Available online at www.sciencedirect.com
ScienceDirect
Waste Management 27 (2007) 1286–1297
waste management
www.elsevier.com/locate/wasman

A decision support system for the operational planning of solid waste collection

Eugênio de Oliveira Simonetto [a], Denis Borenstein [b,*]

[a] Federal Center of Technological Education of Sao Vicente do Sul (CEFET-SVS), CIET, 20 de Setembro, S/N, 97420-000, Sao Vicente do Sul-RS, Brazil
[b] Escola de Administração, Universidade Federal do Rio Grande do Sul, R. Washington Luis 855, Porto Alegre, RS, CEP 90010-460, Brazil

Accepted 30 June 2006
Available online 26 September 2006

Abstract

This study presents the conception, modeling, and implementation of a decision support system applied to the operational planning of solid waste collection systems, called SCOLDSS. The main functionality of the system is the generation of alternatives to the decision processes concerning: (a) the allocation of separate collection vehicles, as well as the determination of their routes and (b) the determination of the daily amount of solid waste to be sent to each sorting unit, in order to avoid waste of labor force and to reduce the amount of waste sent to the landfills. To develop the computer system, a combination of quantitative techniques was used, such as: simulation of discrete events and algorithms/heuristics for vehicle allocation and routing. The system was developed using the Borland Delphi environment and the commercial software Arena to carry out the simulations. We also present a computational study with real-life data from the solid waste collection in Porto Alegre, Brazil, in which we show that the results provided by the computational system outperform the operation planning currently adopted.

1. Introduction

Recycling is, according to O'Leary et al. (1999), the process by which materials otherwise destined for disposal are collected, processed or remanufactured, and are reused. Recycle can be defined as being the separation of domestic waste, such as paper, plastic, glass, and materials, aiming at bringing them back to the industry to be benefited. These materials are once again transformed into tradable products. Solid waste management is receiving increasing attention due to its impact on the public concern for the environment. In general, the municipality is responsible for the collection and transportation of the solid waste. These are very expensive services, being responsible for 75–80% of the solid waste management budget (Bhat, 1996).

The implementation of a solid waste management program is a continuous process, which is gradually developed. The first step is related to public awareness campaigns, convincing the population of the importance of recycling and giving instructions on how to separate the waste in containers for each type of material. Afterwards, a collection plan must be created, defining equipment, vehicles, areas, and the waste collection frequency. After the collection, recyclable materials must be transported to a unit equipped with places for sorting, so that a more judicious selection of the materials is made, aiming at their commercialization. It is important for the population to be adequately instructed, so that only tradable materials are sorted waste for recycling, thus avoiding additional expenses with transportation and handling of waste that cannot be recycled. After the implantation of the separate collection, the municipality must maintain the population permanently active through awareness and environmental education campaigns (Chang and Wei, 2000).

* Corresponding author. Tel.: +55 51 33164053; fax: +55 51 33163991.
E-mail address: denisb@ea.ufrgs.br (D. Borenstein).

0956-053X/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.wasman.2006.06.012

The stages that form the solid waste collection process can be seen in Fig. 1, as well as the decisions inherent to each one of them.

Recycling solid waste is an excellent alternative to provide the preservation of natural resources, energy savings, reduction in the landfill area, creation of jobs and income, and the awareness of the population for environmental issues. However, to have an effective functioning, it is extremely important to implant a properly designed solid waste collection system in a city, where recyclables are separated at home and collected by the municipalities. Despite being an excellent alternative for the reduction of waste destined to landfills, only 4.7%, on average, of wastes are reused or recycled in Brazilian cities, according to CEMPRE (Non-Governmental Organization Company Commitment for Recycling). One of the reasons for this small amount of recycling is due to the bad conditioning of wastes by the population, which is generated by the lack of information about solid waste. Other factors that contribute to the small recycling index of wastes are: (a) the high cost of the solid waste collection for municipalities (O'Leary et al., 1999); and (b) the lack of a system correctly designed and operated in terms of storage capacity and waste processing at the sorting units. The main goal of this paper is to develop a tool for aiding managers to overcome those two barriers.

Several modeling tools have been developed to support solid waste management, including linear programming models, multi-criteria analysis, and simulation (Perrodin et al., 2002). Chang and Wei (2000) and Tung and Pinnoi (2000) present applications of the vehicle routing problem (VRP) for the waste collection in Kaohsiung, Taiwan and Hanoi, Vietnam, respectively. Both studies were developed for only one final destination of wastes, the landfill. Huang et al. (1998) present a *Gray Linear Programming* (GLP) model applied to some regions of Hamilton-Wentworth (Ontario, Canada) aiming at minimizing solid waste transportation costs for the different types of final disposal (composting, recycling, incineration, and landfilling). However, the article neglects the waste transportation of the regions involved until final disposal.

Bhat (1996) uses computational simulation to allocate vehicles for solid waste collection, aiming at minimizing the high costs involved. The paper focuses on the calculation of the mean waiting time of trucks in landfills. Kulcar (1996) presents a study for selecting the best means of solid waste transportation in Brussels. Means of transportation include canal, vehicle, and rail. Both models are useful for the design or redesign of a solid waste collection system, but are not appropriate for operational planning.

Multi-criteria analysis has also been widely used (Morrissey and Browne, 2004). A review of multi-criteria waste management models show that outranking methods (Kangas et al., 2001), ELECTRE III (Hokkanen and Salminen, 1997; Courcelle et al., 1998) and PROMETHEE (van Huylenbroeck, 1995), are found to be the commonly used methods. Analytical Hierarchy Process (AHP) was also applied by MacDonald (1996). Although multi-criteria decision analysis (MCDA) has a great potential to be used in solid waste management design and operation, most of the developed models relegate the decision process as a whole, concentrating on the actual MCDA technique itself.

Most papers mentioned above consider the landfill as being the final disposal site for collected waste. In this type of disposal, there is only an entrance waste flow. Therefore, when the landfill storage capacity is reaching its limit (or has already reached it), the landfill is deactivated. Nonetheless, the solid waste flow, which is the study object of this research, represents a particular case, since at sorting units the waste storage space is reduced and, depending on their processing capacity, there may be problems of physical space allocation. Such a consideration is not addressed by authors who study solid waste logistics, because when they deal with this type of collection, they do it as if the waste flow was destined to landfills. Regarding solid waste collection, it is not possible to focus only on the minimization of transportation cost or the distance covered by the trucks. The physical and waste processing capacity of sorting units must also be considered, since there may often be a solution at a lower cost in terms of transportation, but in

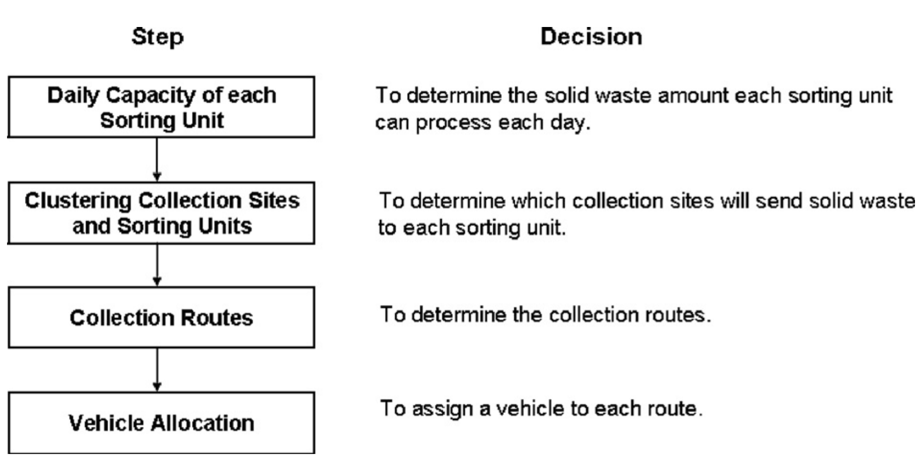

Fig. 1. Solid waste collection process.

which the storage or processing capacities of sorting units are not respected at a given moment.

The main objective of the developed decision support system (DSS) is to support the operational planning of solid waste collection, aiming at a reduction of the costs involved, while also trying to reduce the amount of recyclable waste that is lost due to the lack of control in the storage capacity and work processing at sorting units. Thus, the main contribution of this research is to present an operational management tool that considers the solid waste processing capacity of sorting units. For the development of the computational system, quantitative techniques were used, such as discrete-event simulation (Law and Kelton, 1991) and algorithms/heuristics for solving the well-known VRP (Cordeau et al., 2002). The use of such techniques aims at adding quality to the decision process, since in many cases decisions on planning the solid waste management are made based only on the experience of managers (Chang and Wei, 2000). This fact, according to those authors, contributes to the high cost and low performance of waste collection systems in several cities. The use of quantitative analysis tools for solid waste management is a feasible alternative to the treatment of the complexity inherent to the solid waste collection process, since by using these tools it is possible to represent a situation of the real world, study its behavior (by executing formal models), and making decisions based on the analysis made.

The article is organized as follows: Section 2 describes the developed decision support system – *SCOLDSS*, focusing on its architecture and mathematical formulation. Section 3 presents the results obtained with the use of the DSS in the operational planning of the solid waste collection system in the city of Porto Alegre, Brazil. Finally, Section 4 presents the final considerations of the article.

2. SCOLDSS – The decision support system

SCOLDSS aims at subsidizing the operational decision making process of solid waste managers related to the solid waste logistics, from the collection stage until the waste delivery at sorting units. The computational system specifically supports the following tasks: (i) reducing the amount of solid waste destined to the landfill; (ii) assuring a waste input percentage at each sorting unit; (iii) assigning vehicles to collection trips; (iv) defining their route; and (v) estimating the work capacity (productivity) of sorting units, in relation to the waste arrival and processing (separation). The system basically aids the solid waste collection operational management through the generation, analysis, and assessment of possible operational scenarios for this type of collection. It is considered that the design of the solid waste collection system (in terms of defining the equipment, human resources, areas, and separate collection frequency) has already been previously defined.

The research methodology adopted for the development of *SCOLDSS* is the one usually developed in Operational Research. This methodology consists basically of the following stages: (1) exploratory studies, in which the problem was identified and structured; (2) solution development by building formal models capable of representing the problem (the problem complexity demanded the integration of several modeling techniques, including discrete-event simulation and algorithms/heuristics for the vehicle routing and allocation problems); (3) computational implementation of the solution, using the decision support systems technology; and (4) solution validation through laboratory and field tests, in order to verify if the results obtained are in accordance with the observed reality.

The validation was carried out by using real data from the solid waste collection in the city of Porto Alegre, Brazil. Porto Alegre is the capital of the southernmost state in Brazil, with a population of 1.3 million inhabitants. The municipality of Porto Alegre was a pioneer in the establishment of the solid waste collection in Brazil and its program nowadays is a reference for other cities in Brazil and other parts of Latin America.

To develop *SCOLDSS*, the decision support systems architecture proposed by Sprague and Watson (1993) was used, which is composed of the three following subsystems: database subsystem, model-based subsystem, and user-interface subsystem. *SCOLDSS* architecture can be seen in Fig. 2.

2.1. Database subsystem

The basic premise to build the *SCOLDSS* database subsystem was to select data that were extremely important for providing information to managers, as well as to feed the mathematical and simulation models existing in the model-based subsystem. To develop the database, we have used: (i) studies performed prior to this paper (Huang et al., 1998; Tung and Pinnoi, 2000; Bhat, 1996; Everett and Shahi, 1997; Chang and Wei, 2000); (ii) technical manuals related to Solid Waste Management (O'Leary et al., 1999); and (iii) interviews to investigate requirements from experts in solid waste management.

The relational database model developed in *SCOLDSS*, after the specification of the system requirements, is composed of data structures, attributes, and descriptions. Table 1 shows the high level data structure of *SCOLDSS*.

2.2. Decision model subsystem

The model-based subsystem was created using different techniques of quantitative modelling: the computational simulation of discrete events and the development of algorithms/heuristics for vehicle allocation and routing problems. Simulation is used to determine the sorting unit demands, since it presents a quite dynamic behavior profile, basically attributed to seasonalities and to the population consumption profile. The solid waste collection was modelled as a typical multi-depot VRP with a heterogeneous fleet, in which collection sites offer solid waste to be

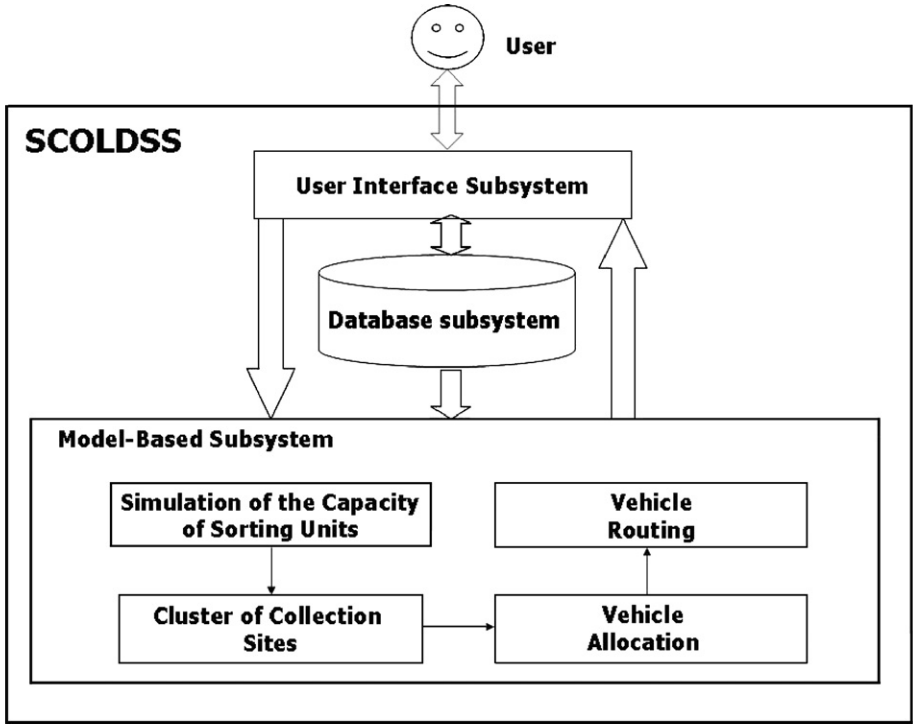

Fig. 2. SCOLDSS architecture.

Table 1
SCOLDSS data structure

Data structure	Attribute	Description
Collection site	Site code	Single identifier of collection site
	Site name	Description of the site where collection is made
	Coordinate X	Representation of the X coordinate of the collection site in the map
	Coordinate Y	Representation of the Y coordinate of the collection site in the map
Collection trip	Site code	Single identifier of collection site
	Date/h	Date and hour in which collection was made
	Amount	Amount of waste (in kg) collected in the site
	Vehicle code	Identifier of the vehicle that performed the collection
Vehicle	Vehicle code	Single identifier of collection vehicle
	License plate	License plate of the collection vehicle
	Type of vehicle	Identifier of the type of vehicle
	Depot code	Identifier of the depot to which the vehicle will be allocated
	Cost per km	Vehicle cost per kilometer driven
Distance	Source site	Identifier of collection/depot site
	Target site	Identifier of collection/depot site
	Distance	Distance between sites in km
Type of vehicle	Type of vehicle	Identifier of the type of vehicle
	Capacity	Vehicle transportation capacity in kg
Depot (sorting unit)	Site code	Identifier of the sorting unit
	Maximum capacity	Sorting unit maximum capacity in kg

demanded by a sorting unit. Algorithms and heuristics were developed to solve this problem.

The use of these techniques is justified by the distinct nature of the problems being addressed. Firstly, the determination of the waste processing capacity is defined by the simulation model; secondly, the determination of solid waste flow (vehicles and routes), as a consequence of simulation results, is solved using heuristic methods for the multi-depot VRP. Based on the interaction of the waste processing simulation at sorting units and the execution of the multi-depot VRP with a heterogeneous fleet, the waste collection vehicle routing, as well as the final destination of the waste carried by them is determined, in order to calculate the waste processing capacity for 1 day.

2.2.1. Simulation model

The simulation model mainly aims at estimating the solid waste processing capacity at sorting units. The determination of the processing capacity is a peculiarity of recyclable wastes and has its origin in the input and output flow of this type of waste at sorting units. This is not the case of solid waste destined to the landfill, because there is no solid waste output (only waste input) in this type of final disposal. The commercial software ARENA (Kelton et al., 2004) was used for simulation.

To execute the simulation, which will depend on the processing capacity of each sorting unit, the following information is necessary:

- *mean rate of waste generation* – mean amount of waste generated by the population (in kg per min). In the mathematical formulation of the decision model, it is represented by variable λ;
- *amount of waste waiting to be processed* – amount of waste waiting (in kg) to be processed in each sorting unit;
- *mean waste processing rate by sorters* – mean amount of waste that each sorter is able to process (in kg per min). In the mathematical formulation of the decision model, it is represented by variable μ.

The identification of the previously described information will influence in determining the *total amount of processed waste* per day at each sorting units. The total amount of processed solid waste, including the recycled ones and the others that will be destined to the landfill have to be taken into account by the simulation, since both temporarily occupy physical space and also consume a given period of time to be processed by workers. The *Pickstation* module of the simulator Arena 5.0 was used to distribute solid waste among sorting units. This module selects the unit to send the raw material (waste) in precedence order, according to the number of resources (personnel) used in each sorting unit (in order to avoid idleness) and by the amount of post-consumption raw material waiting to be processed, since in each sorting unit there is a maximum capacity of waste storage. In this selection, occasional interruptions at work (lunch, change of work team) and the production variation from one shift to another were considered.

The main information generated by the simulation model is the solid waste demand (in kg) that each sorting unit is able to process at a certain day of work, obtained by the average of n simulation runs. The integration module of Arena was used to generate the text file with the results.

2.2.2. Mathematical formulation for vehicle allocation and routing

Before considering mathematical formulations, we introduce some definitions and notations related to this problem. Trips i and j constitute a *compatible pair of trips* if the same vehicle can reach the starting point of trip j after it finishes trip i. Let s and t denote the same depot in the network, where s simply means the depot as a starting point, and t as the terminating point. For the sake of simplicity, we assume in our formulation that: (i) it is not allowed that a vehicle comes from the depot and directly goes to a sorting unit; and (ii) after finishing its collection trip, a vehicle has to go first to a recycling facility for unloading the garbage instead of going to the depot (garage) directly or serving a new trip (this is not a limitation in *SCOLDSS*). In the DSS, two or more collection trips can be carried out in sequence, respecting the vehicle's capacity.

First, we need to construct a network structure that represents the problem. In this structure both the collection trips and recycling facilities are represented as nodes. For each collection trip, we created k associated dummy trips which represent K sorting units. Fig. 3 illustrates the network structure for this problem. The starting time of each *sorting unit associated* (SUA) trip is the ending time of the corresponding collection trip plus the travel time from the ending point of its collection trip to the recycling facility. The duration of each SUA trip is the unloading and service times at the facility. After determining the starting and ending times of each SUA trip, we can construct the vehicle allocation and routing network in such a way that a collection trip is connected to all recycling facilities through the SUA trips. There are no direct connections among collection trips, which meets the problem requirements. A path from s to t in the network represents a feasible vehicle route.

The network is defined formally as follows. Let M be the set of vehicles. Let $T = \{1, 2, \ldots, n\}$ be the set of waste collection trips, and let $R(i) = \{r_{i1}, r_{i2}, \ldots, r_{ik}\}$ be the SUA trips with collection trip i, where k is the number of operational sorting units. These SUA trips represent the sorting units. The starting and ending time of each SUA trip is defined as the method discussed previously. Let $R = \cup_{i \in T} R(i)$ be the set of all associated trips, and let $N = T \cup R$ be the set of whole collection and SUA trips. Let $E1 = \{(i,j) | i \in T, j \in R\}$ be the set of arcs from waste collection trips to the sorting units, and $E2 = \{(i,j) | i \in R, j \in T,$ i and j are compatible pair of trips$\}$ be

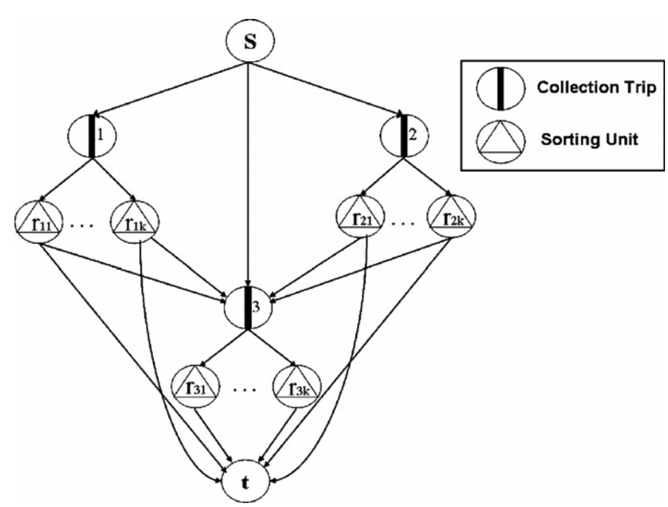

Fig. 3. Vehicle allocation and routing network.

the set of arcs from the sorting units to the collection trips. The vehicle-schedule network is defined as $G = \langle V, Z \rangle$, with nodes $V = N \cup (s, t)$ and arcs $Z = E1 \cup E2 \cup (s \times N) \cup (s \times R) \cup (R \times t)$. Based on this network, the problem can be formulated as follows:

$$\text{Min} \quad \sum_{(i,j)\in Z} \sum_{m\in M} c_{ijm} x_{ijm}$$

$$\text{st} \quad \sum_{j:(i,j)\in Z} \sum_{m\in M} x_{ijm} = 1, \quad \forall i \in N \tag{1}$$

$$\sum_{i:(i,j)\in Z} \sum_{m\in M} x_{ijm} = 1, \quad \forall j \in N \tag{2}$$

$$\sum_{i:(i,j)\in E1} \sum_{m\in M} x_{ijm} = \sum_{k:(j,k)\in E2} \sum_{m\in M} x_{jkm}, \quad \forall j \in R \tag{3}$$

$$\sum_{(i,j)\in Z} q_i x_{ijm} \leqslant Q_m, \quad \forall m \in M \tag{4}$$

$$\sum_{j:(i,j)\in E1} \sum_{m\in M} q_i x_{ijm} \leqslant C_j, \quad \forall i \in T, \ \forall j \in R \tag{5}$$

$$\sum_{j:(i,j)\in E1} \sum_{m\in M} q_i x_{ijm} \geqslant pC_j, \quad \forall i \in T, \ \forall j \in R \tag{6}$$

$$x_{ijk} = \{0, 1\}, \quad \forall i, j \in N, \ \forall m \in M \tag{7}$$

where

- x_{ijm} binary variable that takes on the value 1 when vehicle m visits trip j immediately after trip i, 0 otherwise;
- c_{ijm} cost of associating trip i to trip j using vehicle m, which is usually some function of travel distance;
- q_i amount of waste collected in trip i;
- Q_m capacity of vehicle m;
- p minimum percentage of waste input from the maximum demand of the sorting unit;
- C_j the capacity of sorting unit j. This value depends on the simulation results as follows:

$$C_j = \begin{cases} \mu_j t & \text{if } \lambda_j > \mu_j \\ \lambda_j t & \text{otherwise} \end{cases}$$

where λ_j is the mean rate of waste input to the sorting unit j, μ_j is the mean rate of waste processing at the sorting unit j, and t is the total simulated time.

The objective of the formulation is to minimize the vehicle transportation costs involved. Constraints (1) and (2) ensure that each trip is assigned to exactly one predecessor and one successor. They guarantee also that only one vehicle serves any trip in the system. Constraint (3) guarantees a conservative flow of vehicles arriving and leaving any sorting unit. Constraint (4) ensures that the amount of waste collected in trip i is not higher than the assigned vehicle's capacity. Constraint (5) ensures that the capacity of a sorting unit is not exceeded by the waste collected in trip i. Constraint (6) ensures that a given minimum percentage of waste load will be sent to each sorting unit. Constraint (7) defines the decision variable as a binary one.

Unfortunately, this integer linear programming formulation has too many variables and constraints. A practical example can be visualized in a collection day, in which there are 30 collection sites to be covered, 10 sorting units and 24 vehicles (2 shifts a day) able to perform the collection. Assuming that the collected waste from any of these sites can be sent to any sorting unit and can be collected by any available vehicle, the model has 7200 binary variables. In order to avoid a possible combinatorial explosion within the set of possible solutions using the integer linear programming formulation, we used a heuristic approach in the implementation of *SCOLDSS*, so that we could obtain a faster model processing. As a consequence, the problem was divided into two parts: (i) grouping of collection sites and vehicle allocation, and (ii) vehicle routing. The following sections present how these two subproblems were modeled.

2.2.3. Grouping of collection sites and vehicle allocation

The subsequent stage of using the model based subsystem is characterized by having n sorting units (which demand already have been defined by the simulation model) and m collection sites with recyclable solid waste to be collected by the vehicles. Such description clearly identifies the multi-depot VRP (Bodin and Golden, 1981). The approach proposed by Gillet and Miller (1974) was used for modeling and solving this problem, implemented in the form of "grouping for later routing" heuristic. In this approach, collection sites must first be associated to specific sorting units, through assignments such as "solid waste from collection site x will be sent to sorting unit y". As a result of this step, collection sites are clustered in accordance with the sorting unit in which the solid waste collected will be unload. Also, in this stage the minimum percentage of solid waste input is assured in each of the sorting units, according to the maximum processing capacity provided by the simulation model. The main objective is to avoid imbalanced trip assignments to sorting units, where some facilities may be allocated excessive collection trips, and other facilities may be idle. Such solutions should be rejected when the social benefit of the solid waste program is considered (see Section 3).

When all groupings are formed (collection sites associated to sorting units), a second step is applied for the vehicle allocation. This stage consists of solving the integer linear programming model as follows:

$$\text{Min} \quad \sum_i \sum_k c_{ik} x_{ik}$$

$$\text{st} \quad \sum_{i=1}^{n} q_i x_{ik} \leqslant Q_k, \quad k \in K \tag{8}$$

$$\sum_{k\in K} q_i x_{ik} \geqslant d_i, \quad i = 1, 2, \ldots, nd \tag{9}$$

$$\sum_{k\in K} q_i x_{ik} \leqslant C_i, \quad i = 1, 2, \ldots, nd \tag{10}$$

$$x_{ik} \in \{0, 1\}, \quad i = 1, 2, \ldots, nd, \ k \in K \tag{11}$$

where:

x_{ik} binary variable that takes on the value 1 when a vehicle of type k is associated to a sorting unit i, 0 otherwise;
K set of vehicle types;
q_i amount of the solid waste will be sent to sorting unit i;
Q_k total capacity of vehicles of type k;
c_{ik} cost of associating a vehicle type k to a sorting unit i;
d_i minimal demand of sorting unit i;
C_i capacity of sorting unit i;
nd number of sorting units;
n number of collection trips.

The main objective of this model is to minimize the total costs of assigning vehicles from different types to each collection trip, characterized by a pair of collection site x and sorting unit y. Constraint (8) guarantees that the capacity of vehicles type k is not exceeded. Constraint (9) ensures that a minimum amount of solid waste load will be sent to each sorting unit towards a balanced use of the sorting unit capacities. Constraint (10) guarantees that a sorting unit is not overloaded with solid waste. Constraints (9) and (10) ensure that the solid waste load at a sorting unit i is in the following interval $[d_i, C_i]$. Constraint (11) defines the decision variable as a binary one.

As a final result of this processing, it is defined the amount of solid waste that a given vehicle k will transport to a sorting unit i. If a solid waste collection system is composed by several different types of vehicles, it is necessary to use advanced approaches for the resolution of the allocation. A method based on tabu search is currently being developed to cope with such contexts. After the execution of the algorithm of vehicle allocation, the database subsystem is then fed with the respective types of vehicles associated to each specific sorting unit.

2.2.4. Determining the solid waste collection routes

The aim of this subproblem is to generate the collection routes to be covered, as well as to assign the vehicles that should cover each route. The output of this subproblem has the following structure: vehicle v will cover collection sites a, b, and c (in this order) and unload its cargo in sorting unit x. For the solution development, a heuristic developed by Renaud and Boctor (2002) was used (see Appendix A for details). This heuristic was specifically developed to solve the VRP with a heterogeneous fleet, in case there are vehicles with distinct load capacities. The basic processing stages of the heuristic are: the determination of the distance order in relation to each sorting unit, route generation using the different types of vehicles available, and the selection of the lowest cost combination among the several generated routes. For executing this heuristic, the following additional information is required:

1. The sorting unit to which the planning will be made.
2. The selected collection sites to send waste to the unit (from the grouping stage).
3. The distance between collection sites, as well as their distance until the sorting unit (it is worth mentioning that the distance covered from the garage is being taken into account to calculate the distance related to the sorting units).
4. The mean waste offer at each collection site for each month.
5. The vehicles allocated to the sorting unit (from the vehicle allocation stage).
6. The load capacity of each allocated vehicle.

2.3. User-interface subsystem (dialogue)

The user-interface subsystem in *SCOLDSS* is responsible for the definition of the solid waste collection operational scenarios. This module has graphic and interactive facilities, and menu-data driven dialogues that offer a friendly environment for the user to define all needed data to run the models existing in the DSS. This module is also responsible for the overall control of the DSS, accessing and changing information with other subsystems within the DSS. The main SCOLDSS interface screen is presented in Fig. 4. The map in this figure is used to show the computed vehicle routes (the main output of the DSS). The numbers in the map indicate collection sites.

The interface functioning, when using the decision support system, basically occurs in the following way: the user informs the weekday on which the separate collection planning will be made, the month (in order to consider the occasional seasonalities existing in the process), and the operating waste sorting units. Next, the simulation can be performed in order to determine the amount of waste that each operating unit is able to process every day. Afterwards, the user will execute the functionalities of the system step by step: vehicle allocation, collection route generation, and reports with main results.

The interface validation of *SCOLDSS* was developed with the participation of potential system users (academics and professionals) who, after receiving instructions on its functioning, used it aiming at verifying if it was user-friendly and adequate. The main goal of the interface validation was to achieve consistency between the visions of the system analyst/modeler and the potential user of the model, in a way that is appropriate and cost effective.

2.4. SCOLDSS validation

The *SCOLDSS* system basically consists of the development of quantitative analytical methods and simulation for supporting the operational planning of the solid waste collection. A model can be defined as a representation of the real world, so it is desirable that the representation behavior is the same (or as closest as possible) as the reality being

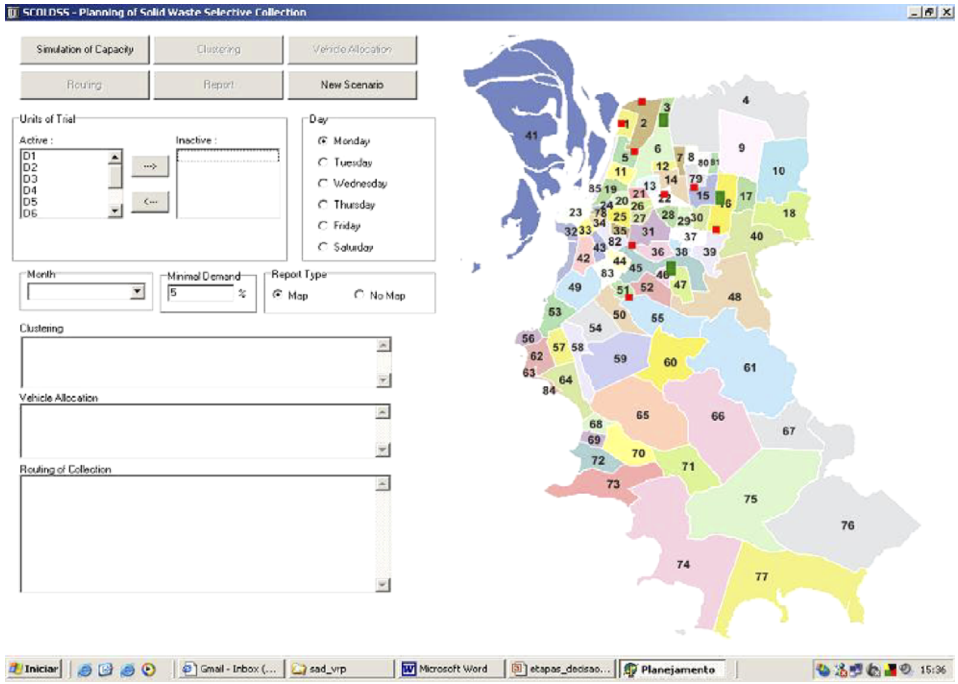

Fig. 4. Main *SCOLDSS* interface screen.

analyzed, under certain specific conditions. This process is called validation, and it is a fundamental step towards an effective computer based system. This section briefly describes the tests carried out to validate the DSS. The emphasis of the validation process is on determining the potential value of the computer based system (Borenstein, 1998).

In the first stage of validation, known as conceptual, data from scientific articles and technical manuals related to solid waste collection were used, in association with interviews with researchers and managers. Furthermore, *in loco* observations of the solid waste collection process were required. *SCOLDSS* is, according to users, user-friendly and presents a significant contribution to managers involved in the operational planning of solid waste collection systems.

In order to verify the internal system structure and to guarantee subsystem accuracy, a subsystem verification and validation (V&V) was carried out for each model module in the system. This validation process has occurred in parallel with the development of each model within the *SCOLDSS* development cycle. As soon as the model was sufficiently developed to be considered as an input-output device this validation took part. Just after being satisfactorily verified and/or validated, the model was integrated to *SCOLDSS*.

The subdivision of the DSS into modules was immediate since its architecture is highly modular. Four basic modules were identified for subsystem V&V, as follows: simulation model, grouping of collection sites and vehicle allocation heuristics, and solid waste collection routes heuristics. The verification and/or validation procedures used varied with the nature and objectives of each module. For the simulation module a paired *t*-test was applied. For the remaining two modules predictive tests were used.

Real data from a sorting unit were used to validate the simulation module, responsible for the estimation of the daily waste processing capacity at sorting units. The simulator behaved correctly during this validation, with a standard deviation of 1.01% in relation to collected real data, which does not compromise the system performance considering that the simulation deals with the maximum processing capacity.

The computational implementation of the heuristics were verified – referring to build the system "right" – by running test cases and comparing their output with the output provided for classic examples in the OR-Library (Beasley, 1990) for the VRP problems. So far, only very minor discrepancies were identified (inferior to 1%), probably consequence of using different solvers and CPU processors. In addition, for each heuristic, sensitivity analysis were performed by systematically changing the input variable values and parameters over a large range of interest and observing the effect upon the heuristics output. Such analysis led to a better understanding of the model-based subsystem with respect to real systems.

Finally, several field tests with real data from the solid waste collection process in the City of Porto Alegre, Brazil were made, aiming at verifying the efficiency and efficacy of the computational system. The main results are described in the next section.

3. Case study

The solid waste collection in City of Porto Alegre involves 150 neighborhoods, with a population of more than 1.3 million. More than 60 tons of solid waste are collected per day and distributed to 8 recycling facilities. The collection and distribution of the solid waste are carried out by the Municipal Department of Urban Cleaning, know as DMLU (from the Portuguese "Departamento Municipal de Limpeza Urbana"). Specifically, for Porto Alegre, 20% of the total budget of DMLU is spent in the solid waste management program, in which 70–75% of the budget is spent in the waste collection and transportation. DMLU has a total annual budget of over US$10 million and employs 3500 workers. It carries out several services, including beach sanitation, public toilets maintenance, garbage and solid waste collection, transportation, and disposal. The sorting units are managed by cooperatives, where members are mostly poor and are not part of the mainstream economy. In these facilities, the recyclables are sorted, appraised, stored, and commercialized. The profit remains with the cooperatives, making it an important income source for more than 450 workers. As a consequence, the solid waste management program has balanced social and ecological benefits.

The collection is weekly performed on each street of the city from Monday through Saturday. The team of solid waste collection is composed of one driver and two garbage collectors, who are specially trained for handling this kind of waste. There are 24 specially designed trucks to support the collection. One of them is always used as a backup truck, in case a severe disruption occurs. Every day, trucks leave the depot at 8:00 am and start a collection route. The routes were defined by the DMLU managers based on the municipality neighborhood division. Fig. 4 presents a map with some collection sites. The idea is to conduct the collection of all streets within the same neighborhood. If a certain neighborhood is too large or has a dense population, the collection can be divided into more than one collection shift.

Although the system is effective, the transportation costs involved are extremely high. The city has not conducted systematic planning for allocating trucks. Consequently, managers in DMLU are concerned about the efficiency of the existing waste-flow methods. Furthermore, it is frequent to obtain poor schedules in terms of imbalanced trip assignments to recycling facilities where some recycling facilities may be allocated excessive collection trips, and other recycling facilities may be idle.

The main purpose of our experiment is to investigate the operational planning of the solid waste collection in Porto Alegre for each working day during a week (3 months were also considered to avoid seasonality biases) and then to compare the results with the operational strategy defined by DMLU. Two main criteria are selected in our study to compare the results by manual planning with the results obtained by *SCOLDSS*: the distances traveled in a collection shift and the number of trips, reflecting the main operational and fixed costs involved in the solid waste collection performed by DMLU.

The solid waste collection data concerning the resources used, waste processing capacity, amount collected at sites, waste distribution, and vehicles needed to validate *SCOLDSS* were provided by the Division of Social Projects, Reuse and Recycling of the DMLU, and can be seen in Table 2.

Data concerning the distances between collection sites and sorting units, as well as the distances among the different collection sites, were estimated using the Geographical Information System of Porto Alegre. Data concerning the number of associates in each sorting unit were obtained from Farah and Barboza (2001). Data concerning mean distances in each collection route were provided by the DMLU.

The experiments were performed for 15 distinct dates, 5 days each in March, April and May. The selected dates were based on DMLU database. They represent average collection days for a whole year. Experiments were performed in a Pentium 4, Processor 2.0 GHz, 256Mb RAM. The results obtained are presented in Tables 3 and 4.

The first aspect to be analyzed concerns the grouping of collection sites made by *SCOLDSS*. In the collection site groupings made by DMLU, there are cases in which the collection sites are quite distant from the sorting units. Such fact much contributes to the increase in the distance covered by collection vehicles. *SCOLDSS*, using the algorithm proposed by Gillet and Miller (1974) for the multi-depot VRP, groups the collection sites closer to the sorting units, reducing the distances traveled in each collection day.

Table 2
Data related to separate collection in Porto Alegre

Resource	Amount
Vehicles	24
Vehicle capacity	Approximately 1600 kg
Vehicle crew	1 driver and 2 collectors
Sorting units	10
Work shifts	2 shifts of 8 h each per day
Waste processing capacity	15 kg/h per person
Waste storage capacity at units	Approximately 2800 kg
Separate collection cost	US$180/ton

Table 3
Comparison concerning distances between the current system and *SCOLDSS*

	Current distance (km)	SCOLDSS distance (km)	Mean reduction (km)	Reduction percentage (%)
Monday	546.5	500.7	45.8	8.39
Tuesday	522.8	478.4	44.4	8.49
Wednesday	442.8	400.4	42.4	9.58
Thursday	591.8	537.2	54.6	9.23
Friday	374.9	343.1	31.8	8.57
Mean	495.7	451.9	43.8	8.82

Table 4
Comparison concerning trips between the current system and *SCOLDSS*

	Number of current trips	Number of SCOLDSS trips	Mean reduction in trips	Reduction percentage (%)
Monday	29	23	6.0	20.71
Tuesday	27	24	3.0	12.70
Wednesday	24	19	5.0	20.83
Thursday	33	27	6.0	18.18
Friday	23	19.3	3.7	17.05
Mean	27.36	22.53	4.83	17.89

Another major aspect concerns the use of the collection vehicles. DMLU currently selects one vehicle for each trip. If the site has a high rate of waste generation, which is able to fill a vehicle (above 85% of its capacity), such strategy is valid. However, there is no justification in allocating a trip to collect 400 kg, considering that the vehicle's transportation capacity is approximately 1600 kg. This fact is quite common in DMLU operational planning. *SCOLDSS*, if possible, attempts to find ways to visit two or three different collection sites in a single trip, aiming at reducing the number of trips and the distance to be covered by the collection vehicles. By using the system, it is possible to obtain a mean reduction of 8.82% in the distance to be covered by the collection vehicles and a reduction of 17.89% in the weekly number of trips. Considering that the mean distance covered by the vehicles is currently 494.43 km/day, the reduction with the use of *SCOLDSS* is very significant, estimated at 43.8 km. The distances covered weekly would suffer a mean reduction of 262.8 km, leading to an annual reduction estimated at 13,665 km. This reduction can represent savings of around 10% of the DMLU annual budget for solid waste collection per year, considering the operational and maintenance costs. Note that this rate of savings could be higher. Although the number of vehicles required is less than in the present operation, these vehicles are fully depreciated. As a consequence, the fixed cost of vehicle deployment is low in relation to the variable operating costs. However, in the case of new vehicles with high depreciation value, the savings are expected to be more significant. This result is very significant to DMLU, because it needs to renew almost half of its fleet.

Concerning the number of trips, the current mean is of 27.3 trips per day (163.8 per week). Using *SCOLDSS*, the average number of trips would be 134.9 weekly trips (reduction of 17.89%), which would result in an annual reduction of 1502 trips. Note that this reduction is obtained even considering that the mean cost of a trip increases from US$6.65 to US$7.37, using the results provided by *SCOLDSS*. This increase is a consequence of the increment in the mean distance covered by each trip and obtained by the computational system, which, however, increases the global operational efficiency of the collection. In order to make such a calculation, only the fuel consumption was taken into account, without considering human resources costs and vehicle maintenance costs, among others.

It can be observed that on weekdays with fewer collection sites to be visited, the lowest improvement rates in the number of trips are obtained using *SCOLDSS*. Such fact is due to the reduction in solutions in the search space, that is, a lower number of options for combinations of sites to be visited by vehicles. Results obtained show improvements that can be made in the solid waste collection operational planning using the *SCOLDSS* system, concerning the reduction of the distance to be covered, as well as the total trips to be made for waste collection.

A fact that should be highlighted, regarding the simulation of the sorting unit processing, concerns the distribution of the collected material among sorting units on collection days. It was verified that on some days certain sorting units had processing capacity, but did not receive any raw material to be processed, creating idleness in the system. By using the minimum demand percentage of 6%

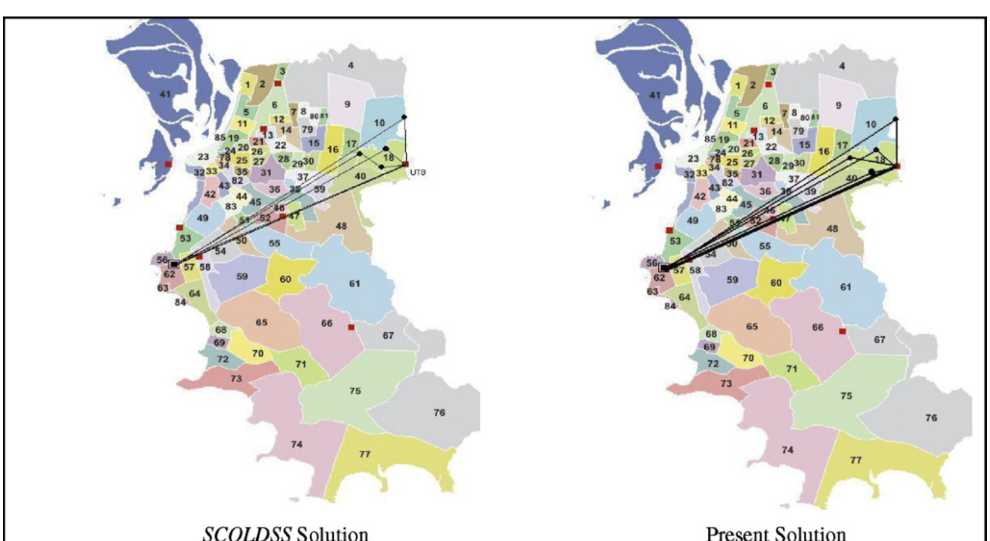

Fig. 5. Maps of separate collection routes comparing DMLU solution and *SCOLDSS*.

in the execution of validations, all eight sorting units started receiving material, but without jeopardizing the other units concerning their waste processing capacities. Thus, the social aspect of the separate collection program is also benefited by the computational system, assuring jobs for every unskilled worker at the sorting units.

As a matter of illustration, a comparison for a specific operational scenario will be presented among the several scenarios performed. In the experiment, concerning Sorting Unit 3 (UT3) and four collection trips (CT1, CT2, CT3, and CT4), the strategy used by DMLU is to perform the collection trips using one vehicle for each separate collection site, with the following routes: UT3–CT1–UT3, UT3–CT2–UT3, UT3–CT3–UT3, and UT3–CT4–UT3. Thus, four vehicles are used. The strategy defined by *SCOLDSS* is as follows: UT3–CT1–UT3, UT3–CT2–UT3, and UT3–CT3–CT4–UT3, therefore, using three vehicles. Fig. 5, in which edges represent vehicle trips, presents a graphic representation of both solutions. In the solution currently found by the DMLU, vehicles cover approximately 78 km, while in the solution proposed by *SCOLDSS* the distance is of approximately 49 km.

4. Concluding remarks

This paper presents the conception and development of a decision support system for operational planning of solid waste collection. The DSS supports the main operational stages of the solid waste collection process, namely the collection by trucks and the solid waste unloading at sorting units. The major contribution of this research is the DSS's capacity to incorporate the control of the storage and processing capacity of the material at sorting units, a fact that was neglected by previous studies in this area. The possible benefits to be obtained by using *SCOLDSS* include: (a) reduction of the distances to be covered by collection vehicles; (b) reduction in the number of trips; and (c) balance in the distribution of waste collected among sorting units.

Specifically for the case study performed with data from Porto Alegre, the following results were obtained:

- Routing solutions, on average, 8.82% better than the routing currently implemented by the DMLU.
- Reduction of 17.89% in the number of collection vehicle trips.
- Through the simulation of waste processing at sorting units and the definition of the minimum demand percentage of waste per unit, the distribution of waste per collection day among the units could be balanced.

SCOLDSS is totally developed and running. It should be considered as a prototype, since it is still in validation process. A demo is available at http://201.11.253.5/~eosimonetto/scoldss. Notwithstanding the short experimentation time, the tests carried out clearly demonstrate that the system has an enormous potential as an effective support tool to be used in real world solid waste systems. However, its implementation is not a straightforward task. The complete data acquisition to run *SCOLDSS* may call for a systemic and organized perspective. Since several municipalities do not record some of the required data, this process can involve some additional costs, mainly with information technology equipment and training. Moreover, given the natural complexity of some techniques used in the system, *SCOLDSS* calls for a relatively long period of experimentation by the users before it can effectively be applied to a real problem. However, it must be noticed that this time cannot be considered as a waste, but as a learning experience that will increase the knowledge of administrators about the operation of a solid waste system.

With further studies, we intend to develop research concerning the knowledge and generation of relevant information on solid wastes, through the development of data warehouses and the application of data mining techniques on databases about solid wastes. The development and application of these techniques will allow the identification of relevant behavior standards from waste generation until its final disposal.

Acknowledgement

The authors would like to thank COPESUL and CNPq, for the financial support to the research. We would like to acknowledge DMLU for providing us real data. Also, the authors would like to express their sincere thanks to the anonymous referees for their valuable suggestions.

Appendix A. Renaud and Boctor's algorithm

Renaud and Boctor's heuristic (2002) for the fleet size and mix vehicle routing problem (FSMVRP) uses different procedures to generate a large set of good routes and then chooses those that satisfy the problem constraints at the lowest cost using a polynomial set partitioning algorithm. Specifically, the proposed heuristic uses five subordinate procedures called: *Order*, *1-petal*, *2-petal*, *Petals Selection* and *Improve*.

The heuristic generates all possible sets of consecutive customers that can be visited by one or two vehicles, constructs the corresponding 1-petal and 2-petal routes, selects the best combination of routes that visits all customers and attempts to improve the obtained solution. In details, the heuristic is composed of the following steps:

Step 1. Orders determination. Use the procedure "*Order*" (Renaud and Boctor, 2002) to select the required number of orders on the set of all vertices.

Step 2. Order selection. If all the selected orders are used, stop. Otherwise, consider one of the unused orders (in the following steps we assume that the vertices are renumbered according to the order being considered). Set $i := 0$.

Step 3. Route initialization. Set $i := i + 1$. If $i > n$, the petal generation process is finished; go to Step 7. Otherwise add to the set of possible routes (petals) the route (v_0, v_1, v_0), and store its cost $C_{ii} = 2c_{0i} + F_h$ where h is the smallest vehicle type that can carry a load of qi. Set $j := i$.

Step 4. 1-Petal route. Set $j := j + 1$ and $S := \{v_i, \ldots, v_j\}$. If $Q(S) \leqslant Q_M$ and $Q(S) \geqslant \Psi Q_h$, where $Q(S)$ is the sum of demands of the set of customers S, Q_M is the capacity of vehicle type having the largest capacity, $\Psi \in [0,1]$, and h is the smallest vehicle type that can carry a load of $Q(S)$, then apply the 1-petal procedure to determine a 1-petal route over S. If the duration of the route obtained is less than or equal to T_h, the maximum allowable route time for the selected vehicle type, store the obtained route and its total cost, denoted C_{ij}.

Step 5. 2-petal route. If $Q(S) \geqslant 2Q_M$ go to step 6. Otherwise, and if $Q(S) \geqslant Q_1$, apply the 2-petal procedure to determine a 2-petal route over S. If a feasible solution is obtained, store it and its total cost. Go to Step 4.

Step 6 . Dominance test. Some of the petals just created may be dominated. For $k = j, j - 1, \ldots, i + 2$, consider the vertex sets $\{v_i, \ldots, v_k\}$ and $\{v_i, \ldots, v_{k-1}\}$. If $C_{i,k-1} \geqslant C_{ik}$, the petal defined over $\{v_i, \ldots, v_{k-1}\}$ is dominated and should be removed. It is replaced by the petal obtained from the one defined over $\{v_i, \ldots, v_k\}$ by removing v_k and adjusting the cost consequently. Go to Step 3.

Step 7. Petals selection. Find the optimal combination of the generated routes that constitute a solution to the FSMVRP by applying the "*Petals-selection*" procedure.

Step 8. Improvement of the initial solution. Use the "*Improve*" (see Renaud and Boctor, 2002) procedure to improve the obtained solution. Store the improved solution if it is the best obtained so far. Go back to step 2.

References

Beasley, J.E., 1990. OR-Library: distributing test problems by electronic mail. Journal of the Operational Research Society 41, 1069–1072.

Bhat, V.N., 1996. A model for the optimal allocation of trucks for the solid waste management. Waste Management & Research 14, 87–96.

Bodin, L.D., Golden, B., 1981. Classification in vehicle routing and scheduling. Networks 11, 97–108.

Borenstein, D., 1998. Towards a practical method to validate decision support systems. Decision Support Systems 23, 227–239.

Chang, N., Wei, Y., 2000. Sitting recycling drop-off in urban area by genetic algorithm-based fuzzy multiobjective nonlinear integer programming modeling. Fuzzy Sets and Systems 114, 133–149.

Cordeau, J.F., Gendreau, M., Laporte, G., Povtin, J.Y., Semet, F., 2002. A guide to vehicle routing heuristics. Journal of the Operational Research Society 53, 512–522.

Courcelle, C., Kestmont, M.P., Typeca, D., 1998. Assessing the economic and environmental performance of municipal solid waste collection and sorting programmes. Waste Management & Research 16, 253–263.

Everett, J.W., Shahi, S., 1997. Vehicle and labor requirements for yard waste collection. Waste Management & Research 15, 627–640.

Farah, M.F., Barboza, H.B (orgs.), 2001. 20 Experiences in Public Management and Citizenship. Editora FGV, Sao Paulo, Brazil (In Portuguese).

Gillet, B., Miller, L.R., 1974. A heuristic algorithm for the vehicle dispatch problem. Operations Research 22, 340–349.

Hokkanen, J., Salminen, P., 1997. Choosing a solid waste management system using multicriteria decision analysis. European Journal of Operational Research 98, 19–36.

Huang, G.H., Baetz, B.W., Patry, C.G., 1998. Trash-flow allocation: planning under uncertainty. Interfaces 28, 36–55.

Kangas, A., Kangas, J., Pykalainen, J., 2001. Outranking methods as tools in strategic natural resources planning. Silva Fennica 35, 215–227.

Kulcar, T., 1996. Optimizing solid waste collection in Brussels. European Journal of Operations Research 90, 71–77.

Kelton, W.D., Sadowski, R.P., Sturrock, D.T., 2004. Simulation with Arena, third ed. McGraw-Hill, New York, USA.

Law, A.M., Kelton, W.D., 1991. Simulation Modeling and Analysis, second ed. McGraw-Hill, New York, USA.

O'Leary, P.R. et al., 1999Decision Maker's Guide to Solid Waste Management, vol. 2. Environmental Protection Agency, Washington DC, USA.

MacDonald, M.L., 1996. A multi-attribute spatial decision support system for solid waste management. Computers, Environment and Urban Systems 20, 1–17.

Morrissey, A.J., Browne, J., 2004. Waste management models and their applications to sustainable waste management. Waste Management 24, 291–308.

Perrodin, Y., Gobbey, A., Grellier-Volatier, L., Canivet, V., Fruget, J.F., Gilbert, J., Texier, C., Cluzeau, D., Gros, R.L., Poly, F., Jocteur-Monrozier, L., 2002. Waste ecocompatibility in storage and reuse scenarios: global methodology and detailed presentation of the impact study on the recipient environments. Waste Management 22, 215–228.

Renaud, J., Boctor, F.F., 2002. A sweep-based algorithm for the fleet size and mix vehicle routing problem. European Journal of Operational Research 140, 618–628.

Sprague, R., Watson, H., 1993. Decision Support Systems: Putting Theory into Practice, third ed. Prentice-Hall, USA.

Tung, D.V., Pinnoi, A., 2000. Vehicle routing-scheduling for waste collection in Hanoi. European Journal of Operational Research 125, 449–468.

van Huylenbroeck, G., 1995. The conflict analysis method: bridging the gap between ELECTRE, PROMETHEE and ORESTE. European Journal of Operational Research 82, 490–502.