & \{z^1(S),\ z^2(S),\ z^3(S)\} \\ \mathrm{st} & S \in \Omega \end{array} \tag{14.1}$$

The total distance traveled ($z^1(S)$) is given by Eq. (14.2).

$$z^1(S) = \sum_{k \in K} \sum_{t \in T} \sum_{g \in G} \mathrm{dis}_k \tau_{ktg} + \tag{14.2a}$$

$$\sum_{j \in V_s} \sum_{i \in V_d} \sum_{m \in M} \sum_{k \in K_m} \sum_{t \in T} \sum_{g \in G} \mathrm{En}_{ki} \tau_{ktg} \mathrm{Lo}_k / QT_m 2 d_{ij} - \tag{14.2b}$$

$$\sum_{j \in V_s} \sum_{i \in V_d} \sum_{m \in M} \sum_{k \in K_m} \sum_{t \in T} \sum_{\substack{g \in G \\ \alpha_{gj} = 1}} \mathrm{St}_{ki} \mathrm{En}_{ki} \tau_{ktg} \mathrm{Lo}_k / QT_m 2 d_{ij} + \tag{14.2c}$$

$$\sum_{\substack{g \in G \\ \alpha_{gi} = 1}} \sum_{\substack{k \in K \\ \mathrm{En}_{ki} = 0 \\ \mathrm{St}_{kj} = 1}} \sum_{t \in T} \sum_{i,j \in V_d} 2 \tau_{ktg} d_{ij} \tag{14.2d}$$

The total distance traveled involves, as mentioned, the inbound distance (14.2a), the outbound distance (14.2b and 14.2c), and also a possible extra distance since it is allowed to vehicles based at depot i to perform closed routes from and to depot j (14.2d). The distance (d_{ij}) of moving a vehicle between depots is then penalized. The outbound distance considers the ending depot of each route and the load collected, to compute the number of needed round-trips to the sorting station. Note that the number of round-trips is not round upward since it is being accounting for the number of round-trips that occur within a finite time period. These are to be repeated in the next period. When, for instance, 10.4 round trips are considered within the period, it means that 10 round trips occur within the period and the 11th occurs in the next period, but some of the load is related to the previous period. It is also considered that if a vehicle, belonging to the sorting station performs closed routes from depot i, the load collected will be unloaded at the sorting station and not at depot i. Therefore, no outbound distance will be accounted for. Term (14.2c) decreases the objective function of such value.

The environmental objective is related to the CO_2 emissions associated with the collection routes and the outbound transportation between depots and the sorting station. Its total value ($z^2(S)$) given by Eq. (14.3).

$$z^2(S) = \sum_{k \in K} \sum_{t \in T} \sum_{g \in G} \mathrm{Co}_k \tau_{ktg} + \tag{14.3a}$$

$$\sum_{j \in V_s} \sum_{i \in V_d} \sum_{m \in M} \sum_{k \in K_m} \sum_{t \in T} \sum_{g \in G} \mathrm{En}_{ki} \tau_{ktg} \mathrm{Lo}_k / QT_m \left(\mathrm{Co}F_{ijm} + \mathrm{Co}E_{ji} \right) - \tag{14.3b}$$

$$\sum_{j \in V_s} \sum_{i \in V_d} \sum_{m \in M} \sum_{k \in K_m} \sum_{t \in T} \sum_{\substack{g \in G \\ \alpha_{gj} = 1}} \mathrm{St}_{ki} \mathrm{En}_{ki} \tau_{ktg} \mathrm{Lo}_k / QT_m \left(\mathrm{Co}F_{ijm} + \mathrm{Co}E_{ji} \right) + \tag{14.3c}$$

$$\sum_{\substack{g \in G \\ \alpha_{gi} = 1}} \sum_{\substack{k \in K \\ \mathrm{En}_{ki} = 0 \\ \mathrm{St}_{kj} = 1}} \sum_{t \in T} \sum_{i,j \in V_d} 2 \tau_{ktg} \mathrm{Co}E_{ij} \tag{14.3d}$$

The CO_2 emissions for the inbound transportation (routes to collect all collection sites) are given by the first term (14.3a), where the emission value of each route k is given by parameter Co_k . The CO_2 emissions from the outbound transportation are also considered (terms 14.3b and 14.3c) where larger vehicles are used. Notice that round trips between the sorting station and the depots are performed, with vehicles traveling empty from the sorting station to the depot and in full truckload (FTL) back to the sorting station. The amount of CO_2 emissions for outbound transportation is given by parameter $\mathrm{Co}F_{ijm}$ when the vehicle travels in FTL from depot i to sorting station j with material m and $\mathrm{Co}E_{ij}$ when the vehicle travels empty in the opposite direction. The last term (14.3d) accounts for the CO_2 emissions of a vehicle, based at depot i, traveling empty to depot j to perform closed routes from and to depot j.

As mentioned above, the social objective minimizes the maximum working hours among drivers. The maximum value of vehicle's total working hours in the planning horizon is given by a positive decision variable $D\mathrm{Max}$ when assuming a fixed driver-vehicle assignment (constraint 14.4).

$$D\text{Max} \geq \sum_{k \in K} \sum_{t \in T} \tau_{ktg} \text{dur}_k + \sum_{\substack{k \in K \\ \text{St}_{kj} = 1 \\ \text{En}_{ki} = 0}} \sum_{\substack{i,j \in V_\text{d} \\ i \neq j}} \tau_{ktg} 2b_{ij}, \quad \forall g \tag{14.4}$$

Then, the function for the social objective is given by Eq. (14.5).

$$z^3(S) = D\text{Max} \tag{14.5}$$

With the objective functions defined, the constraints for the multi-objective model of the MDPVRPI are expressed in constraints (14.6) to (14.13).

$$\sum_{k \in K_\text{m}} \sum_{t \in T} \sum_{g \in G} \tau_{ktg} \mu_{ik} = \text{fr}_{im} \quad \forall i \in V_\text{c}, \forall m \tag{14.6}$$

$$\sum_{k \in K} \tau_{ktg} \text{dur}_k + \sum_{\substack{k \in K \\ \text{St}_{kj} = 1 \\ \text{En}_{ki} = 0}} \sum_{\substack{j \in V_\text{d} \\ j \neq i}} \tau_{ktg} 2b_{ij} \leq H \quad \forall t, \forall g, \forall i \in V_\text{d} : \alpha_{gi} = 1 \tag{14.7}$$

$$\sum_{\substack{k \in K_\text{in} \\ \text{St}_{ki} = 1}} \tau_{ktg} = \sum_{\substack{k' \in K_\text{in} \\ \text{En}_{k'i} = 1}} \tau_{k'tg} \quad \forall g, \forall t, \forall i \in V_\text{d} \tag{14.8}$$

$$\sum_{g \in G} \tau_{ktg} \mu_{ik} + \sum_{g \in G} \tau_{kt'g} \mu_{ik} \leq 1 \quad \forall i \in V_\text{c}, \forall k \in K_\text{m}, \forall m, \forall t, t' \in T, t > t', (t - t') \leq I\text{min}_m \tag{14.9}$$

$$\sum_{g \in G} \tau_{ktg} \mu_{ik} + \sum_{g \in G} \tau_{k't'g} \mu_{ik'} \leq 1 \quad \forall i \in V_\text{c}, \forall k, k' \in K_\text{m}, \forall m, \forall t, t' \in T, t > t', (t - t') \leq I\text{min}_m \tag{14.10}$$

$$\sum_{g \in G} \tau_{ktg} \mu_{ik} + \sum_{g \in G} \tau_{kt'g} \mu_{ik} \leq 1 \quad \forall i \in V_\text{c}, \forall k \in K_\text{m}, \forall m, \forall t, t' \in T, t > t', (t - t') > I\text{max}_m, (t - t') \leq I\text{max}_m + I\text{min}_m \tag{14.11}$$

$$\sum_{g \in G} \tau_{ktg}\mu_{ik} + \sum_{g \in G} \tau_{k't'g}\mu_{ik'} \leq 1 \quad \forall i \in V_{\mathrm{c}}, \forall k, k' \in K_{\mathrm{m}}, \forall m, \forall t, t' \in T, t > t', (t - t') > I\max_m, (t - t') \leq I\max_m + I\min_m \tag{14.12}$$

$$\tau_{ktg} \in \{0, 1\} \quad \forall k \in K, \forall t \in T, \forall g \in G \tag{14.13}$$

Constraint (14.6) ensures that a collection site i with material m has to be collected fr_{im} times over the time horizon. Constraint (14.7) states that the total route duration performed by vehicle g on day t will not exceed the maximum time allowed for a working day (H). If a vehicle g, belonging to depot i, performs a route starting at depot j, the travel time between i and j is considered.

Since all vehicles have to return to their origin depot, constraint (14.8) guarantees that an inter-depot route k, starting at depot i, is part of the solution only if another inter-depot route k' ends at depot i. Considering all depots $i \in V_{\mathrm{d}}$, constraint (14.8) ensures continuity among inter-depot routes enabling a vehicle rotation.

Constraints (14.9) to (14.12) model the minimum and maximum intervals between consecutive collections which can be performed by the same route or by two different routes. Therefore, constraint (14.9) states that the same route for material m has to be performed with a minimum time interval of $I\min_{m,}$ while constraint (14.10) considers the case of two different routes collecting the same site i at consecutive collections. Analogously, constraints (14.11) and (14.12) ensure the maximum interval $I\max_m$ between consecutive collections. Variable's domain is given in constraint (14.13).

Annex B: Solution Procedure

B.1 Step 1: Routes Generation Procedure

The set of recyclable materials M is involved, and given that each material has to be collected in separated routes, each procedure of step 1 is run independently for each material.

The models involved in each procedure are formulated through MILP formulations based on the two-commodity flow formulation (Baldacci et al. 2004). In such formulations, the network is defined by a direct graph $\mathrm{GR} = (V, E)$ with $V = V_{\mathrm{c}} \cup V_{\mathrm{d}} \cup V_{\mathrm{f}} \cup V_{\mathrm{s}}$, being $V_{\mathrm{c}} = \{1, \ldots, n\}$ a set of n customers, $V_{\mathrm{d}} = \{n + 1, \ldots, n + w\}$ a set of w depots, $V_{\mathrm{f}} = \{n + w + 1, \ldots, n + 2w\}$ a replica of the depots set, $V_{\mathrm{s}} = \{n + 2w + 1, \ldots, n + 2w + s\}$ a set of s sorting stations, and $E = \{(i,j) : i,j \in V_{\mathrm{c}} \cup V_{\mathrm{d}} \cup V_{\mathrm{f}} \cup V_{\mathrm{s}}, i \neq j\}$ the edge set.

Each site $i \in V_{\mathrm{c}}$ is characterized by a demand p_i and a service duration t_i. The service duration depends on the average time to collect a container (U), on the average distance between containers within a locality (B), on the average speed within localities (vw) and on the number of containers at each locality (c_i), being $t_i = c_i\left(U + \frac{B}{vw}\right)$. The inbound vehicles have a weight capacity of Q and the outbound vehicles QT. The maximum duration for a working day is given by H. Every edge (i, j) has an associated distance d_{ij} and a travel time b_{ij}, where $b_{ij} = \frac{d_{ij}}{vb}$ and vb is the average speed between localities. An unloading time L is also considered to account for the time to unload a vehicle at the end of each route.

The depot replica set (V_f) is needed since, in the two-commodity flow formulation, routes are defined by paths starting at the real depots and ending at the replica ones. To establish the routes, this formulation requires two flow variables defining two flow paths for any route. One path from the real depot to the replica one modeled by the flow variable representing the vehicle load (variable y_{ij}). In a collection problem, this load increases along the route. The other path from the replica depot to the real one is given by the second flow variable (y_{ji}) that models the vehicle empty space which decreases along the route.

These sets, parameters, and variables are the baseline to all route generating procedures which are briefly described in the next sections.

B.1.1 Procedure 1: MDVRP

In the MDVRP only closed routes are defined. A set of routes K is considered and partitioned by depot, $K = K_1 \cup \ldots \cup K_i$, where K_i is the subset of routes belonging to depot i. Decision variables are the binary variables x_{ijk} that equal 1 if site j is visited immediately after site i on route k ($x_{ijk} = 0$, otherwise) and the corresponding reverse variable x_{jik} when the reverse path is being defined and the flow variables y_{ijk} and y_{jik}; and a binary variable δ_{ik} is defined to assign site i to route k. The objective function also considers the distance to be traveled within each collection site (second term of Eq. (14.14)) and the outbound distance (third term of Eq. (14.14)).

$$\text{Min } \frac{1}{2}\sum_{i\in V}\sum_{j\in V}\sum_{k\in K} x_{ijk}d_{ij} + \sum_{i\in V_\mathrm{c}} c_i S + 2\sum_{i\in V_\mathrm{c}}\sum_{j\in V_\mathrm{f}}\sum_{h\in V_\mathrm{s}}\sum_{k\in K}\frac{y_{ijk}}{QT}d_{hj} \tag{14.14}$$

subject to

$$\sum_{\substack{j\in V\\ j\neq i}} \left(y_{ijk} - y_{jik}\right) = 2p_i\delta_{ik}, \quad \forall i\in V_\mathrm{c}, \forall k \tag{14.15}$$

$$\sum_{i\in V_\mathrm{c}}\sum_{j\in V_\mathrm{f}}\sum_{k\in K} y_{ijk} = \sum_{i\in V_\mathrm{c}} p_i \tag{14.16}$$

$$\sum_{i \in V_c} \sum_{j \in V_f} \sum_{k \in K} y_{jik} \leq |K| Q - \sum_{i \in V_c} p_i \tag{14.17}$$

$$\sum_{i \in V_c} y_{ijk} \leq Q \quad \forall_j \in V_f, \forall k \in K_j \tag{14.18}$$

$$\sum_{\substack{i \in V \\ i \neq j}} x_{ijk} = 2\delta_{jk}, \quad \forall j \in V_c, \forall k \tag{14.19}$$

$$y_{ijk} + y_{jik} = Qx_{ijk} \quad \forall i, j \in V, i \neq j, \forall k \tag{14.20}$$

$$\sum_{k \in K} \delta_{ik} = 1 \quad \forall i \in V_c : p_i > 0 \tag{14.21}$$

$$\delta_{ik} = \delta_{(i+w)k} \quad \forall i \in V_d, \forall k \in K_i \tag{14.22}$$

$$\sum_{i \in V_c} \sum_{j \in V} t_i x_{ijk} + \sum_{i \in V} \sum_{j \in V} b_{ij} x_{ijk} \leq 2(H - L) \quad \forall k \in K \tag{14.23}$$

$$\sum_{j \in V_c} x_{ijk} \leq 1 \quad \forall i \in V_d, \forall k \in K_i \tag{14.24}$$

$$\sum_{i \in V_c} x_{ijk} = 0 \quad \forall j \in V_f, \forall k \notin K_j \tag{14.25}$$

$$\sum_{j \in V_c} x_{ijk} = 0 \quad \forall i \in V_d, \forall k \notin K_i \tag{14.26}$$

$$y_{ijk} \geq 0 \quad \forall i, j \in V, k \in K \tag{14.27}$$

$$x_{ijk} \in \{0, 1\} \quad \forall i, j \in V, k \in K \tag{14.28}$$

$$\delta_{ik} \in \{0, 1\} \quad \forall i \in V_c, k \in K \tag{14.29}$$

The above formulation is an extension for the MDVRP of the formulation proposed by Baldacci et al. (2004) for the CVRP. Constraints (14.15) to (14.20) are rewritten since it is considered index k and the binary variable δ_{ik}. Constraints (14.21) to (14.26) are new constraints that deal with multiple depots and duration constraints. Equation (14.21) guarantees that each locality with positive demand has to be visited by a single route. Constraint (14.22) matches the real depots with their replica, ensuring that a route will start at the real depot and will end at the corresponding replica. Constraint (14.23) guarantees that the duration of each

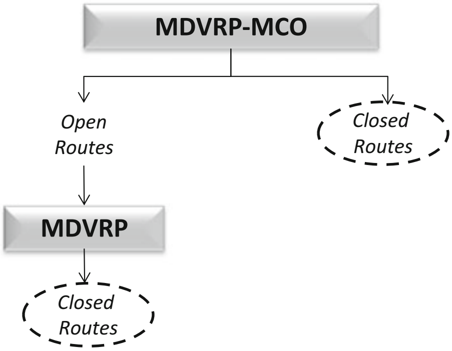


Fig. 14.12 Solution method for the MDVRP

route does not exceed the maximum allowed routing time. Constraint (14.24) ensures that each route will leave its home depot at most once. Finally, constraints (14.25) and (14.26) jointly ensure that a vehicle route cannot leave and return to a depot other than its home depot (real and replica depot). The new variable definition is given in Eq. (14.29).

The proposed formulation, when applied to large instances, is computationally difficult to solve. Therefore, a solution method is proposed to solve the MDVRP (see Fig. 14.12). First, a problem where both closed and open routes are allowed, is solves, the MDVRP with mixed closed and open routes (MDVRP-MCO). The MDVRP-MCO formulation is proposed in the work of Ramos et al. (2013) and is capable of dealing with large instances. Moreover, the majority of the routes in the solution for the MDVRP-MCO are feasible for the MDVRP – the closed routes. For "(the open routes)", the MDVRP formulation is applied having, as input data, only the sites belonging to each open route.

B.1.2 Procedure 2: MDVRPI

The MDVRPI allows inter-depot routes, where vehicles have to return to the home depot on the same working day. Therefore, a vehicle rotation is limited by the maximum duration of a working day (H). To solve the MDVRPI, the solution methodology proposed by Ramos (2012) was used, considering an unlimited vehicle fleet. A MDVRPI Relaxation is solved where inter-depot and closed routes are obtained (see Fig. 14.13). This formulation corresponds to the MDVRP-MCO formulation to which adds constraint (14.30).

$$\sum_{j \in V} x_{ij} + \sum_{j \in V} x_{ji} = \sum_{j \in V} x_{(i+w)j} + \sum_{j \in V} x_{j(i+w)} \quad \forall i \in V_{\mathrm{d}} \tag{14.30}$$

Constraint (14.30) guarantees that the number of routes departing from one depot is equal to the number of routes arriving at that depot. This ensures connectivity between the inter-depot routes and the rotation concept, i.e., a vehicle returns to its

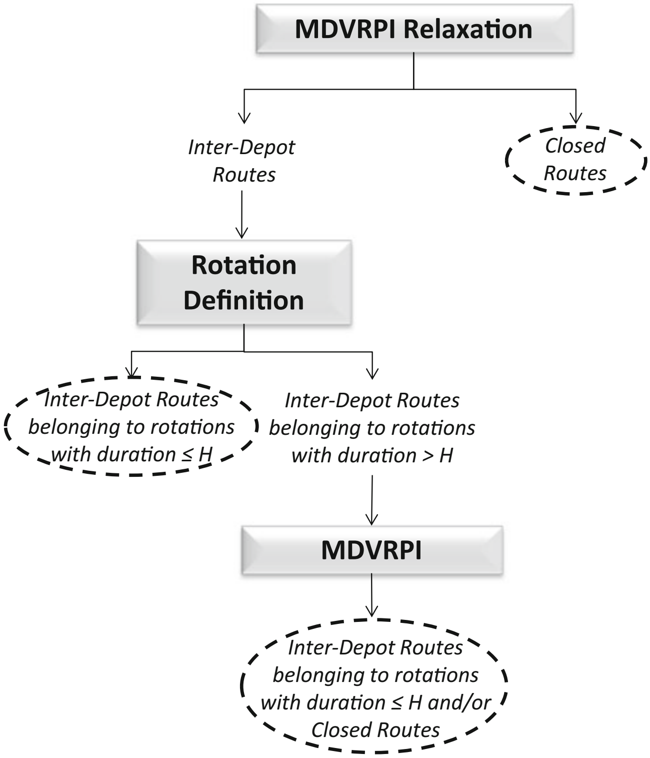


Fig. 14.13 Solution method for the MDVRPI

home depot. However, it is not guaranteed that the vehicle returns within a working day since no duration constraints for rotation are considered in the MDVRPI Relaxation. Notice that in the two-commodity formulation, to any real depot $i \in V_d$, a corresponding copy depot assumed $i + w \in V_f$ (w is the number of depots), and the x_{ij} and x_{ji} modeled the opposite paths.

For the inter-depot routes obtained from the solution of the MDVRPI Relaxation, rotations are defined by linking the inter-depot routes until one reaches the starting depot. The duration of each rotation is then assessed. For rotations that do not respect the working-day time limit, the MDVRPI formulation is solved and rotations redefined to comply with the imposed limit. As a solution, one can have inter-depot routes belonging to rotations that satisfy the maximum duration for a working day and/or closed routes. More details can be founded in Ramos (2012).

B.1.3 Procedure 3: MDVRPI Extension

The MDVRPI Extension solves the problem by visiting all sites only by inter-depot routes. For that, the MDVRPI Relaxation is used, but instead of considering all depots and all collection sites at the same time, only two depots are considering in each run, and only the closest sites to those depots are made available to be collected. Moreover, a constraint is added to enforce routes to start and end at different depots. As a result, only inter-depot routes are defined.

A pair of depots $[dp, dp^{'}] \in V_{\mathrm{d}}$ is considered at a time, and constraints (14.31) and (14.32) are added to the MDVRPI Relaxation formulation, imposing that all routes have to start at depot dp and end at depot $dp^{'}$ to obtain a solution with only inter-depot routes between each pair of depots.

$$x_{ij} = 0, \quad \forall i \in V_{\mathrm{c}}, j = dp + w \tag{14.31}$$

$$x_{ij} = 0, \quad \forall j \in V_{\mathrm{c}}, i = dp' \tag{14.32}$$

Regarding the maximum duration for each inter-depot route in this procedure, it is considered the value $\left(H - L - b_{dp,dp'}\right)$ to guarantee that the vehicle can return to the origin depot within a working day.

After running the three procedures, the set K is built. Each route $k \in K$ is characterized by mileage (dis_k), duration (dur_k), load (Lo_k), and CO_2 emissions (Co_k). The first three parameters are provided by the solutions of the problems solved. The last one, the CO_2 emissions, has to be assessed a posteriori. For that, the emission model proposed by Barth et al. (2004) was used. When a vehicle travels over an arc (i,j), it is assumed that it emits a certain amount of CO_2, which depends on the fuel consumption that, in turn, is a function of many factors (such as, distance traveled, vehicle load – curb weight plus load – speed, road angle, engine features, vehicle frontal surface area, coefficients of rolling resistance and drag, and air density, among others (see Barth et al. 2004)). The conversion factor of 1 l of diesel fuel containing 2.6676 kg of CO_2 was assumed (as proposed in Defra). Note that CO_2 emissions were considered on arcs and nodes since nodes represent collection sites aggregating one or more containers and a certain mileage is traveled within each node.

The computation of the CO_2 emissions for all routes $k \in K$ concludes step 1.

B.2 Step 2: Solution Method for the Multi-objective Problem

In step 2 the multi-objective problem defined in Sect. 14.3 is solved (Fig. 14.4). In such problems it is rarely the case a single point optimizes simultaneously all objective functions (Coello and Romero 2003); therefore trade-offs between the objectives have to be analyzed in line with the notion of Pareto optimality. A solution is Pareto optimal if there exists no feasible solution, which improves one objective without causing a deterioration in at least one other objective. This concept generally does not apply to a single solution, but rather a set of solutions called the Pareto optimal set. The image of the Pareto optimal set under the objective functions is called Pareto front.

The improved version of the traditional ε-constraint method is applied to the problem so that the Pareto front is generated. Mavrotas (2009) proposes that the objective function constraints are transformed into equations (instead of inequalities as in the conventional method) by incorporating slack or surplus nonnegative variables, which are then used as penalization factors in the objective function. This augmented ε-constraint method produces only efficient solutions. In this work three objective functions exists; therefore a total of $(q_2 + 1) \times (q_3 + 1)$ runs are performed to obtain the Pareto front, when q_2 and q_3 are the equal amplitude intervals partitioning the range of each objective function. When the problem becomes infeasible, it means that there is no need to further constrain the corresponding objective function as it will from then on lead to infeasibility (more details in Mavrotas 2009).

When solving the problem under analysis in this work, where three objectives are being tackled, an approximation to the Pareto front is designed by using the augmented ε-constraint method, where the economic objective is optimized and the social and environmental constrained (see Table 14.4).

Finally, to propose a sustainable solution, that is, a compromise solution between the three objectives, a compromise solution method (Yu 1985) is applied, where the Pareto optimal solution closest to the ideal point is obtained. The ideal point (z_I) is defined according to the individual minima of each objective $z_\mathrm{I} = \left(z^1_{\min}, z^2_{\min}, z^3_{\min}\right)$, while the nadir point (z_N) is defined according to the worst values obtained for each objective ($z_\mathrm{N} = \left(z^1_{\max}, z^2_{\max}, z^3_{\max}\right)$. To apply this method, the objective functions are normalized by the differences between the nadir and ideal points, measuring the variability of the objective function within the Pareto set. Afterward, the compromise solution is obtained by minimizing the distance from the Pareto front to the ideal point, where the Tchebycheff metric is used as distance measure:

$$\min\left\{\max_{j=1}^{\phi}\left\{\lambda_j\left|z^j(S) - z^j_\mathrm{I}\right|\right\} : S \in \Omega\right\} \tag{14.33}$$

where ϕ is the number of objective functions in study and λ_j the normalized factor for each objective function:

$$\lambda_j = \frac{1}{r_j}\left[\sum_{i=1}^{\phi}\frac{1}{r_i}\right]^{-1} \tag{14.34}$$

$$r_j = z^j_{\max} - z^j_{\min} \tag{14.35}$$

Table 14.4 Pseudo-code of the augment ε-constraint method

1. *Lexicographic optimization to create the payoff table* 1.1. min $z^1(S)$ *st* eqs. (14.4), (14.6)–(14.13) Output: solution $s_1 = (z^{1*}, z^2, z^3)$ 1.2. min $z^2(S)$ *st* eqs. (14.4), (14.6)–(14.13), $z^1(S) = z^{1*}$ Output: solution $s_2 = (z^{1*}, z^{2*}, z^3)$ 1.3. min $z^3(S)$ *st* eqs. (14.4), (14.6)–(14.13), $z^1(S) = z^{1*}$, $z^2(S) = z^{2*}$ Output: solution $s_2 = (z^{1*}, z^{2*}, z^{3*})$ 1.4. Repeat 1.1 to 1.3 for $z^2(s)$ and $z^3(S)$ 1.5. Write the payoff table for the three objectives
2. *Set ε values* 2.1. Set ranges of the objective functions: $r_2 = z^2_{max} - z^2_{min}$ $r_3 = z^3_{max} - z^3_{min}$ 2.2. Set number of grid points q_2 and q_3 2.3. Set the variation of ε_2 and ε_3: $\Delta\varepsilon_2 = \frac{r_2}{q_2}$ $\Delta\varepsilon_3 = \frac{r_3}{q_3}$

3. *Solve Problem* (where v_2, v_3 are the surplus variables and *eps* is a small number, usually between 10^{-6} and10^{-3})
$n_2 = 0$, $n_3 = 0$
while $n_2 \leq q_2$ and $n_3 \leq q_3$
do
min $\left(z^1(S) - eps\left(\frac{v_2}{r_2} + \frac{v_3}{r_3}\right)\right)$
st
eqs. (14.4), (14.6)–(14.13)
$z^2(S) + v_2 = z^2_{max} - n_2\Delta\varepsilon_2$
$z^3(S) + v_3 = z^3_{max} - n_3\Delta\varepsilon_3$
end do
$n_2 = n_2 + 1$
$n_3 = n_3 + 1$
end while

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