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A new management scheme to support reverse logistics processes in the agrifood distribution sector

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Abstract

During the last decades, reverse logistics and reuse of products have received growing attention as profitable and sustainable business strategies. Looking at the agrifood distribution sector, every day thousands of agrifood stores throw away large quantities of food product no longer suitable for sale. This “waste product”, in the majority of cases, could still find new uses as animal feed or fertilizer. The return flow of food product is a typical problem of reverse logistics. This study proposes a new bi-modular scheme for managing the process of collection of “food waste” resulting from the agribusiness distribution sector and its subsequent distribution to livestock farms and collection centers located in the area of interest. The proposed management scheme consists of two modules:

- module 1: to cluster the observed area into convenient collection sectors by means of clustering algorithms;
- module 2: to identify optimal retrieval routes within each cluster by using Vehicle Routing models.

The province of Cagliari in Sardinia (Italy) has been identified as test area. An extensive data collection process has been performed in order to collect the information necessary to portray the existing scenario. The following businesses have been recorded: grocery stores and supermarkets with at least 400 sqm of retail area, livestock farms with at least 200 heads of cattle, feed mills. A number of variables concerning location, type, size and demand data have been collected for each recorded unit. The management scheme has been implemented in a software platform and successfully applied in the test area. The outcome provides useful insights to stakeholders and suggests avenues for further research in the area in order to develop a more general and intuitive tool for managing reverse logistics processes in agrifood chains.

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1. Introduction

Reduction of food waste and increase in resource use efficiency are receiving growing attention as profitable and sustainable business strategies. Focusing in particular on the agrifood distribution chain the extent of the food waste problem appears relevant. In Italy alone every year grocery stores and supermarkets fail to sell on average between 1 and 1.2 percent of their turnover, corresponding to around 244 thousand tons of food product that are thrown away each year (FBAO, 2013). A recent study involving British food markets estimates an amount of 366 thousand tons of waste per annum at the retail and distribution stage (WRAP, 2010). This means that every day thousands of agrifood stores throw large quantities of food product no longer suitable for sale; this “waste product”, in the majority of cases, could still find new uses as animal feed or fertilizer. The return flow of food products is a typical problem of reverse logistics that refers to the distribution activities involved in food-packaging returns, recycling/recovery, reuse and/or disposal. Such return flow involves the collection of food products and packages at retail outlets, the transfer and consolidation at collection facilities, and finally the recovery of returned products/packages (Accorsi et al., 2011; Das and Chowdhury, 2012).

Most of the research concerning food distribution networks has focused only on one specific aspect of the problem: the facility location problem, the waste allocation problem or the vehicle routing problem (Manzini and Accorsi, 2013). Comprehensive reviews on operational issues in distribution planning can be found in Manzini (2012) and Bartholdi and Hackman (2011). However, the complexity of the activities involved makes the adoption of new and integrated tools and methodologies desirable to support decision making throughout the operations management associated therewith (Filip and Duta, 2015).

In the attempt to respond to the need for integrated tools, this study aims to propose a new bi-modular scheme for supporting the management of logistics processes for collecting agrifood waste produced by the agribusiness distribution sector and its subsequent distribution to livestock farms and feed mills, where it can find a new use as animal feed. The proposed management scheme consists of two distinct but strongly related modules:

- in the first module, in order to optimally plan the waste collection process and to be able to better organize the subsequent distribution to farms and collection facilities, the test area has been divided into sub-aggregates of businesses using clustering algorithms;
- in the second module, by considering independently the various clusters detected in the first module, several variations of the vehicle routing problem have been applied in order to identify the most convenient way to serve the various nodes in each cluster using a fleet of vehicles with limited capacity.

The proposed two-step approach has been implemented in a software platform which can support the decision making process of stakeholders and practitioners for the management of real instances from the agrifood distribution sector. As an example of real application this study illustrates the results of applying the proposed management scheme to the province of Cagliari in Sardinia (Italy).

The structure of the study is as follows: section 2 presents a brief literature review on management models for reverse logistics processes, section 3 describes the logistics problem examined, section 4 illustrates the adopted methodology, section 5 presents the area and the test data and discusses the computational results of the application. Finally section 6 concludes the paper.

2. State of the art

The return flow of food products is a typical problem of reverse logistics and concerns distribution activities involved in food-packaging returns, recycling/recovery, reuse and/or disposal. Reverse logistics activities are often

supported by specific facilities, typically collection centers, where products are recovered, repaired or recycled. As a consequence the network structure needs to be extended with transportation links for return flows from customer locations to collection sites. In the literature, reverse logistics typically refers to activities dedicated to the collection of return flows within the Supply Chain Management (SCM). This latter is one of the areas in logistics which has attracted much attention in the literature (Melo et al., 2009); SCM issues typically include facility location, production, inventory, distribution and routing. Since planning in supply chains involves several levels of hierarchical decisions, these decisions are usually classified as strategic, tactical and operational depending on their effects on the supply chain as a whole (Manzini, 2012; Melo, 2009; Ahumada and Villalobos, 2009). Strategic decisions have long-term effects, tactical decisions have mid-term effects, while operational decisions have short-term effects. Looking in particular at the reverse logistics sector, decisions at the different levels typically concern:

- number and location of collection facilities (strategic level);
- demand flows to be allocated to each collection facility (tactical level);
- management of vehicles and routes in order to fulfil demand needs (operational level).

All these logistics decisions are typically treated separately in the literature and quite recent literature reviews can be found in Arabani and Farahani (2012), Melo et al. (2009), Gebennini et al. (2009). Concerning solid waste management specifically, an updated survey of strategic and tactical issues can be found in Ghiani et al. (2014). Looking at the existing literature, it emerges that most of the research in the area has focused only on one specific aspect of the problem: the facility location problem, the waste allocation problem or the vehicle routing problem (Manzini and Accorsi, 2013). However, the strong interdependence existing among the involved aspects makes the adoption of new and integrated tools and approaches desirable to support decision making throughout operations management (Filip and Duta, 2015; Manzini, 2012; Shen, 2005; Melo, 2009) in order to produce more global solutions. Some attempts in this direction can be found in Mourão et al. (2009) and Rodrigues and Ferreira (2015) who proposed a two-step approach using sectoring and routing models to address a solid waste collection and transportation problem. The suitability of sectoring in the management of waste collection is not new in the literature as it allows one to partition a large area into convenient sectors, thus facilitating management of the related activities (Hanafi et al., 2009; Lamata et al., 1999; Male and Liebman, 1978). Following the approach proposed by Rodrigues and Ferreira (2015), the present study attempts to respond to the need for integrated tools to support decision making in reverse logistics by proposing a new bi-modular scheme implemented in a software platform to support decision makers to best manage the collection of food waste from supermarkets and its distribution to collection sites. The new proposed management scheme consists of tailored iterative algorithms to partition the area into smaller collection basins and efficient vehicle routing models to identify the optimal collection network within each sector.

3. Problem description

Every supermarket in the area of interest produces each day a certain amount of food waste which, if properly collected and processed, can find new uses as animal feed or fertilizer. The volume of food waste can vary widely from one supermarket to another, and even for the same supermarket over time, as it depends on several, changing and heterogeneous factors that are quite difficult to evaluate (among others, order management policies, seasonal variations, promotional campaigns, sales policies, etc.). For the purpose of the present application, the food waste produced by supermarkets and grocery stores can be divided into three main categories:

- loose fruit-and-vegetable waste;
- packed agrifood waste;
- meat waste.

The last category will not be considered in this study because of the specific regulations and procedures to which it is subject for health and safety reasons, while two different management schemes are proposed for the two remaining waste categories:

- separate and independent management of the two types of agrifood waste, by means of existing collection sites (livestock farms for the loose agrifood waste and feed mills for the packed agrifood products) to which the waste can be conferred directly;
- joint management of the two waste categories by means of new collection facilities able to handle both types of waste.

In the first management scheme loose and packed agrifood wastes take two different directions. The loose agrifood waste is delivered to livestock farms directly where, after a period of controlled ripening, it will be used as animal feed. The packed agrifood waste is delivered to feed mills where it will be turned into animal feed.

In the second management scheme both types of waste are delivered to a collection facility and only in a second phase, once they have been separately treated, will they be transferred to livestock farms or feed mills.

Looking at the problem from a transport perspective, the main logistics issues concern:

- in the first management scheme, the partition of the whole area into convenient collection basins where a specific farm or feed mill is located to which the waste can be conferred directly, so as to minimize the total travel cost within each basin;
- in the second management scheme, the identification of the most convenient location for collection facilities and, based on these, the partition of the whole area into convenient collection basins, so as to minimize the total travel cost within each basin;
- in both management schemes, the identification of the optimal pick-up network, i.e. the network that ensures the minimum travel times, within each identified basin.

Figure 1 is a schematic illustration depicting the system under study. In order to address the aforementioned logistics issues, it is necessary to define the cost function that governs the transport network. In fact, optimal plant location, optimal clustering and optimal pick-up paths will all be defined so as to minimize the total transport cost. The next section illustrates the methodology proposed to tackle the three mentioned logistics problems together with a description of the generalized transport cost function adopted to characterize the transport network.

4. Methodology

In order to manage the entire collection process this study proposes a new management scheme consisting of the two following modules:

- module 1: for clustering the observed area into smaller collection basins using two different management schemes, one using existing collection sites (livestock farms and feed mills), the other using new collection facilities;
- module 2: for the identification of the optimal waste pick-up network within each cluster identified by the previous module.

A description of the two modules from a methodological point of view and of the cost function adopted to characterize the transport network is provided in the following paragraphs.

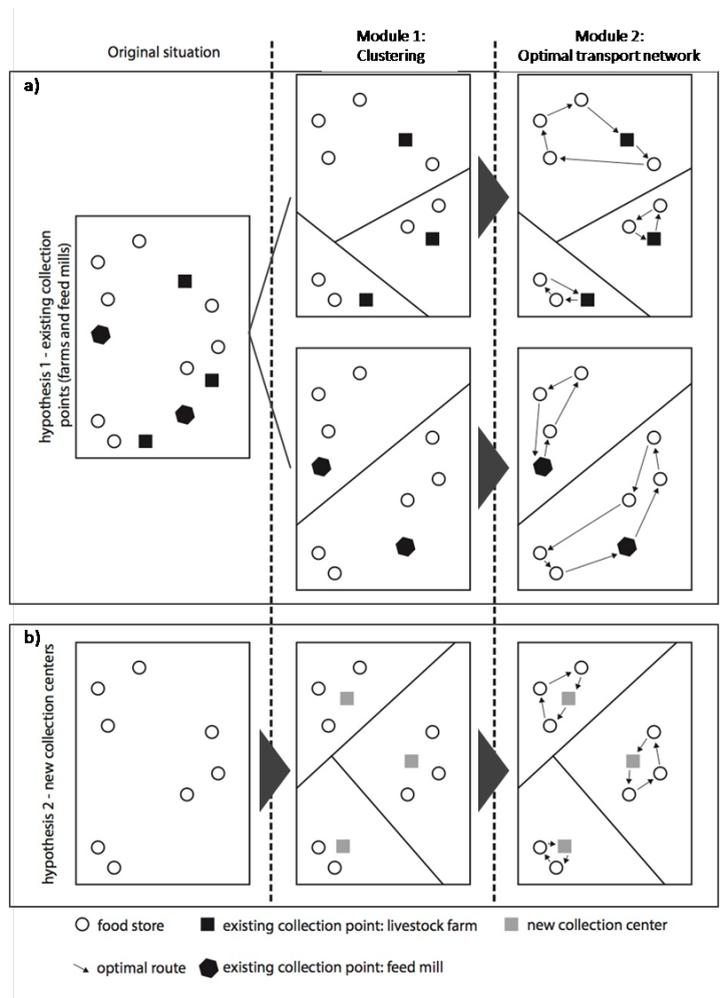


illustration of the proposed existing collection points; b)

Fig.1. Schematic management scheme: a)

new collection centers.
Source: authors.

4.1. Module 1: Clustering of the area of interest

In order to optimally plan the waste pick-up process at the food stores and to be able to better organize its distribution to farms or feed mills it is desirable to partition the area of interest into smaller sectors so as to facilitate these activities. When performing clustering it is essential to ensure a certain degree of flexibility both in the design of the retrieval network and in its management. Two different management schemes for the collection process are proposed:

- *a) Management of the process using independent clusters and existing collection centers.*
 Food stores in the area of interest are grouped into different clusters where a specific farm or feed mill is located to which the waste product can be conferred directly. In order to group food stores into clusters it is necessary to minimize the associated transport cost (to be evaluated by means of the cost function described in section 4.3) taking into account the constraint of the farm collection capacity (kg/day) of the cluster. Since two types of waste product are considered, it is necessary to perform two distinct clusterings, one for loose agrifood wastes and one for packed products.

- *b) Management of the process by means of building new collection facilities.*

In this process it is assumed that the entire collection process is managed through new collection facilities able to handle both types of waste. The number of new collection facilities to be created will depend on the amount of food waste produced daily by the food stores in the area concerned and on the capacity (kg/day) of the plants themselves. From a transport perspective, the main management issues concern the identification of the most convenient location for the collection facility and the identification of clusters of supermarkets that confer their waste to the specific facility. The most convenient location is the place that overall, i.e. considering all the supermarkets within the plant's catchment area, ensures lower transport costs.

The problem of the analysis is a typical problem of constrained optimization arising when there is the need to minimize or maximize a mathematical function of a number of variables subject to certain constraints (Sarker and Newton, 2007). In practice, constrained optimization problems are typically characterized by high complexity, which is usually time-consuming and computationally expensive (Deb, 2012; Rothlauf, 2011), such that it is not possible to always solve the problem analytically. The complexity is due mainly to the large number of variables and constraints that define the size of the problem. The analytical solution is only possible if just a few variables and extremely simple functions are present. In dealing with real problems where the number of variables is not small, it can be convenient to resort to iterative algorithms for solving the problem (Kelley, 1999). This type of algorithm consists of a sequence of actions to be repeated until the algorithm converges to an "acceptable" result or, if not, until a stopping criterion is satisfied.

A description of the quantitative algorithms behind the two management schemes is provided below.

- *a) Management of the process using independent clusters and existing collection centers.*

The problem analyzed can be formalized through a binary relation that establishes a one-to-one correspondence between two sets of points X and Y. The former corresponds to supermarkets, while the latter represents collection centers (farms and feed mills). The problem is to find the most convenient way to allocate the food waste produced by supermarkets to the various collection centers. The large number of variables makes an analytical solution unfeasible. One possible way to solve the problem of optimally allocating the waste product to the various collection centers, is to create an iterative algorithm. Given the specificity of the problem and the need to have a high degree of flexibility in setting priorities in the constraints to be satisfied, it was not possible to use an existing algorithm but an ad hoc algorithm had to be created. Since the collection points are independent of one another, the allocation of the two different types of waste (loose and packed) is in turn independent. For this reason, the algorithm has been programmed to assign a single generic type of waste to a corresponding collection center. Therefore, in order to allocate all the different types of waste, it is necessary to apply each time the algorithm to the specific category of data. Fig. 2 illustrates the different steps of the developed algorithm. A brief description of the algorithm is given below.

- The algorithm tests whether the amount of food waste produced by the supermarkets exceeds the capacities of the collection centers.
- If the previous condition holds true then the problem arises of having to deal with the impossibility of the collection centers to accommodate all the waste produced. In this case it is necessary to identify which supermarkets will not be served by the collection service. Such supermarkets will have to be identified on the basis of cost criteria using the cost function defined in paragraph 4.3.
- Once the supermarkets to be excluded have been identified, the remainder are assigned to a collection center so as to minimize the resulting cost function.

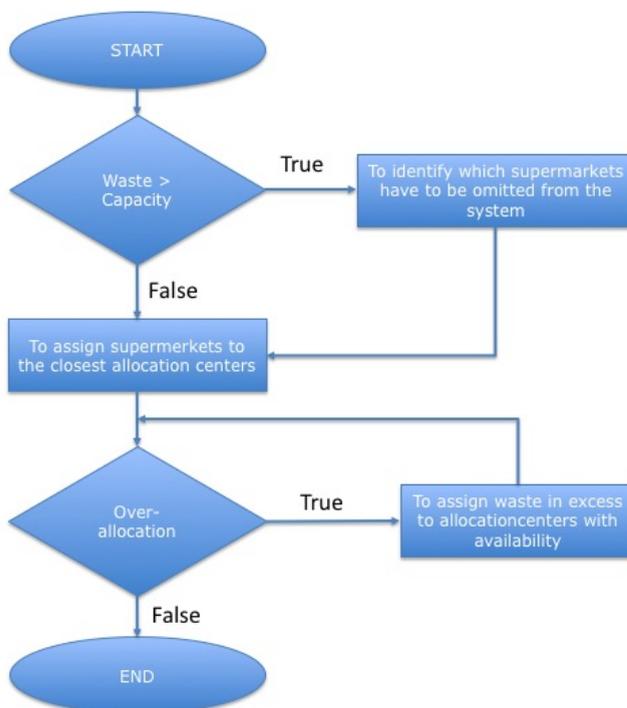


Fig. 2.

Clustering algorithm.

Source: authors.

- After this first assignment it is still possible that some collection centers will receive an amount of waste exceeding their capacity. To overcome this problem, it is necessary to start an iterative loop that selects, for each collection center where there is an over-allocation, those supermarkets that exceed the collection capacity. The selected supermarkets are the more “expensive” ones, meaning that they are characterized by a higher cost with respect to the other supermarkets assigned to the same collection center.
- The “expensive” supermarkets are then assigned to those collection centers whose collection capacity is not yet exhausted. At this point, if the new assignment results again in the phenomenon of over-allocation, the algorithm returns to the previous step and tries to perform a new assignment. The loop stops when each collection center receives an amount of waste that does not exceed its capacity.

b) Management of the process by means of building new collection facilities: a barycentric algorithm.

The context of this second algorithm is as follows. Let us denote with centers *A* the supermarkets that produce food waste, and centers *B* as the collection centers that receive such waste. It is assumed that centers *B* do not already exist. The aim is to decide the most convenient centers *B* to which centers *A* will be allocated in order to minimize a logistical cost function. Even in this situation an analytical solution is not feasible because of the large number of parameters to include in the model. For this reason an iterative algorithm has been created *ex-novo*. The different steps of the algorithm are shown in Fig. 3.

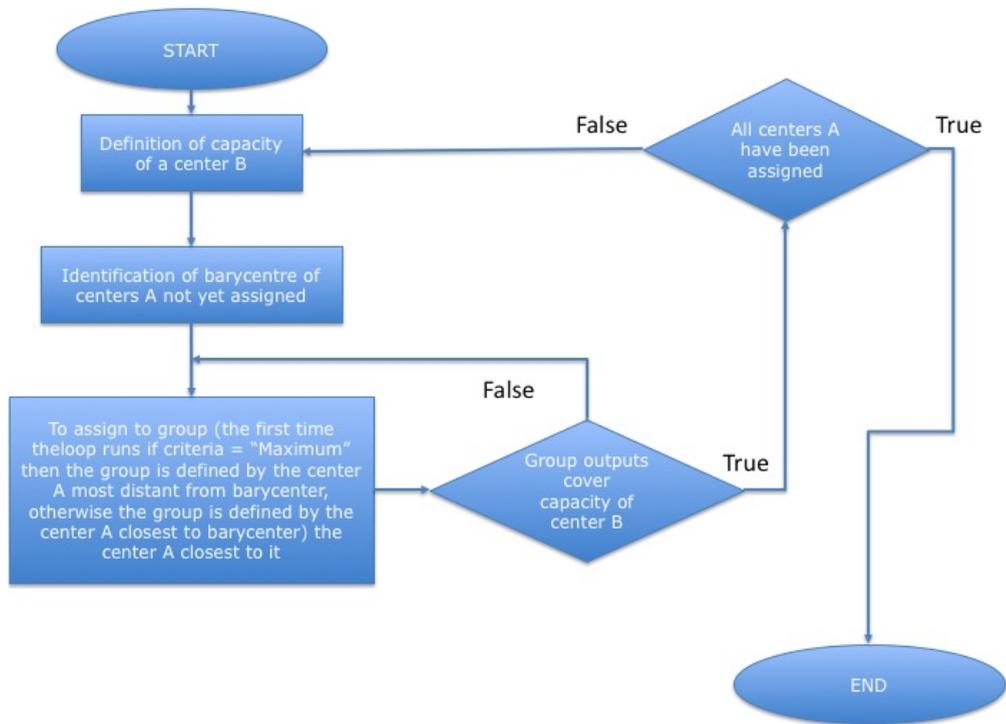


Fig. 3. Barycentric algorithm.
Source: authors.

A brief description of the algorithm is given below.

- The loop starts by determining the capacity of a center B .
- The barycentre of centers A not yet assigned is identified.
- A second loop starts. The first time it runs it chooses the center A that defines the group: if the criteria “Maximum” is applied then the group is defined by the center A most distant from the barycenter, otherwise the group is defined by the center A closest to the barycenter. During subsequent runs (i.e. all runs except the first) simply the closest center A to the group is assigned to it.
- This second loop runs until the amount of group outputs does not cover the capacity of center B . Once the second loop stops, if some centers A have not yet been assigned, then the first loop runs again, otherwise it means all centers B have been identified and the algorithm stops.

Both algorithms have been developed using the programming language and environment for statistical computing R^\dagger .

[†] R version 3.2.2.

4.2. Module 2: Identification of optimal pick-up routes

Once the test area has been divided into clusters it is necessary to proceed with the optimization of the transport network within each cluster in order to minimize the overall transport cost associated therewith. Optimizing the transport network means determining the optimal collection sequence, i.e. the order in which the nodes have to be served, as well as the number and optimal capacity of the vehicles to be used and optimal routes and number of trips to made.

The complexity and the economic importance of the problem make the use of mathematical models desirable to support the decision process associated therewith. Because of its characteristics, the problem at hand appears well suited for applying the Vehicle Routing Problem (VRP). The VRP is typically described as the problem of designing optimal delivery- or collection-routes from one or more depots to a given number of customers, while satisfying several constraints. There exists a wide variety of VRPs and a broad literature on this class of problems and an extensive review can be found in Laporte (1992) and Desrochers et al. (1990). The particular problem examined here, can be described as a new variant of the broadly studied *Multi Depot Vehicle Routing Problem* (MDVRP) with additional constraints. The MDVRP (see Toth and Vigo, 2002) consists in visiting a set of customers with known demand by means of a fleet of identical capacity vehicles located at different depots, while minimizing the total distance traveled or the total travel time. In the original and most studied version of the MDVRP, vehicles must return to the same depot they started from. However, there are many applications in logistics and goods delivery in which vehicles are allowed to end their trip in another depot, as described in Mancini (2015).

In the problem addressed here, named *Multi Depot Vehicle Routing Problem with Intermediate Delivery Satellites* (MDVRPIDS), vehicles must deliver the collected goods to collection points, to be processed and turned into fertilizer, before returning to the depot. Collection points can be visited more than once along the same route if the vehicle's capacity is lower than the cumulative demand to be picked-up along that route, but there is a time duration limit for each route. Different service times are considered to visit collection points. A heterogeneous fleet composed of vehicles with different capacity and different capacity restrictions for the collection points are also considered. Similar problems have been addressed in the literature, such as the *Multi Depot Vehicle Routing Problem with Inter-Depot Routes* (MDVRPI), addressed in Crevier et al. (2007), in which vehicles may be replenished at intermediate depots along their route. Another similar problem is the *Vehicle Routing Problem with Satellite Facilities* (VRPSF), introduced by Bard et al. (1998) and studied, under the name *Vehicle Routing Problem with Intermediate Replenishment Facilities* (VRPIRF), by Tarantilis et al. (2008). The problem addressed is a single depot VRP in which vehicles may be replenished at satellite facilities along their route. The MDVRPIDS cannot be described as one of the above problems as it requires additional constraints, implying that the last visited node along a route, before returning to the depot, must be a collection point, because vehicles must deliver all the collected goods before ending their run. Moreover, while in other problems visits to intermediate facilities are optional, in the problem analyzed at least one visit to a collection point is mandatory for each route. Moreover, in MDVRPIDS a heterogeneous fleet is considered. To solve this problem a specific Mixed Integer Programming Formulation (MIPF) for the MDVRPIDS has been developed.

Let us introduce the following notation:

- C : set of pick-up points (supermarkets);
- P : set of collection points;
- D : set of depots;
- K : set of vehicles;
- $V = C \cup P \cup D$: set of nodes in the network;
- Ω : maximum route duration;
- M : is a very large constant which activates constraints (12) and (17) only if the arc X_{ijk} is actually part of the solution;
- ε : is a very small constant whereby if at least one pick-up point is assigned to a vehicle then that vehicle is actually used in the solution;
- t_{ij} : travel time from node i to node j ;

- q_c : demand to be collected at pick-up point c ;
- H_k : capacity of vehicle k ;
- L_p : capacity of collection point p ;
- s_i : service time at node i ;

The decision variables under study are:

- X_{ijk} : binary variable taking value of 1 if vehicle k covers the arc connecting nodes i and j , 0 otherwise;
- Y_{ik} : binary variable taking value of 1 if pick-up point i is served by vehicle k , 0 otherwise;
- Q_i : variable representing the cumulative quantity of goods loaded onto the vehicle once visited node i ;
- R_p : variable representing the quantity of goods delivered to collection point p ;
- Z_k : binary variable taking value of 1 if vehicle k is used, 0 otherwise;
- T_k : variable representing the duration of the route covered by vehicle k .

The model can be described as follows:

$$\min \sum_{k \in K} \sum_{i \in V} \sum_{j \in V} t_{ij} X_{ijk} \quad (1)$$

subject to:

$$\sum_{k \in K} Y_{ik} = 1 \quad \forall i \in C \quad (2)$$

$$Z_k \geq \varepsilon \sum_{i \in C} Y_{ik} \quad \forall k \in K \quad (3)$$

$$\sum_{i \in D} \sum_{j \in V} \sum_{k \in K} X_{ijk} = \sum_{k \in K} Z_k \quad (4)$$

$$\sum_{j \in V} X_{ijk} = \sum_{j \in V} X_{jik} \quad \forall i \in V, \forall k \in K \quad (5)$$

$$X_{jik} < Y_{ik} \quad \forall i \in C, \forall j \in V, k \in K \quad (6)$$

$$X_{ijk} < Y_{ik} \quad \forall i \in C, j \in V, k \in K \quad (7)$$

$$\sum_{j \in V} \sum_{k \in K} X_{ijk} = 1 \quad \forall i \in C \quad (8)$$

$$\sum_{j \in V} \sum_{k \in K} X_{jik} = 1 \quad \forall i \in C \quad (9)$$

$$Q_i \geq Q_j + q_i \sum_{k \in K} X_{jik} - M \left(1 - \sum_{k \in K} X_{jik} \right) \quad \forall i \in C, \forall j \in V \quad (10)$$

$$Q_i = 0 \quad \forall i \in D \cup P \quad (11)$$

$$Q_i \leq H_k Y_{ik} + M(1 - Y_{ik}) \quad \forall i \in C, k \in K \quad (12)$$

$$\sum_{j \in P} X_{ijk} = 0 \quad \forall i \in D, k \in K \quad (13)$$

$$\sum_{j \in C} X_{jik} = 0 \quad \forall i \in D, k \in K \quad (14)$$

$$\sum_{j \in D} X_{jik} = 0 \quad \forall i \in D, k \in K \quad (15)$$

$$\sum_{j \in P} X_{jik} = 0 \quad \forall i \in P, k \in K \quad (16)$$

$$R_i \geq Q_j - M(1 - X_{jik}) \quad \forall i \in P, \forall k \in K, \forall j \in C \quad (17)$$

$$R_i \leq L_i \quad \forall i \in P \quad (18)$$

$$T_k = \sum_{i \in V} \sum_{j \in V} (t_{ij} + s_i) X_{ijk} \quad \forall k \in K \quad (19)$$

$$T_k \leq \Omega \quad \forall k \in K \quad (20)$$

$$\sum_{i \in D} \sum_{j \in V} X_{ijk} \leq 1 \quad \forall k \in K \quad (21)$$

$$X_{ijk} \in \{0,1\} \quad \forall i \in V, \forall j \in V, \forall k \in K \quad (22)$$

$$Y_{ik} \in \{0,1\} \quad \forall i \in C, k \in K \quad (23)$$

$$Z_k \in \{0,1\} \quad \forall k \in K \quad (24)$$

The objective function (1) consists in minimizing total travel times. Constraint (2) ensures that each pick-up point is assigned to a vehicle, while constraint (3) implies that a pick-up point can be assigned to a vehicle only if the vehicle is actually used. Constraint (4) requires that any vehicle used comes from a depot. The continuity of the route is ensured by constraint (5). Constraints (6) and (7) imply that a pick-up point can be visited by a vehicle only if it has been assigned to that vehicle, while constraints (8) and (9) ensure that each pick-up point is visited only once. Constraint (10) allows to calculate the amount of goods loaded into a vehicle after each visit to a node. When the vehicle reaches a collection point it is completely emptied and the quantity of goods on board is reset to zero by the constraint (11). Constraint (12) ensures that the capacity limit of the vehicles is observed. The first node visited by a route must be a pick-up point, while the last node a collection point. These conditions are fulfilled thanks to the constraints (13) and (14), respectively. Constraints (15) and (16) prevent movements between two depots and between two collection centers. Constraint (17) allows to calculate the total amount of goods delivered to a collection point, which must not exceed its capacity (18). The total time (travel + loading/unloading) of a route is calculated in (19) and must not exceed the maximum permissible (20). Constraint (21) implies that each vehicle can exit the depot at most once, ensuring at the same time connectivity of the routes. Finally, the constraints from (22) to (24) specify the domain of the variables.

4.3. Cost function

Transport networks are usually represented by means of network graphs in which the various elements correspond to a phase of the journey and, as such, they need to be characterized in terms of cost. A path in a network graph is typically defined as a sequence of consecutive arcs that connect an origin to a destination node. Therefore the generalized cost of a path (GC_{path}) can be expressed as the sum of the generalized costs of the arcs (GC_{arc}) and of the nodes (GC_{node}) that compose the path, see equation (25).

$$GC_{path} = \sum_{arc \in path} GC_{arc} + \sum_{node \in path} GC_{node} \quad (25)$$

A brief explanation of the GC_{arc} and of the GC_{node} appearing in equation (25) is provided below.

Generalized cost of the arc (GC_{arc})

For the purpose of the present analysis, the generalized arc cost function is meant to include three main cost items, see equation (26):

- Vehicle running costs;
- road tolls or charges (pay parking, congestion charges, etc.);
- travel time.

$$CG_{arc} = \text{Arc Length} \times \text{Vehicle Running Cost} + \text{Tolls} + \text{Travel Time} \times \text{Travel Time Value} \quad (26)$$

A brief explanation of the various elements appearing in equation (26) is given in Table 1.

Table 1. Terms composing the CG_{arc} function.

	Description
Arc Length (km)	length of the arc in km
Vehicle Running Cost (€/veh-km)	running cost per kilometer of the vehicle used to collect the waste
Tolls (€)	tolls and/or charges for the use of roads, if any
Travel Time (h)	ratio between length of path (km) and average vehicle speed (km/h)
Travel Time value (€/h)	cost associated with travel time. The hourly gross cost of a driver is used as a proxy for travel time value.

Generalized cost of the node (GC_{node})

Two main types of nodes are identified within the network:

- Pick-up nodes– supermarkets where the waste product is picked-up;
- Delivery nodes – livestock farms and collection facilities that receive the waste product.

The generalized cost of a node can be expressed as shown by equation (27).

$$CG_{node} = \text{Loading/Unloading Time at the node} \times \text{Loading/Unloading Time Value} \quad (27)$$

The *loading/unloading time at the node* is the time necessary to perform loading/unloading operations at the node, it also includes waiting times, if any. For the present application a number of specific loading/unloading times have been encoded depending on the type of node served and on the waste considered, a description of these times is provided in Table 2. The *Time value for loading/unloading operations* provides an indication about the cost of the operations performed at the node. It may include the parking cost (if any), the gross cost of the driver, the gross cost of an additional operator to assist with loading/unloading operations, etc.

Table 2. Loading/unloading times at the node.

	Description
Fruit and vegetable Time (h)	time required to perform loading operations of the loose fruit and vegetable fraction at the pick-up node
Packed Waste Time (h)	time required to perform loading operations of the packed agrifood fraction at the pick-up node
Farm Time (h)	time required to perform unloading operations of the loose fruit and vegetable fraction at the farm site (delivery node)

Collection Plant Time (h)	time required to perform loading/unloading operations of the waste product at the collection facility (delivery node)
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The illustrated cost function has been used to characterise the elements of the transport network.

5. Application

The two modules have been implemented in a specially designed software prototype and tested in the area of application. This section briefly describes the test area and the data used and illustrates the computational results of the application.

5.1. Application area and data collection

The province of Cagliari in Sardinia (Italy) has been identified as application area (see Fig. 4). The province counts 71 municipalities, 543 310 inhabitants and covers 4569 square kilometers. Concerning the province structure a high prevalence of small towns emerges: around 60% of municipalities have a population of less than 3000 inhabitants, 30% have a population ranging between 3000 and 10000 inhabitants, only 9 municipalities exceed 10000 inhabitants.

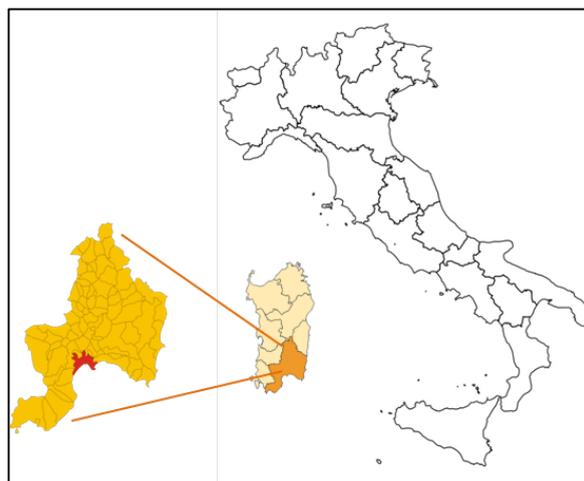


Fig. 4. Application Area. Source: authors.

An extensive data collection process has been performed in order to gather the information necessary to portray the existing scenario for the purpose of the application. The intensive program of *in situ* investigation has concerned:

- grocery stores and supermarkets, with at least 400 square meters of retail space;
- livestock farms (pigs, cows, buffalo), with a minimum of 200 registered heads of cattle;
- feed mills.

108 supermarkets/grocery stores (*gs*), 23 livestock farms (*lf*) and 2 feed mills (*fm*) matching the selection criteria have been recorded in the area of interest. The variables collected for each recorded unit are listed below.

- *Supermarkets and grocery stores*: store name, address, geographical coordinates, total sales area (sqm), sales area of the fruit and vegetables section (sqm), yearly volume of produced food waste (kg per year) divided into loose and packed agrifood waste.

- *Livestock farms*: farm name, address, geographical coordinates, type of farming (pigs, cows or buffalo), number of heads of cattle. The last variable has been used to estimate the maximum daily amount of agrifood waste that can be accepted by the farm considering an average daily food requirement of 25 kg per cow and 2,5 kg per pig.
- *Feed mills*: name, address, geographical coordinates, quantity of animal feed produced weekly (quintals per week).

In order to organize the waste collection process it was first necessary to determine the total amount of food waste generated by the supermarkets in the area of interest. A sample of supermarkets operating in the test area was involved in a preliminary survey for the purpose of determining a reliable estimate of the volume. The sample comprises 32 supermarkets divided, on the basis of the sales area, into:

- 13 small stores, with a sales area of less than 1000 sqm;
- 12 medium stores, with a sales area ranging from 1001 to 1500 sqm;
- 7 large stores, with a sales area of over 1501 sqm.

Information concerning the yearly quantities of agrifood waste, divided into loose and packed, recorded during 2013, were collected for each store in the sample. Subsequently, a larger sample of supermarkets in the area was contacted by telephone in order to confirm or correct the values. On the basis of the information provided by the supermarkets taking part in the two surveys and of the analysis of their territorial context of inclusion (small or large town/city), a set of reference fields has been defined. Tables 3 and 4 show the resulting average daily values of food waste, loose and packed respectively, that characterize small, medium and large food stores in the area examined. The first column shows the average daily volumes (kg/day) of agrifood waste that characterize the three classes of food stores together with the indication of the minimum and maximum values. In the second and third columns these general values are further differentiated for large and small towns to distinguish between stores located in large towns/cities and stores located in smaller towns. These values of reference provide an indication as to the average amount of agrifood waste produced by a food store in the test area on the basis of its class (small, medium, large) and of its territorial context of inclusion (small or large towns/cities). For instance, a supermarket with a sales area of 1200 sqm located in a small town, throws away every day around 17 kg of loose fruit and vegetable waste and 31 kg of packed agrifood waste, according to Tables 3 and 4, respectively.

Table 3. Food waste – Average daily values: Loose fruit and vegetable waste.

Class	General Values		Large towns/city values		Small towns values	
	Average Daily waste (kg/day)	min - max (kg/day)	Average Daily waste (kg/day)	min - max (kg/day)	Average Daily waste (kg/day)	min - max (kg/day)
Small stores	9,45	7 – 13,5	8,6	7 – 12,5	10,5	8 - 14
Medium stores	13,3	8 - 20	12	8 - 15	17	11 - 20
Large stores	18,15	13 -28	na	na	na	na

Table 4. Food waste – Average daily values: Packed agrifood waste.

Class	General Values		Large towns/ cities values		Small towns values	
	Average Daily waste (kg/day)	min - max (kg/day)	Average Daily waste (kg/day)	min - max (kg/day)	Average Daily waste (kg/day)	min - max (kg/day)
Small stores	21,7	12 - 27	20,5	12 - 25	22	15 - 27
Medium stores	29,5	24 - 35	28	20 - 35	31	27 -39
Large stores	61,9	40 - 70	na	na	na	na

Overall, according to the data collected, the 108 supermarkets recorded in the area throw away around 2878 kg/day of packed agrifood waste and 1144 kg/day of loose agrifood waste.

5.2. Application results

This paragraph illustrates the computational results of the application of the bi-modular management scheme in the test area. A brief description of the main outputs resulting from the application of each module is provided.

- *Module 1: Clustering of the area of interest*

As seen in section 4.1, the module 1 clusters the area of interest according to two different approaches:

- a) management of the process using independent clusters and existing collection centers;
- b) management of the process by means of building new collection facilities.

A description of the results of the application of both management schemes in the test area is provided below.

a) Management of the process using independent clusters and existing collection centers.

As an example of detailed results, Table 5 shows the output of the clustering involving supermarkets and livestock farms. The 108 supermarkets are grouped into thirteen clusters; each cluster is assigned to a specific livestock farm. For each cluster, the second column shows the livestock farm of reference (*lf*) while the third column lists the grocery stores (*gs*) belonging to the cluster.

Table 5. Supermarkets-Livestock farms clustering.

Cluster ID	Livestock farm ID	Grocery Stores / Supermarkets ID	N. of units
1	lf_6	gs_76, gs_81, gs_84, gs_86	4
2	lf_1	gs_103, gs_104, gs_105, gs_106, gs_47, gs_67, gs_68, gs_69, gs_93	9
3	lf_2	gs_52, gs_53, gs_54	3
4	lf_3	gs_61, gs_71, gs_72, gs_96, gs_97	5
5	lf_23	gs_62	1
6	lf_10	gs_58, gs_59, gs_60, gs_70	4
7	lf_12	gs_63, gs_64, gs_94, gs_95	4
8	lf_14	gs_9, gs_10, gs_12, gs_14, gs_15, gs_18, gs_20, gs_22, gs_25, gs_26, gs_27, gs_29, gs_30, gs_31, gs_32, gs_33, gs_34, gs_36, gs_37, gs_38, gs_39, gs_40, gs_41, gs_42, gs_55, gs_57, gs_65	27
9	lf_15	gs_11, gs_13, gs_16, gs_17, gs_19, gs_21, gs_23, gs_24, gs_28, gs_35, gs_66, gs_73, gs_74, gs_75, gs_77, gs_78, gs_79, gs_80, gs_82, gs_83, gs_85, gs_87, gs_88, gs_89, gs_90, gs_91, gs_92	27
10	lf_16	gs_100, gs_101, gs_98, gs_99	4
11	lf_17	gs_1, gs_2, gs_3, gs_4, gs_5, gs_6, gs_7, gs_8, gs_48, gs_49, gs_50, gs_51, gs_56	13
12	lf_20	gs_102, gs_43, gs_44, gs_45, gs_46	5
13	lf_22	gs_107, gs_108	2

Looking at the results of the clustering, a high prevalence of small clusters can be observed, 10 out of 13 count less than 10 stores. This can be easily explained by considering the structure of the area examined, characterized by a very large number of small towns rather distant from each other. The two main clusters are the two grouping the supermarkets located in the provincial capital and its suburbs. This is in fact the most densely populated area with a large number of supermarkets rather close to each other.

Table 6 shows the output of the supermarkets –feed mills clustering. In this case, the 108 supermarkets are grouped into three large clusters, each cluster is assigned to one of the three collection plants available in the area. For each cluster, the second column gives the collection center of reference (*pl*) while the third column lists the food stores (*gs*) belonging to the cluster.

Table 6. Supermarkets - Collection plants clustering.

Cluster ID	Collection plant ID	Grocery Stores / Supermarkets ID	N. of units
1	pl_1	gs_100, gs_101, gs_52, gs_53, gs_54, gs_58, gs_59, gs_60, gs_62, gs_70, gs_98, gs_99	12
		gs_1, gs_10, gs_102, gs_107, gs_108, gs_11, gs_12, gs_13, gs_14, gs_15, gs_16, gs_17, gs_18, gs_19, gs_2, gs_20, gs_21, gs_22, gs_24, gs_25, gs_26, gs_27, gs_28, gs_29, gs_3, gs_30, gs_31, gs_32, gs_33, gs_34, gs_35, gs_36, gs_37, gs_38, gs_39, gs_4, gs_40, gs_41, gs_42, gs_43, gs_44, gs_45, gs_46, gs_48, gs_49, gs_5, gs_50, gs_51, gs_55, gs_56, gs_57, gs_6, gs_61, gs_63, gs_64, gs_65, gs_66, gs_7, gs_71, gs_72, gs_79, gs_8, gs_9, gs_90, gs_91, gs_92, gs_94, gs_95, gs_96, gs_97	70
2	pl_2	gs_103, gs_104, gs_105, gs_106, gs_23, gs_47, gs_67, gs_68, gs_69, gs_73, gs_74, gs_75, gs_76, gs_77, gs_78, gs_80, gs_81, gs_82, gs_83, gs_84, gs_85, gs_86, gs_87, gs_88, gs_89, gs_93	26
3	pl_3		

b) Management of the process by means of building new collection facilities.

According to the data collected, the 108 food stores in the area of interest throw away every day around 2878 kg of packed food waste. Three different plant processing capacities are assumed for determining the optimal location of the new collection centers for processing the waste:

- 1000 kg/day;
- 2000 kg/day;
- 3000 kg/day.

Tables 7, 8 and 9 show the results of the barycentric algorithm illustrated in section 4.1. Table 7 shows the result of the barycentric algorithm considering a plant processing capacity of 1000 kg per day: three collection plants and three clusters of supermarkets are identified for each plant. Table 8 shows the result of the barycentric algorithm considering a plant processing capacity of 2000 kg per day: two collection plants and two clusters of supermarkets are identified for each plant. Finally, Table 9 shows the result of the barycentric algorithm considering a plant processing capacity of 3000 kg per day: one plant and only one cluster of supermarkets are identified for the plant. The radius of the optimal area identified is 2.5 km. This size allows decision makers to have considerable leeway in determining, within the area identified as more convenient from a transport perspective, the space more suitable for the installation of the plant, in compliance with urban planning restrictions and environmental constraints.

In Tables 7, 8 and 9, the first and second columns show the collection plant ID and its processing capacity respectively, while the third column gives the total amount of food waste destined to the plant, the fourth column the grocery stores that confer their waste to the plant.

Table 7. Supermarkets clustering – new collection plants (plant capacity: 1000 kg/day).

Collection Plant ID	Plant Capacity (kg/day)	Total food waste (kg/day)	Grocery stores (gs) belonging to the cluster
pl_1	1000	997	gs_1, gs_100, gs_101, gs_102, gs_103, gs_104, gs_107, gs_108, gs_2, gs_20, gs_25, gs_3, gs_34, gs_4, gs_48, gs_49, gs_5, gs_50, gs_51, gs_52, gs_53, gs_54, gs_55, gs_56, gs_58, gs_59, gs_6, gs_60, gs_62, gs_63, gs_64, gs_65, gs_66, gs_7, gs_8, gs_9, gs_93, gs_94, gs_95, gs_98, gs_99
pl_2	1000	998	gs_105, gs_106, gs_16, gs_17, gs_21, gs_23, gs_24, gs_27, gs_28, gs_29, gs_35, gs_38, gs_39, gs_47, gs_67, gs_68, gs_69, gs_73, gs_74, gs_75, gs_76, gs_77, gs_78, gs_79, gs_80, gs_81, gs_82, gs_83, gs_84, gs_85, gs_86, gs_87, gs_88, gs_89, gs_90, gs_91, gs_92
pl_3	1000	883	gs_10, gs_11, gs_12, gs_13, gs_14, gs_15, gs_18, gs_19, gs_22, gs_26, gs_30, gs_31, gs_32, gs_33, gs_36, gs_37, gs_40, gs_41, gs_42, gs_43, gs_44, gs_45, gs_46, gs_57, gs_61, gs_70, gs_71, gs_72, gs_96, gs_97

Table 8. Supermarkets clustering – new collection plants (plant capacity: 2000 kg/day).

Collection Plant ID	Plant Capacity (kg/day)	Total food waste (kg/day)	Grocery stores (gs) belonging to the cluster
pl_1	2000	1989	gs_1, gs_10, gs_100, gs_101, gs_102, gs_103, gs_104, gs_107, gs_108, gs_12, gs_13, gs_14, gs_15, gs_18, gs_2, gs_20, gs_21, gs_25, gs_26, gs_27, gs_28, gs_29, gs_3, gs_31, gs_32, gs_33, gs_34, gs_36, gs_38, gs_4, gs_40, gs_42, gs_48, gs_49, gs_5, gs_50, gs_51, gs_52, gs_53, gs_54, gs_55, gs_56, gs_57, gs_58, gs_59, gs_6, gs_60, gs_62, gs_63, gs_64, gs_65, gs_66, gs_67, gs_68, gs_69, gs_7, gs_70, gs_73, gs_74, gs_75, gs_77, gs_78, gs_79, gs_8, gs_80, gs_82, gs_83, gs_87, gs_89, gs_9, gs_90, gs_92, gs_93, gs_94, gs_95, gs_98, gs_99
pl_2	1000	889	gs_105, gs_106, gs_11, gs_16, gs_17, gs_19, gs_22, gs_23, gs_24, gs_30, gs_35, gs_37, gs_41, gs_43, gs_44, gs_45, gs_46, gs_47, gs_61, gs_71, gs_72, gs_76, gs_81, gs_84, gs_85, gs_86, gs_88, gs_96, gs_97

Table 9. Supermarkets clustering – new collection plants (plant capacity: 3000 kg/day).

Collection Plant ID	Plant Capacity (kg/day)	Total food waste (kg/day)	Grocery stores (gs) belonging to the cluster
pl_1	3000	2878	gs_1, gs_10, gs_100, gs_101, gs_102, gs_103, gs_104, gs_105, gs_106, gs_107, gs_108, gs_11, gs_12, gs_13, gs_14, gs_15, gs_16, gs_17, gs_18, gs_19, gs_2, gs_20, gs_21, gs_22, gs_23, gs_24, gs_25, gs_26, gs_27, gs_28, gs_29, gs_3, gs_30, gs_31, gs_32, gs_33, gs_34, gs_35, gs_36, gs_37, gs_38, gs_39, gs_4, gs_40, gs_41, gs_42, gs_43, gs_44, gs_45, gs_46, gs_47, gs_48, gs_49, gs_5, gs_50, gs_51, gs_52, gs_53, gs_54,

gs_55, gs_56, gs_57, gs_58, gs_59, gs_6, gs_60, gs_61, gs_62, gs_63, gs_64, gs_65, gs_66, gs_67, gs_68, gs_69, gs_7, gs_70, gs_71, gs_72, gs_73, gs_74, gs_75, gs_76, gs_77, gs_78, gs_79, gs_8, gs_80, gs_81, gs_82, gs_83, gs_84, gs_85, gs_86, gs_87, gs_88, gs_89, gs_9, gs_90, gs_91, gs_92, gs_93, gs_94, gs_95, gs_96, gs_97, gs_98, gs_99

Module 2: Identification of optimal pick-up routes

The MIPF for the MDVRPIDS described in section 4.2 has been applied to determine the optimal collection routes within the clusters defined by the previous module. Computational tests were carried out addressing separately the clusters obtained in module 1. The average small clusters are solved to the optimum, solving the model, with the Xpress[‡]solver, in less than a second. The largest cluster cannot be solved to the optimum in short computational times, therefore the best solution obtained in a computational time of 100 seconds has been taken as the optimum one. Comparative tests were conducted solving separately neighboring clusters and then considering them simultaneously as if they were a single cluster. In both cases, the best solution found considering the clusters at the same time is identical to that obtained by considering them separately. This confirms the correctness of the clustering procedure and the utility of this approach for splitting the problem into easier-to-solve sub problems. The results show also that vehicle capacity is not a tight constraint, while the constraint concerning the maximum length of the route is tighter. In fact optimal routes provide only one visit to a collection point.

As a detailed example, the results of the application of the MDVRPIDS to the cluster 8 obtained for the supermarkets-livestock farms clustering is provided. As can be observed in Table 5, cluster 8 has 27 supermarkets that confer their loose food waste to livestock farm *lf_14*. The output of module 1 becomes the input to module 2. In order to determine the optimal collection route, the following assumptions are made:

- only a vehicle with a loading capacity of 500 kg is available for the collection process ($|K|=1, H_1=500$);
- the total route duration Ω is set equal to 4.5 hours (270 minutes);
- service time s_i is set equal to 5 minutes for each node (pick-up and collection points).

Table 10 summarizes the input data characterizing the tested instance.

Table 10. Input data for the application of the MDVRPIDS model.

Cluster ID	Livestock farm ID	Grocery stores (IDs) in the cluster	Depot ID	Vehicle capacity (kg)	Loading/unloading time at the node (minutes)	Max route time (minutes)
8	lf_14	gs_9, gs_10, gs_12, gs_14, gs_15, gs_18, gs_20, gs_22, gs_25, gs_26, gs_27, gs_29, gs_30, gs_31, gs_32, gs_33, gs_34, gs_36, gs_37, gs_38, gs_39, gs_40, gs_41, gs_42, gs_55, gs_57, gs_65	pl_2	500	5	270

The model has been solved to the optimum with the Xpress solver. The optimal pick-up sequence obtained from application of the MDVRPIDS on the tested instance is as follows, between brackets the cumulative load (kg) of the vehicle in the various nodes:

‡ FICO® Xpress Optimization Suite.

pl_2 (0), gs_38 (13,1), gs_39 (31,2), gs_12 (40,5), gs_27 (49,8), gs_29 (59,1), gs_26 (68,4), gs_22 (77,7), gs_37 (90,8), gs_41 (108,9), gs_30 (118,2), gs_36 (131,3), gs_42 (149,4), gs_18 (158,7), gs_33 (171,8), gs_57 (184,9), gs_32 (198), gs_55 (207,3), gs_20 (216,6), gs_34 (229,7), gs_9 (239), gs_25 (248,3), gs_31 (257,6), gs_10 (266,9), gs_14 (276,2), gs_15 (285,5), gs_40 (303,6), gs_65 (312,9), lf_14 (-312,9), dep_2 (0)

The total route duration is 196,7 minutes, while total route length is 65.7 km.

The route starts and ends at the depot *pl_2*; the vehicle starts its route empty and ends its routes empty after having discharged the whole load at the livestock farm.

Further results of the application of the MDVRPIDS model can be found in Table 11, the assumptions made to determine the optimal collection route are the same as in the previous test. Table 11 summarizes the results of applying the model to the remaining clusters consisting of at least 10 units. The first column indicates the cluster ID, the second shows the livestock farm of reference, the third lists the optimal pick-up sequence and indicates between brackets the cumulative load (kg) of the vehicle at the various nodes, while the fourth column shows the depot ID. The last two columns show total route length (km) and total route duration (minutes) respectively.

Table 11. Results of application of the MDVRPIDS model to clusters 9 and 11.

Cluster ID	Livestock farm ID	Optimal pick-up sequence (cumulative load at node in kg)	Depot ID	Total route length (km)	Total route duration (minutes)
9	lf_15	pl_2 (0), gs_75 (9,3), gs_83 (18,6), gs_85 (27,9), gs_87 (46),gs_89 (64,1), gs_82 (73,4), gs_78 (82,7), gs_80 (92), gs_92 (101,3),gs_91 (110,6), gs_90 (128,7), gs_88 (146,8), gs_79 (156,1), gs_77 (165,4), gs_74 (174,7), gs_73 (184), gs_23 (193,3), gs_17 (202,6), gs_19 (211,9), gs_24 (221,2),gs_11 (230,5), gs_35 (243,6), gs_16 (252,9), gs_21(262,2), gs_13 (271,5), gs_28 (280,8), gs_66 (290,1), lf_15 (-290,1), pl_2 (0)	pl_2	61,5	212
11	lf_17	pl_2 (0), gs_56 (9,3), gs_2 (18,6), gs_8 (31,7), gs_4 (41), gs_6 (50,3), gs_50 (59,6), gs_48 (68,9),gs_51 (82), gs_49 (91,3),gs_1 (100,6), gs_3 (109,9), gs_5 (119,2), gs_7(132,3), lf_17 (-132,3), pl_2 (0)	pl_2	67	132

6. Conclusions

Every day thousands of agrifood stores throw away large quantities of food product no longer suitable for sale, which in the majority of cases could still find new uses as animal feed or fertilizer. The return flow of food products is a typical problem of reverse logistics and, as such, includes all the distribution activities involved in food and packaging returns, recycling/recovery, reuse and/or disposal of returned products. This study proposes an integrated two-step approach for managing the logistics process of collection of “food waste” produced by the agribusiness distribution sector and the related distribution to livestock farms and collection facilities located in the area of interest. The proposed management scheme comprises two distinct but strongly interconnected modules:

- module 1 clusters the observed area into smaller collection basins by using dedicated algorithms of constrained optimization and specific cost functions;
- module 2 identifies optimal pick-up and delivery routes within each cluster by applying a specially designed mixed integer programming formulation for the vehicle routing problem.

The proposed bi-modular approach has been implemented through the development of a web platform and successfully tested in the province of Cagliari in Sardinia (Italy). The application has identified an optimal way to organize agrifood-waste collection service for the scenario analyzed. Moreover, this management scheme makes it possible to test alternative and hypothetical scenarios characterized by different supply and demand arrangements, and also to simulate and evaluate the effects of variations that may occur in the scenario of interest. Outcomes provide

useful insights of the phenomenon examined and suggest avenues for further improvements of the proposed tool. Further efforts will be made in order to develop an additional module, to precede the two already developed, that is able to forecast the volume of agrifood waste produced by a supermarket starting from one or more variables that characterize the supermarket itself.

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