Tactical and Operational Planning in Reverse Logistics Systems with Multiple Depots

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Abstract

This work develops new mixed-integer linear programming models and new solution's approaches to support tactical and operational planning decisions in reverse logistics systems involving multiple depots. Depots' service areas delimitation, routes' definition and scheduling, CO_2 emissions quantification and drivers labour hours balance were addressed. With all these aspects in mind, the contribution of this work is to build the basis for a solution tool that supports a sustainable operation of reverse logistics networks. Namely, by increasing efficiency of recyclable waste collection systems, while diminishing their environmental impacts and increasing social concerns. The models were applied to different real case studies.

Keywords: Reverse logistics, Waste collection, Multiple depots, Sustainability, Service areas, Routing, MILP models.

1 Introduction

Reverse logistics can be defined as "the process of planning, implementing and controlling backward flows of raw materials, in-process inventory, packaging and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal" (de Brito and Dekker, 2004). Following this definition, reverse logistics concentrates on streams where there is some value to be recovered, entering the outcome into a new/existent supply chain. Among other recovery options one is the recycling which, imposed by the European Union (EU), has forced member states to develop new collection systems. The traditional routes defined for undifferentiated waste do not fit the particularities of recyclable materials and different vehicles, different collection rates and different bin locations are required. This situation motivated the surge of two different waste collection systems: selective and undifferentiated. The costs involved in selective collection are higher than in undifferentiated collection, but recycling targets have anyway to be accomplished. On the other hand, recycling helps to protect the environment since it mitigates resource scarcity, decreases demand for landfill space and involves savings in energy consumption. But, the activity of collecting the recyclable waste is mainly a transportation activity, implying Greenhouse Gas emissions (GHG), resource consumption, and noise, amongst other negative impacts to the environment. Moreover, several human resources take part of the collection activities and an equity workload distribution among them should be planned. To respond to this challenge waste collection companies must invest on the effective planning and operation of their logistics structures while considering economic, environmental and social objectives. Due to the complexity involved at the planning and operation of such systems, tools that may support the planners' decision, within such companies, are required and represent a challenge to the academic community. Since this research was triggered off by three waste collection systems case-studies where strategic decisions have already been taken, the focus of the work is on tactical and operational decisions and the aim is to contribute to the development of solution approaches that may help decision makers of reverse logistics systems.

The innovative aspects of this research rely on the study of three characteristics of logistics networks that have been seldom studied: type of routes (closed *versus* open), number of products (single *versus* multiple) and objective function (economical *versus* environmental *versus* social). The majority of the published works has focused on closed routes, single-product and deal with an economical objective function. This work goes further by studying also open routes, multiple products and by dealing with environmental and social objectives in addition to the traditional economical objective.

Given the goal of defining service areas and vehicle routes simultaneously, the baseline model is the so-called Multi-Depot Vehicle Routing Problem (MDVRP). Different variants are then addressed, such as open routes, inter-depot routes, periodic, multiple products, and environmental and social objective functions. New models and solution's approaches are developed to address each problem. The models developed are validated by literature instances and by real case studies, where the collection of end-of-life products is planned in three real reverse logistics systems operating in Portugal.

The remainder of the paper is structured as follows. In section 2 a brief review of literature on routing problems and its variants is presented. In the following sections the main results of each studied variant are described. Section 3 addresses the MDVRP with Open Routes, section 4 the MDVRP with Inter-Depot Routes, section 5 the MDVRP with Multiple Products and Economic and Environmental concerns. Section 6 addresses a multi-objective Multi-Product, Multi-Depot Periodic Vehicle Routing Problem with Inter-Depot Routes. Final remarks and future work directions are drawn in section 7.

2 Literature Review

Routing problems consist on defining the optimal delivery or collection routes from a central depot to a set of geographically scattered customers, subject to various constraints. Such problems are common to a large range of logistics systems and have a significant economic impact on the planning and operation of these systems (Laporte, 2007). However, the logistics systems can have diversified features giving rise to different variants of routing problems. It may involve a single or multiple depots, homogeneous or heterogeneous vehicle fleet, stochastic or deterministic demand, closed or open routes, among others.

The MDVRP appears as a generalization of the Vehicle Routing Problem (VRP) where beyond the definition of vehicle routes, the allocation of customers to depots must also be determined. Therefore, the MDVRP simultaneously establishes the service areas of each depot and the associated vehicle routes. The vehicle routes are defined such that: (1) each route starts and ends at the same depot; (2) each customer is visited exactly once by a vehicle; (3) the total demand of each route does not exceeds the vehicle capacity; (4) the total duration of each route, including travel and service times, does not exceeds a pre-set time limit. The best solution is the one that minimizes total routing cost.

Several models have been developed for the MDVRP, exploring both exact and approximate approaches. However, since this is a NP-hard combinatorial problem, the models proposed in the literature are predominantly heuristics-based. Few exact algorithms have been present in the literature. Laporte et al. (1984), as well as Laporte et al. (1988), developed exact branch and bound algorithms for solving the symmetric and asymmetric versions of the MDVRP, respectively. More recently, Baldacci and Mingozzi (2009) developed an exact method for solving the Heterogeneous Vehicle Routing Problem (HVRP) that is capable of solving, amongst other problems, the MDVRP. On the other hand, when analysing the heuristic algorithms to solve MDVRP, several ones have been proposed such as: Tillman and Cain (1972), Golden et al. (1977), Chao et al. (1993), Renaud et al. (1996), Cordeau et al. (1997), Salhi and Sari (1997), Lim and Wang (2005), Parthanadee and Logendran (2006), Crevier et al. (2007), Pisinger and Ropke (2007), Ho et al. (2008), Dondo and Cerda (2009), among others.

When considering that the vehicle may not return to the route starting point, an open route is defined (Schrage, 1981). In the Open Vehicle Routing Problem (OVRP), vehicle routes start at the depot and end at one of the customers, defining routes as paths and not cycle tours. This problem often appears when the vehicle fleet is hired and the contractors are paid based on the kilometres driven. Since this problem appears as a common problem in real logistics systems, its study by academia has been intensified in the last decade. Several methods have been proposed where again heuristics and exact approaches have been explored. Sariklis and Powell (2000), Tarantilis and Kiranoudis (2002), Brandao (2004), Fu et al. (2005), Repoussis et al. (2007), Salari et al. (2010) are examples of some works where heuristic approaches have been proposed for solving the OVRP or its variants. On the exact methods, Bektas and Elmastas (2007) developed an integer formulation for solving the OVRP with capacity and distance constraints, which is applied to a real-life school bus routing problem. Also, Letchford et al. (2007) looked into the exact approaches and presented a branch-and-cut algorithm for the capacitated open vehicle routing problem.

While the MDVRP considers a planning horizon of just one time unit, the Periodic Vehicle Routing Problem (PVRP) considers a planning horizon of several time units giving that customers 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. These two problems (the MDVRP and PVRP) have received a great deal of attention, but the combination of them – the Multi-Depot Periodic Vehicle Routing Problem (MDPVRP) has rarely been studied in the literature, and consequently only few models have been developed (see the works of Hadjiconstantinou and Baldacci (1998), Parthanadee and Logendran (2006) and Vidal et al. (2012)).

In all the above works, the objective function was defined as the minimization of either the total distance travelled, total time or the total routing cost, being the latter objective in most cases a linear function of distance or time. Nonetheless, some recent works have also explored environmental issues in vehicle routing problems (Bektas and Laporte (2011), Erdogan and Miller-Hooks (2012)). The combination of the three dimensions of sustainability has never, to the best of our knowledge, been approached in vehicle routing problems with multiple depots.

3 The Multi-Depot Vehicle Routing Problem with Open Routes

The Multi-Depot Vehicle Routing Problem with Open Routes (MDVRP-OR) has not yet been studied in the literature. In a logistics system with multiple depots, route's starting location can be different from the ending one, but all routes have to start and end at one of the network depots. Therefore, vehicle routes can be Hamiltonian cycles (closed routes) or just Hamiltonian paths between two depots (open routes), being both admissible. This study has been motivated by a real-life problem of a waste cooking oil collection system characterized by the existence of multiple depots with an outsourced vehicle fleet. The objective of the company is to minimize the total cost involving the number of vehicle routes required and the total distance travelled when visiting all the collection sites.

The MDVRP-OR builds k vehicle routes in such a way that: (1) each route starts and ends at a depot (not necessarily the same); (2) each collection site is visited exactly once by a vehicle; (3) the total demand of each route does not exceed the vehicle capacity Q ; (4) the total duration of each route, including travel and service times, does not exceeds a pre-set time limit T ; so that (5) the total routing cost is minimized.

To formulate the MDVRP-OR based on the two-commodity flow formulation we use the same decision variables as Baldacci et al. (2004) - x_{ij} and y_{ij} - and add two decision variables to carry out the duration constraints - e_{ij} and a_{ij}. A third variable k is also introduced allowing for the minimization of the number of vehicles or vehicle routes (which are equivalent under this context). Therefore, the decision variables in this formulation are:

• x_{ij}, a binary variable that represents the routing solution:
$=1$, if site j is visited immediately after site i; 0, otherwise;

• y_{ij}, a flow variable that represents the load in the vehicle route when edge (i, j) is crossed. The flow y_{ji} represents the empty space on vehicle route when edge (i, j) is crossed; therefore $y_{ij} + y_{ji} = Q$, at any edge (i, j);

• e_{ij}, a continuous variable representing the exit time from site i to site j ;

• a_{ij}, a continuous variable representing the arrival time to site j from site i ;

• k, an integer variable representing the number of vehicles needed.

All routes start at one of the real depots (set V_d) and end at one of the copy depots (set V_f) (see Figure 1).

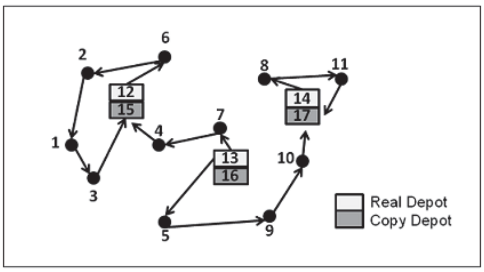

Figure 1: Routes illustration for the MDVRP-OR.

The real-life problem, with more than 100 collection sites, was solved through the CPLEX branch-and-cut algorithm, showing a 2% gap after eight hours of computational time. The proposed routing planning solution resulted in an 11% savings in total cost when compared to the company current solution. As CPLEX branch-and-cut algorithm managed to solve the MILP model applied to the real problem within a reasonable computational time for tactical decisions (eight hours), no other solution method was needed.

4 The Multi-Depot Vehicle Routing Problem with Inter-Depot Routes

The Multi-Depot Vehicle Routing Problem with Inter-Depot Routes (MDVRPI) allows routes between two different depots but imposes vehicles to return to the origin depot within a working day. A vehicle can perform multiple routes per day being those routes either closed and/or inter-depot routes. The set of routes performed by the same vehicle is called rotation (see Figure 2).

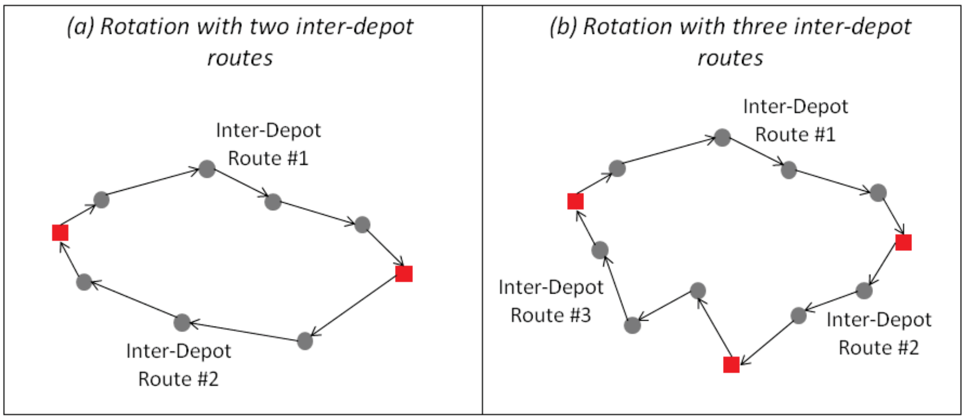

Figure 2: Examples of rotations with (a) two and (b) three inter-depot routes.

The rotation concept brought extra complexity to the problem, since the model has to define feasible rotations made by closed and/or inter-depot routes, assuring that the maximum time limit for a working day is not exceeded. A new mathematical formulation is developed where both rotations and routes are defined. The solver CPLEX was not capable of solving the model applied to literature instances of large dimension and a solution methodology was developed. This solution methodology is based on two relaxations of the original problem: the duration constraints and the number of vehicles available (see Figure 3).

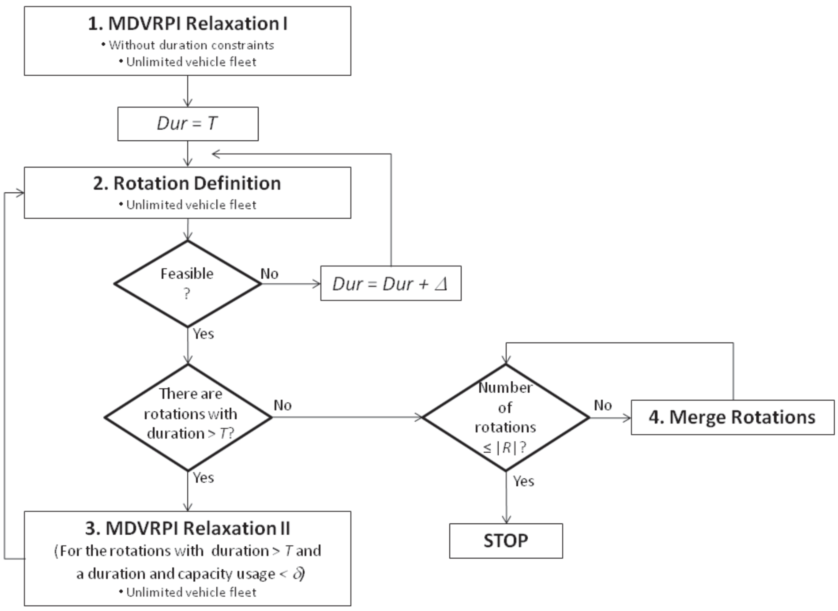

Figure 3: Solution methodology flowchart for the MDVRPI.

Half of the literature instances were then solved by the first module of the solution methodology even though the duration constraints and the number of vehicles available were not being considered. The solutions founded for all literature instances were compared with the work of Crevier et al. (2007) where the MDVRPI is tackled but assuming that all vehicles are based in a central depot rather than in multiples depots (what renders Crevier's et al. work to a Vehicle Routing Problem with Intermediate Replenishment Facilities). Economical savings in all instances up to 9.7% are attained if the MDVRPI with the vehicles based in multiple depots is solved.

5 The Multi-Product, Multi-Depot Vehicle Routing Problem with Economic and Environmental Concerns

In the classical MDVRP the objective function is distance, time or cost minimization. Here a different objective function has been analysed reflecting an environmental concern - minimization of the CO_2 emissions. A recyclable packaging waste collection system is studied where multiple products have to be collected, transported to the depots (inbound transportation) and then to a sorting station (outbound transportation). Such system manages their operations under a municipality-perspective: service areas and collection routes were defined respecting the municipalities' boundaries.

When multiple products are at stake, two alternative solutions can be created regarding service areas. The recyclable materials at each collection site: a) have to be collected from the same depot (service areas by depot); b) can be collected from different depots (service areas by recyclable materials). These two alternatives are studied and the results are compared. The Multi-Product, Multi-Depot Vehicle Routing Problem (MP-MDVRP) is formulated by a MILP model and a decomposition solution approach (see Figure 4) is developed to solve the real case.

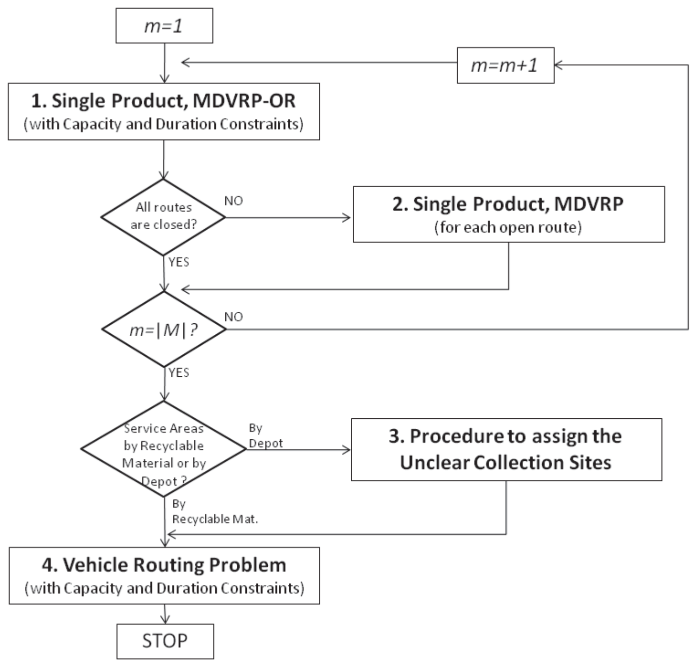

Figure 4: Solution methodology flowchart for the MP-MDVRP.

The distance and energy minimization are studied as objective functions. The latter depends on the distance, load and speed, as well as vehicle and road characteristics. The CO_2 emissions are function of the energy requirements. Effectiveness tests are performed where the optimal solution and computational times obtained by CPLEX are compared with the solution provided by the proposed decomposition method. It was concluded that the decomposition method finds a good or even the optimal solution in much less time than CPLEX alone. The maximum deviation between the optimal solution and the one proposed by the decomposition method was of 2%, inducing that an effective solution method was developed.

The decomposition method was applied to the real case study, where three service areas configurations were analysed and two objective functions compared. If the current service areas are maintained and only the vehicle routes optimized, annual savings of 13% in both cost and CO_2 emissions are observed. If service areas are restructured by depot, annual savings of 19% in cost and 24% in CO_2 emissions would be obtained. Lastly, if service areas are restructured by recyclable material, annual savings of 22% in cost and 27% in CO_2 emissions can be reached. Comparing the two objective functions (minimize distance *versus* energy), different solutions are obtained. The energy-minimizing objective produces service areas with more sites assigned to the sorting station as it minimizes the outbound transportation where vehicles transport heavier loads. Moreover, route topology also changes under the energy-minimization objective since this formulation seeks solutions where vehicles travel less distance with heavy load, so either the heaviest collection sites are placed latter in the route or more routes with lesser load are defined. However, the final results regarding total distance travelled and CO_2 emissions for the real-case study did not differ substantially. These results allow us to conclude that the distance travelled has a major contribution for CO_2 emissions. Therefore, when distance is minimized (a proxy for the economic goal), it is simultaneously contributing to mitigate the negative environmental impact of transportation.

6 The Multi-Product, Multi-Depot Periodic Vehicle Routing Problem with Inter-Depot Routes with Economic, Environmental and Social Concerns

To accomplish the main objective of this work, that is, to contribute to an increase in efficiency, diminish environmental impact and increase social concerns in reverse logistics networks, namely, in waste collection systems, the social objective is here tackled. A multi-objective approach was used to devise a solution where costs are balanced with environmental and social concerns. As it is involved the definition and scheduling of vehicle routes in a multiple depot system, where inter-depot routes are allowed, the problem is modelled as a Multi-Depot Periodic Vehicle Routing Problem with Inter-Depot Routes (MDPVRPI). This problem consists of simultaneously selecting a set of visit days for each client, defining the service areas of each depot and establishing vehicle routes for each day of the planning horizon.

The planning of a sustainable logistics system, where the three dimensions of sustainability are taken into account, is seldom studied in the literature and, therefore, this work aims at contributing to fulfil this gap. The social dimension is the less studied of the three objectives and consequently almost no metrics are proposed to deal with this aspect in the literature. In this work, this dimension is assumed linked to the promotion of equity among the human resources (in this case, the drivers) and the objective function regarding the social issue considers the minimization of the maximum number of working hours among the drivers.

Since the goal is to obtain a solution where costs are balanced with environmental and social concerns, the problem will be solved through a decomposition approach where two steps are defined (see Figure 5).

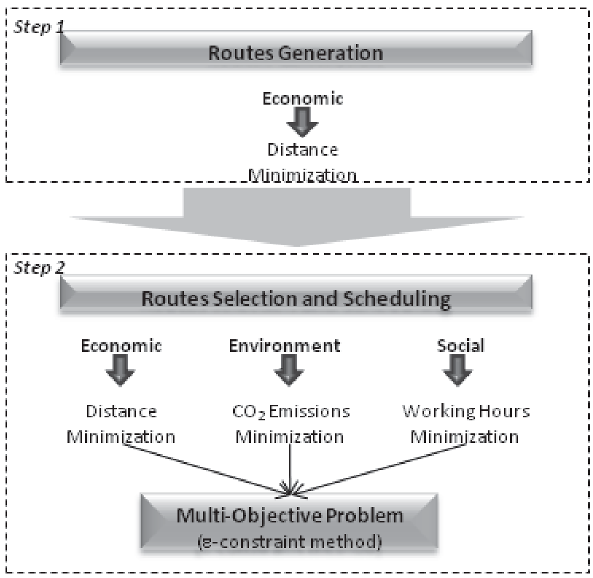

Figure 5: Solution approach overview for the MP-MDPVRPI.

In a first step, a set of feasible routes is generated considering the economic objective (using the MILP models described previously). Then, in a second step, when selecting and scheduling the routes, the three objectives are first considered individually by assessing the following metrics: total travelled distance as the economic objective (note that distance is a linear function of the variable costs); CO_2 emissions as the environmental objective; and number of working hours of each driver as the social objective. Lastly, a multi-objective approach based on the epsilon-constraint method is applied to define an approximation to the Pareto's frontier, which can be used by the decision-maker to select the solution to be adopted.

When economic and environmental objectives are minimized, unbalanced solutions are obtained in terms of working hours by driver. On the opposite side, when the social objective is minimized, a balanced solution is obtained where all drivers have the same number of driving hours (see Figure 6). However, this equity solution leads to a significant increase in distance and CO_2 emissions (see Figure 7).

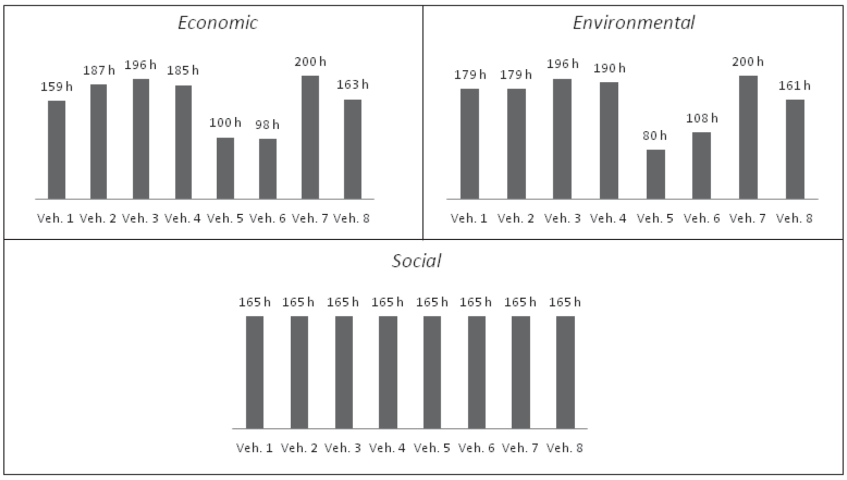

Figure 6: Number of working hours by vehicle in the three solutions.

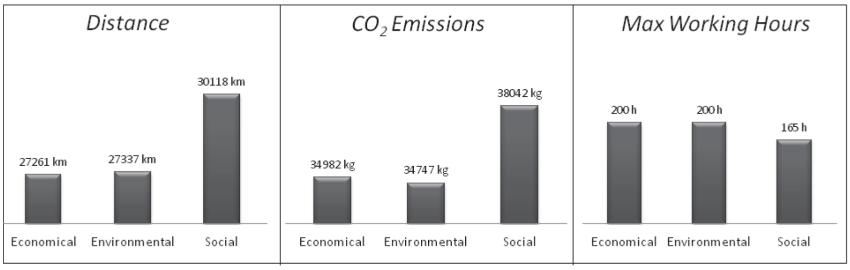

Figure 7: Distance, CO_2 emissions and maximum working hours for the three objective functions.

On the other hand, when accounting for the three objective simultaneously, an efficient solution is identified (a compromise solution, see Figure 8) where the distance to the ideal point is minimized. The Tchebycheff norm is used as distance measure. The ideal point (z^I) is defined according to the individual minima of each objective, in this case z^I = (27 261 km, 34 747 kg CO_2, 165 h) and the compromise solution z^C obtained is z^C = (28 013 km, 35 653 kg CO_2, 174 h).

As main conclusion it can be stated that an innovative approach to planning sustainable logistics systems is proposed. Tactical and operational decisions are coped and different solutions are obtained when each dimension of sustainability is addressed individually. The main contribution of this work is to integrate within a single solution the three dimensions of sustainability where innovative aspects that should be considered when planning reverse logistic systems are modelled such as service areas, routes definition as well as routes scheduling, CO_2 emissions and human resources working hours.

7 Final remarks and further work

Generic models for the tactical-operational decisions levels of reverse logistics systems with multiple depots have been developed throughout this work, which were validated by literature instances and by real case studies. As main goal, the objectives have been to increase efficiency, diminish environmental impact and increase social benefit. The economic objective function has been widely studied but the environmental and social ones have been less addressed. Some challenges were faced when dealing, for the first time, with the latter objectives. To cope with the environmental concern, a comprehensive study

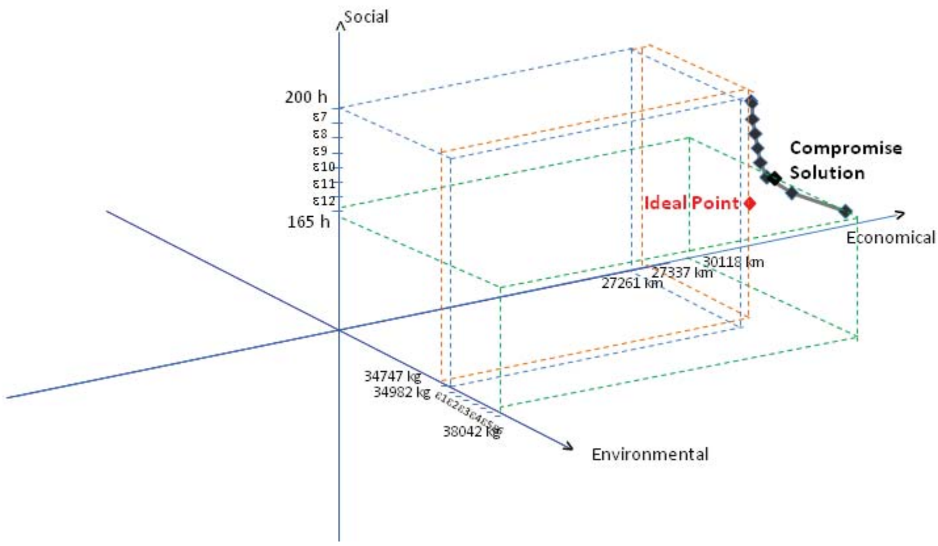

Figure 8: Approximation to Pareto's frontier considering the three objectives simultaneously, with the compromise solution and ideal point highlighted.

on vehicle emissions models was rolled out, where some mechanics and physics insights had to be studied. Regarding the social objective, the difficulty was on how to translate the social concern into metrics and decision variables.

Besides the novelty of the objective functions addressed, some key characteristics that have not being often studied in the literature were also tackled in this research, as the open routes between two depots, the inter-depot routes and the rotation concept, considering simultaneously the inbound and outbound transportation flows, and the existence of multiple products. Despite these characteristics are commonly present in real world cases, they have not been tackled profoundly by the academia.

Based on the developed work, future research topics are foreseen to generalise the problem addressed. An alternative to the single-material routes could be studied, where vehicles with compartments are used to collect two or even the three materials simultaneously without mixing them (the Multi-Compartment Vehicle Routing Problem). Also stochastic models could be developed in order to cope with more realistic scenarios regarding the quantities to be collected. Following the tactical and operational decisions tackled in this work, a future research topic could also be the inclusion of strategic decisions into the models developed, where the number and location of the depots and sorting stations are decided along with the service areas and vehicle routes. Furthermore, companies are now introducing greener vehicles (like hybrid or electric vehicles) to their fleet in order to minimize the CO_2 emissions in the transportation activity. It will be interesting to study the impact of introducing some electric vehicles in the vehicle fleet of recyclable waste collection systems and analyse which routes are assigned to such vehicles and which are assigned to diesel vehicles, by assessing the final impact in terms of costs and CO_2 emissions.

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