Waste Management xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Reverse logistics network for municipal solid waste management: The inclusion of waste pickers as a Brazilian legal requirement

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ARTICLE INFO

Article history:
Received 13 October 2014
Accepted 23 February 2015
Available online xxxx

Keywords:
Reverse logistics network
Municipal solid waste
Solid waste legislation
Waste pickers

ABSTRACT

This study proposes a reverse logistics network involved in the management of municipal solid waste (MSW) to solve the challenge of economically managing these wastes considering the recent legal requirements of the Brazilian Waste Management Policy. The feasibility of the allocation of MSW material recovery facilities (MRF) as intermediate points between the generators of these wastes and the options for reuse and disposal was evaluated, as well as the participation of associations and cooperatives of waste pickers. This network was mathematically modelled and validated through a scenario analysis of the municipality of São Mateus, which makes the location model more complete and applicable in practice. The mathematical model allows the determination of the number of facilities required for the reverse logistics network, their location, capacities, and product flows between these facilities. The fixed costs of installation and operation of the proposed MRF were balanced with the reduction of transport costs, allowing the inclusion of waste pickers to the reverse logistics network. The main contribution of this study lies in the proposition of a reverse logistics network for MSW simultaneously involving legal, environmental, economic and social criteria, which is a very complex goal. This study can guide practices in other countries that have realities similar to those in Brazil of accelerated urbanisation without adequate planning for solid waste management, added to the strong presence of waste pickers that, through the characteristic of social vulnerability, must be included in the system. In addition to the theoretical contribution to the reverse logistics network problem, this study aids in decision-making for public managers who have limited technical and administrative capacities for the management of solid wastes.

1. Introduction

Regarding Municipal Solid Waste – MSW, Agenda 21 proposes the reduction of waste generation and an efficient reuse of generated waste (UN, 1993). Therefore, various regulations and guidelines were prepared to enable the implementation of adequate MSW Management (MSWM) and to establish responsibilities affecting all stages from the exploration of raw materials to the disposal of the MSW (Campos, 2014; Chen et al., 2010; Machado, 2012).

Amongst the regulations created for the appropriate management of the MSW in Brazil, Law No. 12.305/2010 is important (Brazil, 2010), as it instituted the Brazilian Solid Waste Policy (BSWP), which regulates the solid waste management as an expansion of some objectives of Agenda 21 on a national level (Chaves et al., 2014). The primary objectives established by this law are to put an end to dumps by the end of 2014 and to implement selective collection, reverse logistics (RL) and the composting of organic materials (Brazil, 2010; Guarnieri et al., 2014).

The BSWP also defines basic guidelines with regard to the economic and environmental sustainability of the MSWM system, addressing various minimum targets to be achieved, including reduction, reuse and recycling, as well as the transfer of refuse to environmentally appropriate forms of final disposal (Jabbour et al., 2014; IPEA, 2012b). Other targets considered by the BSWP are the social inclusion and economic emancipation of collectors of reusable and recyclable materials (waste pickers) (Xavier et al., 2014), in addition to the use of measures to incentivise and enable regionalised MSWM (Scheinberg, 2012; Wilson et al., 2012; Guarnieri and Cerqueira Streit, in press). The formalisation of the inclusion of the waste pickers occur through selective collection, whose gradual implementation is regulated and will allow the

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http://dx.doi.org/10.1016/j.wasman.2015.02.036
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MSWM to be economically self-sustaining (Brazil, 2010). However, Campos (2014) indicates that a challenge to put into practice the BSWP is the planning, design, implementation and operation of selective collection and of the necessary MRFs.

This article proposes a reverse logistics network involving MSWM to solve the challenge of managing these wastes in an economic way considering the new legal requirements and the inclusion of waste pickers. The study aimed to examine the allocation of material recovery facilities (MRF) as intermediate points between the generators of these wastes and the places for reuse and disposal, as well as the participation of associations and cooperatives of waste pickers. These MRFs are not transhipment points, but points of sorting and cargo consolidation on a small scale that reduce the cost of transport and enable the collection door-to-door by waste pickers. The main contribution of this network is the reduction, in the long term, of solid waste transport cost from households to the MRFs with consequent reduction in greenhouse gases emissions and also, including informal sector as an important stakeholder of the MSW, as required in BSWP. Thus, this model seeks to fill the literature gap including other aspects as political, regulations and social facets related to SWM that should be taken into account along with the minimising costs objective (Ghiani et al., 2014). Ghiani et al. (2014) affirm that a new challenge in operational research is represented by studying and modelling a unified framework in which decisions related to the collection sites, transfer stations, processing facilities and landfills location are combined with decisions on shipping multi-commodity waste flows on the basis of how profitable it is to convert fractions of the waste into recycling materials.

The design of reverse logistics networks address the number of collection, recovery and disposal centres needed; their locations and capacities; and the product flows amongst these facilities (Ferri et al., in press; Chaves et al., 2014; Ramezani et al., 2013; Pishvaee et al., 2010). A network was modelled mathematically and validated through the analysis of scenarios in the municipality of São Mateus in the state of Espírito Santo (Brazil), which was chosen for the case study because it is a medium-sized city and is representative of a large portion of Brazilian municipalities.

The centralisation of materials and the consequent increasing of the volume of waste tends to facilitate commercial negotiations for the purchase and sale of recyclable materials because it is possible to structure and formalise buying and selling processes on a large scale (Damásio, 2014). With this opportunity, the associations increase the variety of wastes with commercial potential for recycling, their inclusion in the markets and, therefore, their income (Guarnieri and Cerqueira Streit, in press; IPEA, 2013; AMUNES, 2014b; Paul et al., 2012; Chen et al., 2010). This is important in developing countries such as Brazil, where approximately 23% of families are in a situation of vulnerability (characterised by social vulnerability, which identifies the capacity of family members – including both supporting and vulnerable members – to display resilience to adverse situations, such as barriers in access to knowledge, access to work, resource availability, infant/child development and living conditions) (IPEA, 2012a; Furtado, 2012; Auler et al., 2014).

Considering the environmental, legal, social and technical aspects, the reverse logistics network aimed at managing MSW proposed facilitates some objectives of Agenda 21 at a local level (Chaves et al., 2014; Llamas-Sanchez et al., 2013), assisting the municipalities in handling the challenges of a multi-dimensional issue (Guerrero et al., 2013; Othman et al., 2013; Sujauddin et al., 2008). Wilson et al. (2012) and Marshall and Farahbakhsh (2013) emphasise that a holistic view integrating the interconnectedness of socio-cultural, environmental, economic and technical spheres is particularly necessary in developing countries, where the complexities of MSW systems are often greater.

Despite the appropriated formulation phase, the BSWP implementation phase has faced many obstacles, mainly at the local level, due to the low administrative capacity to address such a complex legal instrument (Jabbour et al., 2014; Chaves et al., 2014; Godoy, 2013; Gomes, 2012; Jacobi and Besen, 2011; Lisboa et al., 2013). This difficulty also occurs in other developing countries, as shown by Barton et al. (2008), Chen et al. (2010), Couth and Trois (2010), Paul et al. (2012), Troschinetz and Mihelcic (2009) and Wilson et al. (2009).

Although the Brazilian reality is examined, this model can be an example to integrate the informal sector and to minimise costs for the MSWM in other developing countries that face the same challenges. A reverse logistics network could provide a useful tool to help municipalities in their decision-making process related to the adequacy of SWM to address national policies requirements. The state of SWM varies widely amongst nations, regions, cities, communities, households, and even individuals. It is for this reason that systems approaches, which are founded upon specific or locally appropriate methodologies, are so crucial to the future of SWM practices (Chang et al., 2011; Marshall and Farahbakhsh, 2013).

The remainder of this paper is organised as follows. Section 2 presents a brief literature review about SWM and a panorama of the MSWM in Brazil which allows a support for understanding the aspects considered in the proposed reverse logistics network. In Section 3 we describe the mathematical model for this generic reverse logistics network for MSW. In order to validate the model, we show the parameters for the São Mateus case in Section 4. Section 5 presents the practical application of the mathematical model through scenarios. For this, first we expose the considered scenarios and then we analyse and discuss the results. Finally, conclusions are presented in Section 6.

2. Materials and methods

2.1. Municipal solid waste management: brief literature review

In developing countries, the recent urbanisation increased concentration of people which implies an accumulation of waste that needs to be properly managed and disposed. With limited resources, only basic technologies for treatment and disposal, and deficient enforcement of relevant regulations, serious problems remain for the MSWM in developing countries (Chen et al., 2010; Couth and Trois, 2010).

One of these challenges also involves understanding that the MSW has two streams: the formal and the informal sectors. The informal sector is an important stakeholder group in MSW mainly in developing countries; however, until recently they were not recognised as a legitimate (Campos, 2014) and, consequently, not considered in the MSWM. As waste management is an important social, economic and environmental requirement, public–private partnership schemes to MSW should incorporate the informal sector (Couth and Trois, 2010).

Wilson et al. (2009) present successful examples of SWM systems developed including the informal sector. Cooperation between the informal and the formal sector can be part of the solution in SWM, but it requires support to the informal sector (Sembiring and Nitivattananon, 2010; Wilson et al., 2009). They are considered as the most directly vulnerable group in municipal SWM (Paul et al., 2012).

Chen et al. (2010) proposed a framework for integrated waste management that must consider factors that affect MSWM in developing countries as legal regulations/policy and the inclusion of waste pickers in the collection, transportation, storage and treatment/disposal phases. Nevertheless, some factors influence

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recycling of MSW in developing countries such as: government policy, government finances, waste characterisation, waste collection and segregation, household education, household economics, MSWM administration, MSWM personnel education, MSWM plan, local recycled-material market, technological and human resources and land availability (Troschinetz and Mihelcic, 2009).

In South Africa and many other African countries, targets imposed by regulations are ambitious and the deadline is short. Prospects to meet those objectives have not been very encouraging especially because insignificant financial resources have been applied in municipal level (Couth and Trois, 2010). The onus of managing this waste lies with local authorities. Despite the potential advantages to developing countries in recycling the MSW (indicated by Barton et al., 2008), finance remains a major barrier.

If waste generation rates continue growing, cost increases will be most severe in low income countries (more than 5-fold increases) and lower-middle income countries (more than 4-fold increases) (World Bank, 2012). It is possible to reduce the overall costs of waste management for the formal sector with the examples of the Philippines, Nigeria and China cases (Paul et al., 2012; Nzeadibe, 2009; Wilson et al., 2009). Nigeria expends efforts to improve governance through the reform of solid waste management in urban area and the contribution of waste pickers inclusion, job creation and poverty alleviation is noted (Nzeadibe, 2009). Scheinberg et al. (2006) indicate as a positive intervention to assure waste pickers access to sorting space at transfer stations and landfills in addition to supporting better market leverage and/or diversification of activities through, e.g., cooperatives. Informal waste workers lack capital and are vulnerable to exploitative commercial arrangements. They have poor bargaining power because they are mostly unorganized (Paul et al., 2012).

A major limitation to the integration of informal waste pickers is the social acceptance of their activity as a viable source of income (Oguntoyinbo, 2012). For successful implementation of sustainable SWM, small-scale solutions should be pursued based on the creation of real jobs for interest of informal sector (Couth and Trois, 2010). To minimise this barrier, some countries, like Brazil, have chosen to encourage the involvement of waste pickers through the payment for environmental services.

Economic feasibility is fundamental to the collection of waste. MRFs require investment and sometimes require separate collection of dry recyclables. It should be more cost-effective for the local government to collect waste (Couth and Trois, 2010). Selection of the appropriate MSW facility location and the suitable reverse logistics network can be viewed as a complex decision-making problem that requires an extensive evaluation process of the potential MSW plant locations and other factors which include economic, technical, legal, social or environmental issues (Aragonés-Beltrán et al., 2010).

It is necessary is to balance the costs and interests. As an example, a critical assumption of studies assessing comparatively waste management options concerns the constant average cost for selective collection (Massarutto et al., 2011). However, the social and environmental benefits, which measurement is more complex, should be considered. Door-to-door collection guarantees a more effective and widespread way to handle waste like in Cape Town (South Africa), where informal settlements are recognised and therefore receive municipal waste collection and cleansing services (Couth and Trois, 2010).

Previous studies of waste management in reverse logistics mainly aimed at industry waste (as electronic and material waste) and hazardous waste. Despite the significance of reverse logistics for regional MSWM, few studies focused on SWM systems. Zhang et al. (2011) proposed an inexact reverse logistics model for MSWM systems. Aragonés-Beltrán et al. (2010) employed analytic network process to select the best location for the construction of a MSW plant in the Metropolitan area of Valencia (Spain). Badran and El-Haggar (2006) developed a location–allocation model for planning MSWM in an Egypt city and some heuristic techniques for solving it. Erkut et al. (2008) presented a new multicriteria mixed-integer linear programming model to solve the location–allocation problem for MSWM on the regional level in Greece. Ghiani et al. (2012) proposed an integer programming model that helps decision makers choose the sites to locate the unsorted waste collection bins in a residential town as well as their capacities to be located at each collection site. Ghiani et al. (2014) present a review of operations research applied to solve SWM problems. However, these models do not consider the involvement of the informal sector.

Li and Tee (2012) propose a mixed integer multi-objective linear programming reverse logistics model to integrate the formal and informal ewaste sectors through the use of different recovery options. The model was able to create generalizations of when it would be appropriate to use certain options or certain combinations of options especially regarding the amount to be given to the informal sector as compensation for no longer treating and integrating with the formal ewaste sector. This mathematical model was applied to different scenarios to determine the different combined recovery options that minimise the costs of both stakeholders. In this sense, the network proposed in this paper can provide a planning tool to consider the economic inclusion of waste pickers in a MSWM.

2.2. Municipal solid waste management in Brazil

During the twentieth century, Brazil transformed itself into an industrialised economy. Between 1960 and 2010, Brazil jumped from 2766 municipalities to 5565 reaching a rate of urbanisation on the order of 84.4%, that is more than 160 million Brazilians living in urban territories (IBGE, 2012). These flows contributed to the emergence of urban areas lacking minimum conditions for inhabitability that were not accompanied by the concomitant growing of basic public services such as education, health and basic sanitation (Chaves et al., 2014; UNEP, 2005).

The generation of MSW grew by 4.1% between 2012 and 2013, which is higher than the 3.7% population growth rate of the country during this period. Approximately 10% of this waste was not collected in 2013, which is equivalent to 6.9 millions of tons. Despite having a high collection index (90.4%), regarding the destination of the MSW collected, the results observed in Brazil are precarious: 58.3% of the waste collected in 2013 had an inappropriate final disposal and was sent to dumps or controlled landfills lacking the necessary mechanisms for protection of the environment and the health of the population (ABRELPE, 2014). The exponential growth in the volume of generated solid wastes associated with the lack of planning resulted in the proliferation of inadequate disposal (Song et al., in press).

Recycling has gained more attention in Brazil with the BSWP (Brazil, 2010) enacted in 2010. There is a great economic potential for recycling in Brazil. However, the programmes for the recovery of waste under the coordination of the local government are just beginning; they operate precariously and represent less than 4% of the recycled waste in the country (Brazil, 2012). In recent years, there has been a relative increase in the recycling of solid waste in Brazil that aims to reach 20% in 2015. This increasing recycling rate is achieved by the strong exploitation of the labour of waste pickers (Campos, 2014; Brazil, 2012).

Selective collection in Brazil has been performed by the local government, by municipal contractors, by associations and by cooperatives of waste pickers for recyclable materials and by scrap dealers. The selective collection is performed both on a door-to-door schedule or adopting Small Volume Delivery Stations (PEVs) that

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can be combined for garbage collection (Campos, 2014). There is no reliable information on the scope of the selective collection programmes in Brazil: the data varies from 17.9% to 62.0% of municipalities with selective collection initiatives (ABRELPE. 2014; Campos, 2014).

BSWP considers the residue an economic asset with social value, job and income generator and citizenship promoter (Article 6); and requires the integration of waste pickers in shared responsibility for product life cycle (Article 7). Article 18 sets the priority of access to federal funds to municipalities that in their SWM services ‘‘deploy the selective collection with the participation of cooperatives or other forms of association of reusable and recyclable material collectors formed by individuals of low income ‘‘. Articles 42–44 explain the possibility of creating financial incentives, credit and fiscal stimulus for recycling and for the consolidation of waste pickers cooperative organizations (Brazil, 2010). This law is supported by a ProCollector Programme to integrate and articulate the actions of the federal government aiming reuse and recycling in partnership with the waste pickers. They are key-actors responsible for collecting nearly 90% of all recycled material in Brazil (IPEA, 2013).

In this sense, government provides resources and support for the formalisation (association or cooperative) of this category that is officially recognised as a professional occupation. They perform the collective selection, but it is necessary to integrate informal waste sector within the material recovery facilities as stated in BSWP (Campos, 2014). With adequate financial support, infrastructure and social assistance, the collectors have shown interest to formally participate in MSW network (AMUNES, 2014b; IPEA, 2013; MNCR, 2006). In some municipalities, the cooperatives are engaging in SWM conducting several services and receiving payment for environmental services. This mechanism increases the average income of waste pickers, stimulates the formalisation in cooperatives and encourages increased efficiency with awards (IPEA, 2010). Even if these initiatives are recent and challenging, successful examples as Asmare Cooperative in Belo Horizonte (Brazil) remain as a model (IPEA, 2013). In Brazil, associations and cooperatives of waste pickers have gained considerable visibility, and public policies for their integration have been designed at many levels of government-national, subnational, and local (Dias, 2011).

To achieve this modernisation in SWM, local action strategies must be well defined and managed by municipalities, since each region has specific characteristics and difficulties that are specific to its cities' growth patterns, as well as the local potential, needs and volume of generated waste. As in many developing countries (Barton et al., 2008), Brazilian municipalities face many challenges in implementing this policy. This situation is evidenced by the case of the city of São Mateus, located in the state of Espírito Santo, Brazil. This is a medium-sized city with slightly more than 120,000 inhabitants and comprises a central region characterised by commerce, residential areas (including slums) and industrial areas. The city still discards its urban solid waste in a dump located in an inappropriate area (very close to the water table and without any type of treatment) (AMUNES, 2014b). Since the sanitary landfill has not been constructed due to the lack of environmental licensing required by the BSWP, the municipality will have to bear the financial cost of sending this waste to a city 142 km away to be disposed of appropriately (AMUNES, 2014a).

Currently, the handling of wastes in the municipality is based on door-to-door collection performed by compacting trucks without any pre-selection of the wastes that are sent to the open-air dump. The municipality has only one formal association of collectors of recyclable materials. Fig. 1 summarises the scheme of solid waste management in São Mateus.

The lack of commitment and administrative capacity from the local government (AMUNES, 2014b) has negatively influenced the development of the MSWP. As a consequence, the city has not yet developed an Environmental Education Plan, implemented the selective collection of MSW or satisfactorily integrated the collectors of recyclable materials within this process, according to requirements of the BSWP. Due to this oversight, the municipal government were fined by the Public Prosecutor of the state of Espírito Santo and have been directed by the agency as to the procedures for compliance (AMUNES, 2014a), despite the delay in fulfilment of the timelines (Chaves et al., 2014).

As this municipality reflects the reality of various other Brazilian and developing countries cities, the validation of a reverse logistics network through scenarios that consider diverse local specificities and consider the informal sector was shown to enrich studies in this area. Hence, the following section proposes a reverse logistics network for MSW, which was mathematically modelled (Section 3) and validated using the case of the municipality of São Mateus, Espírito Santo.

2.3. Proposed reverse logistics network for MSW management

In facility location problems, usually it is considered a set of candidate points during the location phase which must meet demands while optimising a function that involves costs (Owen and Daskin, 1998; Daskin, 2011; Fleischmann et al., 2000). According to Melo et al. (2009), there are two sets of facilities

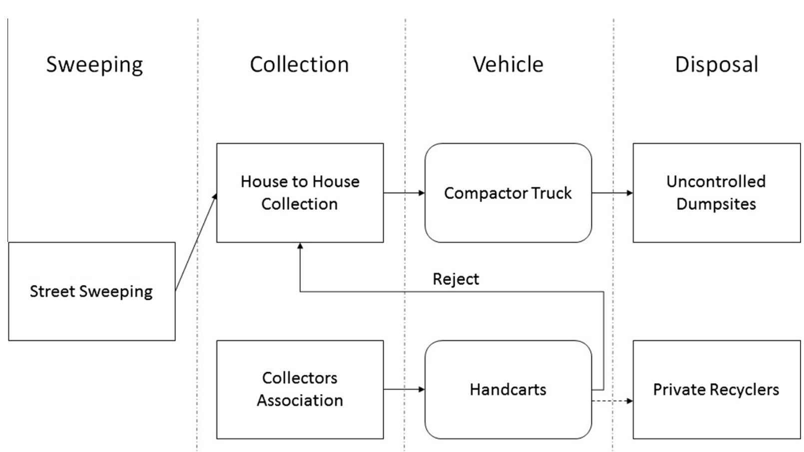

Fig. 1. Schematic representation of solid waste management in São Mateus. Adapted from: Hazra and Goel (2009).

within reverse logistics: collection centres, which are installations that receive used products, and locations for recovery or remanufacturing, in which the products are refurbished or remanufactured. Besides, a third set of facilities involved in reverse logistics networks includes the locations for the final disposal of the products, that is, sites where the products or materials are incinerated or discarded (De Brito, 2003; Pishvaee et al., 2010; Ramezani et al., 2013). In this context, the structure of the distribution network can be extended to encompass the flow of returns from clients to the locations for repair, refurbishing or appropriate final destination. Fig. 2 represents the reverse flow of MSW within a reverse logistics network.

The proposed MSW reverse logistics network is divided into three stages. In the first stage, the MSW is generated, then collected and sent to the second stage, which is responsible for sorting the materials that make up the collected wastes. MSW is composed of recyclable waste (MSW_R) and general solid waste (MSW_G). MSW_R, represented by the brown flow lines, includes materials such as paper and glass, separated in residences through selective collection and collected by a dedicated vehicle. MSW_G, represented by the black flow lines, consists of refuse and organic material that will be collected by another type of vehicle. MSW_G may be considered the wet fraction of the garbage and MSW_R the dry fraction, as this portion does not have a significant quantity of organic material in its composition. Thus, the reusable materials through recycling or incineration can be separated, for example, from those that cannot be reused and will be discarded in a sanitary landfill (Zhenqiang et al., 2012; Lambert et al., 2011).

The second stage, represented in Fig. 4 by the squares, is composed of two distinct types of locations responsible for the sorting and storage of the different types of wastes. MSW_R is destined for MRF_R and MSW_G is destined for MRF_G. The MRF_R facilities comprise a set of equipment designed to segregate the recyclable fraction into various types of waste materials that require appropriate final destinations. In such a way, it is possible to direct the recyclable fraction to various actors, such as a recycling company or a recycler dealer. The wastes from this recycling fraction will be appropriately transported to a sanitary landfill. The wet fraction present in MSW_G that can also be reused through composting must be sent to an appropriate location due to the odours inherent in this process, as other process specificities. Thus, the MRF cannot be located in arbitrary locations within the municipality. Additionally, it is worth emphasising that the equipment, capacities and installations required for the two types of MRFs are distinct, making it necessary to adapt each to both the type and quantity of MSW that the MRF will receive.

MRFs work as reverse consolidation points where returned products are sorted and consolidated into large shipments or trans-shipments destined for recycling facilities (Campos, 2014; Min et al., 2006; Min and Ko, 2008). These reverse consolidation points make it possible balance the revenue generated from the sale of recyclable materials and the costs related to the installation and operation of the entire MSW reverse flow process, including the logistical costs related to the transport of MSW to these facilities (Ferri et al., in press). Taking into consideration that the logistics costs directly affect the MSWM, the MRFs are justified by the reduction in the volume of wastes destined for the landfill, thus reducing the transport costs and increasing the useful life of the sanitary landfill, in addition to enabling the sale of recyclable materials (Ferri et al., in press). Additionally, for long distances, the use of transfer stations that limits the route of the collection vehicles is recommended (D'Almeida and Vilhena, 2000). In this case, the MRFs promote the transfer of MSW to larger vehicles that perform the transport to the final disposal location (Min and Ko, 2008; Dekker et al., 2012).

The use of these centres is justified as they separate materials that can be reused from those that must be discarded and consolidate the different materials selected. A larger volume of waste allows for the acquisition and installation of equipment, the specialisation of the storage facilities according to the various

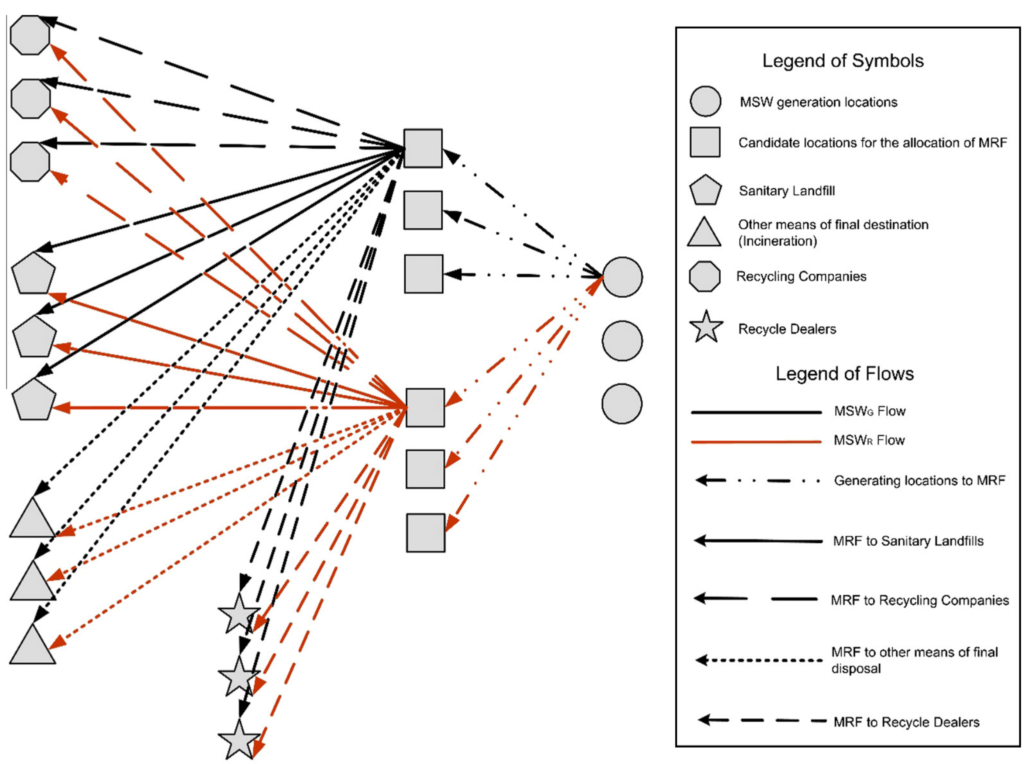

Fig. 2. Reverse logistics network for MSW.

types of materials handled and the transport of wastes that cannot be recycled locally (Tuzkaya and Gülsün, 2008). The waste pickers' cooperatives can also operate as a MRF if they are included the MSW.

Finally, the third stage involves the reuse options, in this case through recycling companies (including composting of organic material) and other means of final disposal, such as energy recovery companies, in addition to appropriate disposal in sanitary landfills (De Brito, 2003; Lambert et al., 2011). The recycle dealers, represented by stars in Fig. 4, are significant in the reverse flow of recyclable wastes in Brazil and other countries. However, recycle dealers act between the second and third stage of the network and are often responsible for promoting a link between the screened wastes and their final destination by consolidating materials for resale to recycling companies or for energy recovery.

The planning of a reverse logistics network is an important point in supply chain management. Therefore, decisions related to the number of installations, their locations, and their respective capacities, as well as the flows amongst facilities, directly affect the total cost of the reverse logistics network (Dekker et al., 2012; Pishvaee et al., 2010; Amiri, 2006). With this approach, the goal is to locate the reverse consolidation points at the lowest possible cost, such that every client is served and the capacity restrictions are respected.

The next section presents our mathematical model for the MSWM which is based on the studies of Geoffion and Graves (1974) and Jayaraman et al. (2003). Discrete, multiple-product, qualified models, such as that proposed by Geoffion and Graves (1974), that seek to locate load distribution centres are relevant to scenarios such as those described here and the mixed integer-linear programming (MIP) problem in which fractional demands at origination sites are assigned to collection sites, which are again assigned to the destination site, as proposed by Jayaraman et al. (2003), guided our study.

Programming (MIP) has been used in the literature to design optimised reverse logistics network such as in Achillas et al. (2010), Jayaraman et al. (2003), Schwartz Filho (2006) and Pishvaee et al. (2010). We have followed this approach and our mathematical model maximises the profit obtained with the reverse logistics network for the MSWM.

3. Mathematical modelling

The mathematical modelling proposed to make the solid waste handling system possible is designed to maximise the profit obtained throughout the MSWM, considering the sale of recyclable materials as a potential source of income. The model involves all of the links defined in Fig. 4, which consider MSW generating locations, the candidate locations for MRF (both MRF_R and MRF_G) and the locations responsible for the final destination of each material selected from the MSW collected (sanitary landfills, recycling companies and energy recovery companies). The model makes the insertion of an intermediate stage between the second and the third stage possible, thus considering intermediate associations involved in MSW handling, see Fig. 4.

Thus, let:

- G be the set of MSW generating locations;
- C be the set of candidate locations able to host MRF for MSW (MRF_R and MRF_G);
- K be the set of types of MSW collected (MSW_R and MSW_G);
- F^k be the set of capacity ranges allowed for a MRF that will receive waste of the type $k \in K$;
- P^k be the set of materials obtained from MSW type $k \in K$;
- L be the set of potential sanitary landfill locations for MSW disposal;
- R be the set of potential recycling company locations for receiving different types of materials $p \in P$;
- E be the set of potential locations related to energy recovery, such as incineration, for receiving different types of materials $p \in P$; and
- I be the set of potential recycle dealer locations for receiving different types of materials $p \in P$.

As a function of the practical application of the model, the MRFs have capacity ranges, making it more complex due to the possibilities of combinations amongst the flows and the capacity ranges of the MRFs. Hence, to meet the needs imposed by the BSWP, all MSW of the type $k \in K$, generated at location $g \in G$, represented by QTD_g^k, must be destined for an open facility at $c \in C$. However, if a facility $c \in C$ is open in a given capacity level $f \in F$, which is different for each product $k \in K$, all of the MSW received by c must be within its capacity level. The capacity range $f \in F$ for facility $c \in C$ has a lower limit $CAPlower_f^k$ and an upper limit $CAPupper_f^k$, which must be respected.

The fixed cost of installation of a MRF varies according to the location, capacity level and the type of MSW that will be screened. In such a way, let CI_{cf}^k be the fixed cost for the installation of facility $c \in C$, designed for MSW type $k \in K$, working at the capacity range $f \in F$.

In contrast to the fixed cost of installation, the fixed cost of operation of a facility varies only according to the capacity range and the type of MSW that will be screened. Therefore, let CO_f^k be the fixed cost of operation associated with the facility designed to serve MSW of type $k \in K$ working at the capacity range $f \in F$.

Every waste has a transport unit cost to be transported from its location of origin $g \in G$ to an MRF centre located at $c \in C$, with this cost depending on the type of waste to be collected, the distance travelled and the quantity to be transported. Therefore, consider that α_{gc}^k represents transport unit cost between the generating locations $g \in G$ and the candidate locations for a MRF $c \in C$ for MSW of type $k \in K$. Thus α_{gc}^k represents the transport unit costs between the first and second stage of the proposed reverse logistics network (see Fig. 2).

Between the second and third stages, the transport unit costs related to sending materials $p \in P$, from a MRF at $c \in C$ to a sanitary landfill at $l \in L$ are represented by β_{clp}; in addition, ρ_{cl} represents the unit costs of transport for sending all of the waste to the sanitary landfill.

Also regarding the transport unit costs, let γ_{crp} and τ_{cep} be the unit costs for sending different materials types of $p \in P$ from a MRF at $c \in C$ to a recycling company at $r \in R$ and to an energy recovery company at $e \in E$, respectively.

The recycle dealers of recyclable materials, despite acting between the second and third stages of the reverse logistics network, consolidating materials for resale to the recycling companies or for energy recovery, will be considered as actors belonging to the third layer in the model, given that flows of materials after this stage will not be considered in this model. Thus, parameters σ_{cip} contain the transport unit costs between the candidate locations for an MRF $c \in C$ and the recycle dealers of recyclable materials $i \in I$ for material of type $p \in P$.

Regarding revenue, SR_{rp} and SI_{ip} represent, respectively, the sale price of material of type $p \in P$ to a recycling company $r \in R$ and to an recycle dealer of recyclable material at $i \in I$.

To enable the transformation of MSW from type $k \in K$ into recyclable materials of type $p \in P$, consider that GC_p^k represents the gravimetric composition, in percentage, related to the quantity of materials of type $p \in P$ existing in waste of type $k \in K$.

The percentages of reuse of the different types of materials $p \in P$ from MSW type $k \in K$ that can be recycled are represented by RE_p^k.

For the decision variables, let:

- $x_{gc}^k \geqslant 0$ be a variable that represents the quantity of MSW type $k \in K$ sent from location $g \in G$ to the open facility at $c \in C$;
- $z_{clp}^k \geqslant 0$ be a variable that represents the quantity of material of type $p \in P$, from MSW type $k \in K$, sent from location $c \in C$ to a sanitary landfill at $l \in L$;
- $w_{cl}^k \geqslant 0$ be a variable that represents the quantity of refuse (which cannot be recovered and must properly disposed) of MSW type $k \in K$ sent from location $c \in C$ to a sanitary landfill at $l \in L$;
- $u_{crp}^k \geqslant 0$ be a variable that represents the quantity of material of type $p \in P$, from MSW of type $k \in K$, sent from location $c \in C$ to a recycling company at $r \in R$;
- $\upsilon_{cep}^k \geqslant 0$ be a variable that represents the quantity of material of type $p \in P$, from MSW of type $k \in K$, sent from location $c \in C$ to an energy recovery site at $e \in E$;
- $\ell_{cip}^k \geqslant 0$ be a variable that represents the quantity of material of type $p \in P$, from MSW of type $k \in K$, sent from location $c \in C$ to an recycle dealer of recyclable material at $i \in I$;
- $FI_c^k \geqslant 0$ be a variable that represents the fixed cost of installation of a MRF open at $c \in C$ to serve MSW from type $k \in K$. This variable is calculated as a function of the selected capacity range;
- $FO_c^k \geqslant 0$ be a variable that represents the fixed cost of operation of a MRF open at $c \in C$ to serve MSW from the type $k \in K$;
- $V_c^k \geqslant 0$ be a variable that represents the total quantity of MSW, from the MSW of type $k \in K$, that an open MRF at $c \in C$ receives; and
- $y_{cf}^k \in \{0,1\}$ be a binary variable that represents the opening ($y_{cf}^k = 1$) or not ($y_{cf}^k = 0$) of facility $c \in C$ in the capacity range $f \in F$ to serve MSW from the type $k \in K$.

To such a degree, the mathematical formulation for locating the facilities for the screening and disposal of MSW within the reverse network is presented below.

Maximise

$$\begin{aligned}&\sum_{k\in K}\sum_{p\in P}\sum_{c\in C}\sum_{r\in R}(SR_{rp}-\gamma_{crp})u_{crp}^k+\sum_{k\in K}\sum_{p\in P}\sum_{c\in C}\sum_{i\in I}(SI_{ip}-\sigma_{cip})\ell_{cip}^k\\&-\sum_{k\in K}\sum_{p\in P}\sum_{c\in C}\sum_{l\in L}\beta_{clp}z_{clp}^k-\sum_{k\in K}\sum_{p\in P}\sum_{c\in C}\sum_{e\in E}\tau_{cep}\upsilon_{cep}^k\\&-\sum_{k\in K}\sum_{c\in C}\sum_{l\in L}\rho_{cl}w_{cl}^k-\sum_{k\in K}\sum_{g\in G}\sum_{c\in C}\alpha_{gc}^k x_{gc}^k-\sum_{k\in K}\sum_{c\in C}(FI_c^k+FO_c^k)\end{aligned}\tag{1}$$

Subject to:

$$QTD_g^k=\sum_{c\in C}x_{gc}^k\quad\forall g\in G;\ k\in K\tag{2}$$

$$V_c^k=\sum_{g\in G}x_{gc}^k\quad\forall c\in C;\ k\in K\tag{3}$$

$$V_c^k\leqslant\sum_{f\in F^k}CAPupper_f y_{cf}^k\quad\forall c\in C;\ k\in K\tag{4}$$

$$V_c^k\geqslant\sum_{f\in F^k}CAPlower_f y_{cf}^k\quad\forall c\in C;\ k\in K\tag{5}$$

$$FI_c^k=\sum_{f\in F^k}CI_{cf}^k y_{cf}^k\quad\forall c\in C;\ k\in K\tag{6}$$

$$FO_c^k=\sum_{f\in F^k}CO_f^k y_{cf}^k\quad\forall c\in C;\ k\in K\tag{7}$$

$$\sum_{f\in F^k}y_{cf}^k\leqslant 1\quad\forall c\in C;\ k\in K\tag{8}$$

$$\begin{aligned}\sum_{g\in G}RE_p^k GC_p^k x_{gc}^k=\sum_{l\in L}z_{clp}^k+\sum_{r\in R}u_{crp}^k+\sum_{e\in E}\upsilon_{cep}^k+\sum_{i\in I}\ell_{cip}^k\quad\forall c\in C;\\ k\in K;\ p\in P\end{aligned}\tag{9}$$

$$\begin{aligned}V_c^k=\sum_{p\in P}\left(\sum_{l\in L}z_{clp}^k+\sum_{r\in R}u_{crp}^k+\sum_{e\in E}\upsilon_{cep}^k+\sum_{i\in I}\ell_{cip}^k\right)\\+\sum_{l\in L}w_{cl}^k\quad\forall c\in C;\ k\in K\end{aligned}\tag{10}$$

$$y_{cf}^k\in\{0,1\}\quad\forall c\in C;\ k\in K;\ f\in F\tag{11}$$

$$x_{gc}^k\geqslant 0\quad\forall c\in C;\ g\in G;\ k\in K\tag{12}$$

$$z_{clp}^k\geqslant 0\quad\forall c\in C;\ k\in K;\ l\in L;\ p\in P\tag{13}$$

$$w_{cl}^k\geqslant 0\quad\forall c\in C;\ k\in K;\ l\in L\tag{14}$$

$$u_{crp}^k\geqslant 0\quad\forall c\in C;\ k\in K;\ r\in R;\ p\in P\tag{15}$$

$$\upsilon_{cep}^k\geqslant 0\quad\forall c\in C;\ k\in K;\ e\in E;\ p\in P\tag{16}$$

$$\ell_{cip}^k\geqslant 0\quad\forall c\in C;\ k\in K;\ i\in I;\ p\in P\tag{17}$$

$$FI_c^k\geqslant 0\quad\forall c\in C;\ k\in K\tag{18}$$

$$FO_c^k\geqslant 0\quad\forall c\in C;\ k\in K\tag{19}$$

$$V_c^k\geqslant 0\quad\forall c\in C;\ k\in K\tag{20}$$

Objective Function (1) is divided into seven main parts. The first two represent the total profits obtained by sending material to the recycling companies and to the recycle dealers of material, respectively. The profit is calculated by subtracting the total costs for the transport of materials to the chosen destination from the total revenue generated by the sale of recyclable materials.

Still regarding Objective Function (1), the total costs for sending materials to the sanitary landfills and to the energy recovery companies are considered next, in addition to the total costs for the transport of all refuse to the appropriate final destination, the sanitary landfills. Next, the costs related to the MRFs are calculated, represented by the total costs for transport of the waste and by the total fixed costs for the installation and operation of a MRF.

Constraints (2) ensure that all the waste generated at a point of origin must be sent to the MRFs. Constraints (3) guarantee that all of the waste sent to a facility arrives at the facility. Constraints (4) and (5) ensure that the waste sent to an open facility respects the capacity range used. Constraints (6) and (7) ensure that the fixed costs of installation and operation, respectively, for a facility are obtained according to the capacity range at which the facility was opened. Constraints (8) guarantee that at most one capacity level can be used for an opened MRF.

Constraints (9) ensure that all material that can be reused will be sent to some final destination site. In contrast, Constraints

(10) ensure that all refuse entering the system will be destined for a sanitary landfill. Constraints (11)–(20) are associated with the domain of the decision variables.

The application of this model provides an optimal result for the problem in question, maximising the total profit obtained by the system, enabling the social inclusion of the class of workers involved in the collection and sale of wastes. In the next section, the methods employed to obtain the parameters unique to the municipality of São Mateus are described.

4. Obtaining the parameters for the São Mateus case

4.1. Definition of the sets

The municipality of São Mateus, Espírito Santo, consists of 39 neighbourhoods that generate MSW according to Fig. 3. The municipality also has seven small, informal MRF_R, which will be known as associations, which consist of associations of waste pickers, represented in Fig. 3 by the recycling symbol.

Although these associations lack formal registration, they already have a rudimentary infrastructure, human resources and experience in the collection and screening of materials, even though these activities are performed in an unstructured manner and without planning. Currently the municipal government have not formally included these groups in MSWM, so this analysis indicates the effective viability of these locations as MRF_R, as well as the ideal capacity range for each of them. Thus, considering the notation shown in the previous section, we have $|G| = 39$ and $|C| = 46$, where $|\cdot|$ represents the size of the set being analysed.

The BSWP establishes that the final environmentally appropriate disposal of wastes must be implemented and gradually increased over time (Brazil, 2010). To make it possible, the implementation of a selective collection system and informing the inhabitants about the system is necessary for the waste to be sorted at the generating source (Bassani, 2011). Thus, two types of MSW collected at generating locations are considered, therefore $|K| = 2$. Thus, $k = 1$ general MSW_G and $k = 2$ represents pre-screened MSW_R, which will be collected through selective collection.

Based on the existing literature, nine types of recyclable materials from the collected MSW will be considered initially: Steel; Aluminium; Carton Packaging; Organic Material; Paper; Cardboard; PET (Polyethylene terephthalate); Plastic; and Glass (CEMPRE, 2014; Bassani, 2011). Thus $|P| = 9$. Organic material, despite being associated with the wet fraction flow (MSW_G), can be recycled through composting. The other wastes will be considered as refuse. The requirement for the segregation of dangerous wastes, such as light bulbs, batteries and tires, amongst others, means that such wastes will be destined for another reverse distribution channel, as recommended by the BSWP (SINIR, 2014).

The municipality of São Mateus is part of a public consortia solution for construction of a Sanitary Landfill which will to serve the municipalities located in the north of the State of Espírito Santo (SEPLADE, 2014). Thus we consider $|L| = 1$.

To determine the recycling companies used in the case study regarding MSW management in the São Mateus municipality, the recycling companies in the region according CEMPRE (2014) were contacted. However, only one recycling company for each type of material $p \in P$ was found in the Espírito Santo state. Therefore $|R| = 1$.

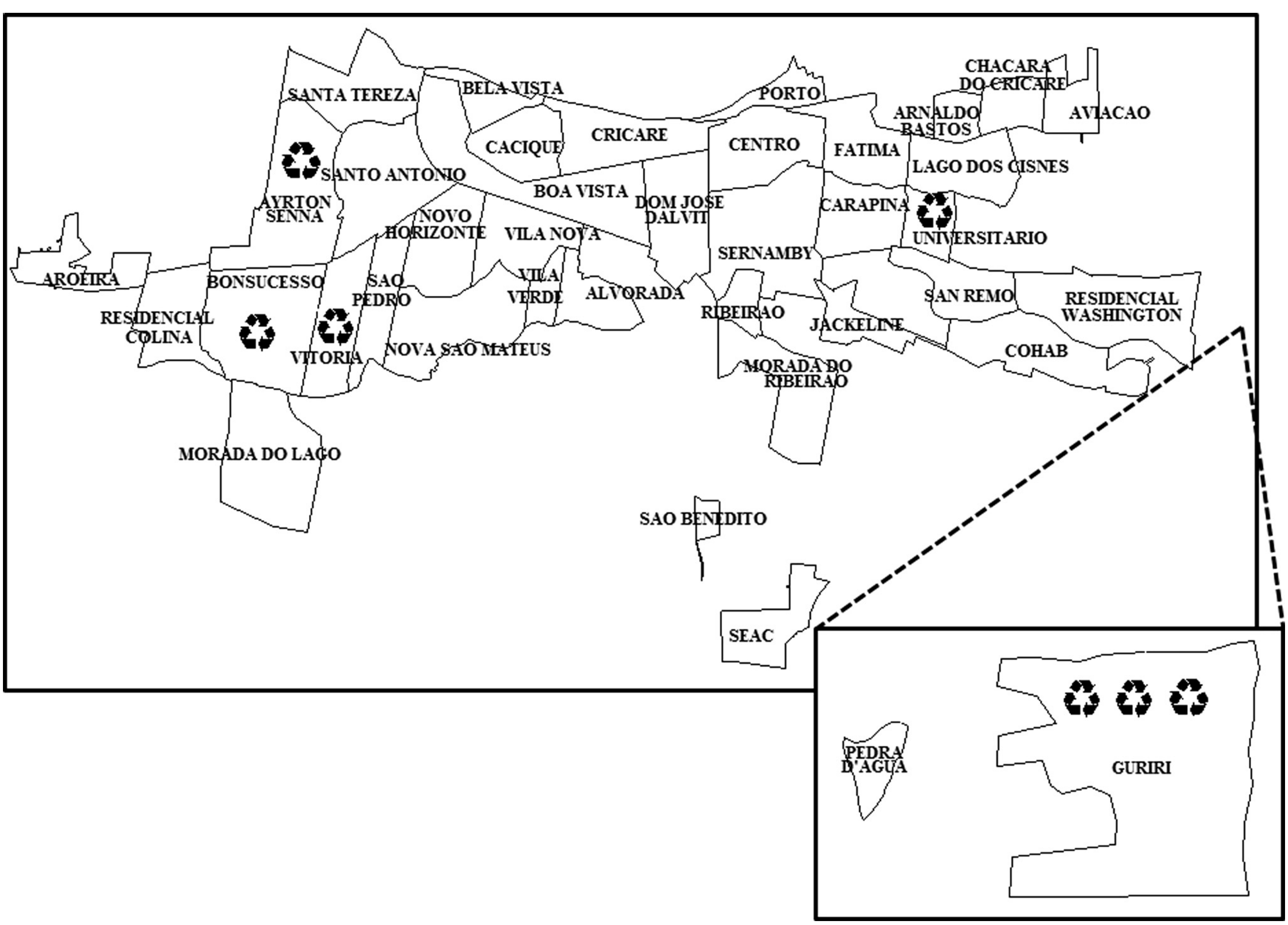

Fig. 3. Map of the municipality of São Mateus-ES. *Source*: Prepared by the authors.

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To define the number of recycle dealers of recyclable materials, a study was performed similar to that for the recycling companies. Therefore, analogous to the recycling companies, only one site will be considered for the recycle dealers. Therefore $|I| = 1$.

Incineration is a controversial method of waste disposal, due to issues such as emission of gaseous pollutants extensively discussed by Ecke and Svensson (2008). Regarding to the incineration of MSW, burning is generally used in countries with little land availability, but this option has been increasingly discarded due to the serious environmental impacts associated with it (De La Torre, 2012). Another negative aggravating factor related to incineration is the generation of toxic components present in the gases and ashes that, when inhaled, can cause a number of diseases (Waldman, 2011). In developing countries, the characteristics of the waste, often high in organic matter, is highly suitable for composting and anaerobic digestion and not inappropriate for waste to energy plants (Barton et al., 2008). We agree with Larsen et al. (2010) that enhancing recycling and avoiding incineration are recommendable because the environmental performance is improved. The municipal costs for collection and treatment of waste were reduced with increasing recycling, mainly because the high cost for incineration was avoided. Additionally, to make the establishment of incineration companies economically viable, it would be necessary to incinerate a great amount of the solid waste produced in the municipalities (Waldman, 2011), including the percentage that can be recycled, hence hindering the achievement of the goals of reduction, reuse and recycling established in the BSWP. Also, this is a practice discouraged by the public prosecutor of Espírito Santo State and faces great resistance of the National Waste Pickers Movement. Therefore, we consider $|E| = 0$ in our case study. Local characteristics can be considered in other studies and change this parameter.

The capacity ranges were defined based on federal technical reports. Distinct values were defined for the different types of wastes $k \in K$, with $|F^1| = 4$ for MSW_G and $|F^2| = 5$ for MSW_R. Thus, the ranges correspond to the necessary MRF sizes required to manage the MSW received (SRHU, 2009, 2010).

4.2. Gravimetric composition and recycling percentage

For the gravimetric composition, two distinct percentages will be used, one for MSW_R and the other for MSW_G (Pessin et al., 2006). Considering that the gravimetric composition of MSW is directly connected with the effective implementation of selective collection, it must be considered that general waste and waste from selective collection have very distinct compositions. In the first case, general waste includes refuse, organic material and materials that can be recycled but that were not separated. With selective collection, the percentage of recyclable materials in general waste will decrease and will be represented in the composition of the dry garbage fraction. It is important to note that selective collection is implemented gradually, that is, this alteration in compositions is also gradual. The dry fraction has a specific gravimetric composition.

Although the municipality of São Mateus does not have the gravimetric composition of MSW_G this was estimated based on the national average, reported at the Orientation Manual for Solid Waste Plans (Brazil, 2012). For the MSW_R, we have used data from the municipality of Vitória (ES), provided in Bassani (2011). Fig. 4 shows the gravimetric composition used taking into account the type of MSW.

4.3. Fixed costs of installation and operation of an MRF

The fixed cost of installation is associated with the costs for acquisition of land, construction of the physical installations, acquisition of machines and equipment and training of personnel (Schwartz Filho, 2006). Thus, this cost varies according to the capacity range, which depends on the used area and equipment effectiveness. The fixed costs of operation refer to the costs of salaries and payroll taxes, maintenance of the location and the equipment, and utility expenses, including electricity and water supply as well as telephone (Schwartz Filho, 2006).

For the fixed cost of the installation, we have used the ones reported by Ferri et al. (in press) which are shown in Fig. 5. We can see that the costs increase non-linearly as a function of increased capacity range. This result is interesting because linear approximations are generally used when such data are not available.

Groups A–F were defined based on similar land costs amongst the neighbourhoods of the municipality, which affects the fixed costs of similar installations in some neighbourhoods for all of the capacity ranges.

4.4. Sale prices

The sale prices for the materials analysed (Steel; Aluminium; Organic Material; Paper; Cardboard; PET; Plastic; and Glass) were compiled from various recycling companies and scrap dealers in Espírito Santo, as recorded in CEMPRE (2014). The sale price of

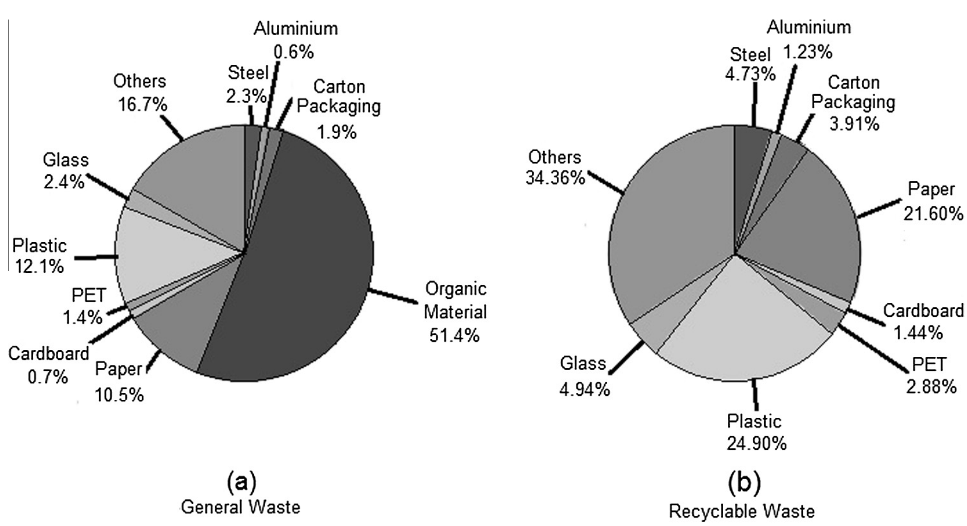

Fig. 4. Gravimetric composition. *Source*: adapted from Brazil (2012, p. 7) and Bassani (2011, p. 92).

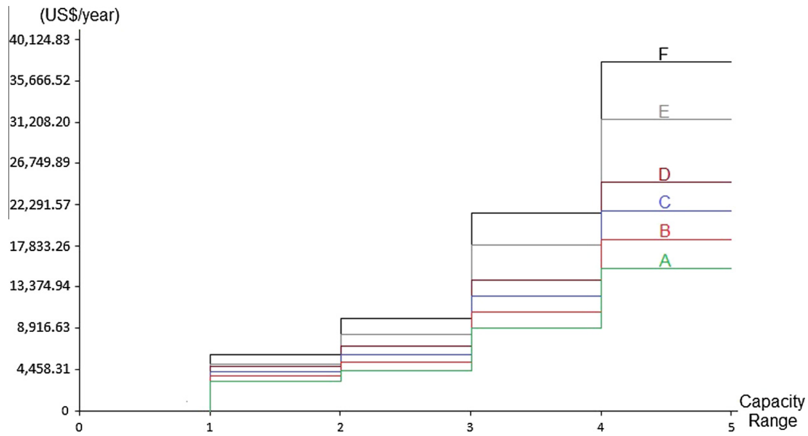

Fig. 5. Pattern of fixed costs of installation.

these materials varies according to their type and condition. For example, a pressed and clean material has a higher market value. For the MRF_R, it was assumed that every type of material will be sold in the quality conditions (pressed and clean) and will be grouped in bales.

We assumed that the Recyclers buy all material types, except Carton Packaging and Organic Material, from MRF. No market data were obtained with the recycling for the carton packaging. Organic material does not have a market value; it must be composted to the addition of value, transforming it into organic fertiliser. Thus, the sale of the organic fertiliser produced will be considered as a potential source of revenue because this material will not be incinerated. The sale of organic material will be considered only for the recycle dealers, assuming that all MRF_Gs of type $k = 1$ will be points of sale for fertiliser. The sale prices used are reported in Table 1.

We can observe that the ideal situation for maximising revenue would be to sell the screened wastes directly to the recycling companies. However, some recycling companies, such as Klabin, an important player in paper and cardboard industry, are large companies located geographically distant from the municipality of São Mateus and do not purchase small quantities. Therefore, in some cases, it is better to negotiate with the recycle dealers. This logic is the same as that one applied to the spread of distribution channels; however, the flows are opposite, characterising a reverse distribution chain.

4.5. Transport costs

4.5.1. From local generator to MRF

To define the transport unit cost from a local generator to an MRF, α_{gc}^{k}, $g \in G, c \in C, k \in K$, it was necessary to determine the distances between the local generators g and the candidate locations c and the freight which is given in US$/km/ton.

Hence, given the spatial locations of the neighbourhood economic centres and the cooperatives, Euclidean distances were obtained between every pair $(g, c), g \in G, c \in C$ and subsequently corrected by +10% according to Pimentel (2004).

In relation to shipping costs, the values associated with the use of a compacting truck for waste type $k = 1$ and a box truck as the transport vehicle for waste type $k = 2$ were researched. For selective collection, compacting trucks were chosen because such vehicles are not recommended when the materials will later be segregated for recycling (Massukado, 2004). Compacting vehicles promote the contamination or moistening of materials that can be recycled, potentially hindering recovery. Thus, for the São Mateus case, considering that the cost of selective collection is 4.3 times higher than for regular collection, the values for MSW types $k = 1$ and $k = 2$ are, respectively, US$ 1.33/km/ton and US$ 5.74/km/ton (Parreira et al., 2010).

Table 1
Sale price of materials. *Source*: Adapted from CEMPRE (2014).

Type of material	Interceptor (US$/ton)	Recycling (US$/ton)*
Steel	89.17	133.75
Aluminium	891.66	1248.33
Carton packaging	89.17	–
Organic material	44.58	–
Paper	66.87	133.75
Cardboard	66.87	133.75
PET	222.92	579.58
Plastic	222.92	579.58
Glass	98.97	148.46

* The symbol "–" indicates that the materials are not sold by the actor in question.

4.5.2. From MRF to sanitary landfill

These costs consider all of the elements of investment and vehicle operational costs. The personnel costs – salaries, payroll taxes, uniforms and personal protection equipment – were also considered. It results in a cost index of US$0.0535/km/ton (SRHU, 2009).

The municipality of São Mateus is part of a public consortia solution where the sanitary landfill is located 41 km far from São Mateus, on highway BR 381 (SEPLADE, 2014). This highway is reached by just one intersection close to the border of the city. So, given that the candidate points for the MRF have variable distances to this intersection, we have added them 41 km to compute the distance between each MRF and the Sanitary Landfill. All parameters employed are available in Appendix A.

To test the applicability of the model shown in Section 3, data obtained for the São Mateus municipality case and computational experiments based on idealised scenarios are presented in the next section.

5. Practical application of the mathematical model through scenarios

5.1. Considered scenarios

A practical application of the mathematical model of the reverse logistics network proposed was performed for the municipality of

São Mateus, as this city is in the planning phase of its Municipal Solid Waste Policy, designed to comply with national and state policies (AMUNES, 2014a). Therefore, in this case, the proposal of a reverse logistics network could aid in the planning and management of MSW. To better understand the case, it is important to emphasise some singularities found in this case study that affect the application of the proposed mathematical model.

Previously, MSW in São Mateus was collected and sent directly to the open-air dump located on the periphery of the city. According to the parameters defined by the BSWP, the municipalities of the state of Espírito Santo were grouped by regional characteristics into four regions to perform a public consortia solution for the appropriate disposal of the MSW in sanitary landfills. The headquarters of the public consortia solution of the Northern Region of Espírito Santo is the municipality of São Mateus, where the installation of a regional licensed sanitary landfill and regional transfer stations is planned. It is worth emphasising that the Government of Espírito Santo will build all of the structures needed in the regions mentioned with its own resources, with the operation of each system being delegated by concession to private companies (SEPLADE, 2014).

Despite the existence of a regional solution, the municipalities belonging to this consortium still do not have local solutions to optimise the management of MSW in compliance with legislation. To evaluate the location of the MRF in the municipality of São Mateus, considering factors specific to the municipality, it was necessary to utilise scenarios to aid in decision making with regard to the implementation of the entire Reverse Logistics Network (Oliveira, 2011). Thus, the 6 scenarios summarised in Table 2 were used.

The BSWP foresees a gradual increasing in the implementation of selective collection, and therefore, the following hypotheses were adopted: initially, 20% of the population will participate in the programme, and with the passage of time and increased awareness of the population, this value would increase to 40%, followed by 60% and later 80%; this is the most optimistic scenario, based on the study by Oliveira (2011). Therefore, Scenarios 2, 4, 5 and 6 in Table 2 have four sub-scenarios predicting the gradual increase described.

For Scenario 3, it was assumed that only 20% of the population participates in the selective collection programme, generating, thus, thirty six sub-scenarios. There is no sub-scenario in Scenario 1, and this scenario also does not predict the participation of the population in selective collection programmes; therefore, the percentage of inclusion of selective collection is 0%. It is worth emphasising that this scenario does not predict the reuse of recyclable materials and only includes MRF_G. Thus, in total, there are 53 distinct proposed simulations, used to demonstrate the viability and adaptability of the proposed model for the existing problem.

Table 2
Summary of the scenarios.

Scenario	Description
1	Scenario without selective collection – considers the current reality of the municipality
2	Optimal Scenario – exclusion of some neighbourhoods and inclusion of the existing associations in the set of candidate locations
3	Considering Scenario 2 and opening of MRF_G and MRF_R varying from 1 to 6
4	Social Scenario – considering Scenario 2, fixed opening of MRF for MSW and SC in all associations
5	Considering Scenario 2, fixed opening of only 1 MRF for general MSW in a location pre-determined by the municipality
6	Projection Scenario – considering Scenario 2, perform a projection of the population increase over 10 years

The scenarios presented in Table 2 are detailed below:

- Scenario 1: Simulates the current situation in the municipality; that is, selective collection was not implemented. This scenario aids in decision making, serving as a parameter for comparisons amongst the best proposals. Based on this scenario, some locations are excluded from the set of candidates due to regional, social and demographic issues. These neighbourhoods, which are located in the central region of the municipality, have a high demographic density, which leads to little availability of space for the installation of these facilities, for which expropriations would be needed, in addition to causing more intense vehicle traffic and limiting the passage of trucks. These factors make up the tangible and intangible aspects that influence the decisions for the locating storage and screening centres in the municipality of São Mateus.
- Scenario 2: Predicts the performance of selective collection, in addition to including the existing associations as possible candidates for receiving an MRFR. Based on this scenario, certain regions were excluded from the set of candidate locations to receive an MRF_R.
- Scenarios 3: The number of facilities to be opened for both types of MRF was set in an increasing manner. Thus, the pattern of locations in terms of sites selected, flows allocated and costs could be found. To facilitate the implementation of these variations, the creation of a new parameter N^k was necessary. This parameter represents the total number of facilities to be opened to receive waste type $k \in K$. Thus:

$$\sum_{c \in C} \sum_{f^k \in F^k} y_{cf}^k = N^k \quad \forall k \in K \tag{21}$$

- Scenario 4: Seeking to meet the legal requirements outlined in the BSWP for the inclusion of waste pickers, this scenario assumes the opening of facilities in all of the currently existing associations. All formal and informal associations of waste pickers (workplace, location, number and profile of members) were mapped of São Mateus. They manifest the interest in participating in an MSW network and all those interviewed reported, if there was support from municipality government (Ferri et al., in press). This scenario also enables the opening of MRFs at other locations, making it possible to verify the impact of the inclusion of the existing associations on the proposed reverse logistics network. For the correct application of this scenario, it was necessary to alter Constraint (8), by modifying the sign from "less than or equal to" to "equal" in all of the restrictions affecting candidate locations with an existing cooperative.
- Scenario 5: Promotes a more precise evaluation with regard to the comparison between the general proposal of this study and the proposal of the Municipal Plan for Basic Sanitation of the municipality of São Mateus, which has not been approved. The Municipal Plan for Basic Sanitation of the municipality plans for the construction of a Municipal Exchange Centre, which in this study will be considered a MRF (SEPLADE, 2014). For this scenario, the opening of only one MRF for general MSW in the location pre-determined by the municipality was set; and
- Scenario 6: Predicts 10% population growth over a time interval of 10 years (SEPLADE, 2014) to evaluate the behaviour of the reverse logistics network structure with the increase in demand for MSW.

5.2. Results and discussion: analysis of scenarios

The mathematical model (1)–(20), and its variations discussed in the previous section, was implemented in C/C++ language and

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tested with CPLEX 12.5 (ILOG IBM, 2012) using a computer equipped with an Intel ® Core™ 2 Solo processor (1.4 GHz, 800 MHz FSB) and 4 GB of RAM memory.

Table 3 shows the results obtained with respect to total profit, total cost, total revenue and number of facilities opened for Scenarios 1, 2, 4, 5 and 6. All MRF_G and MRF_R, with their exact locations and capacity ranges, as well as the results for sub-scenarios of the Scenario 3, are available in Appendix A.

Scenario 1 represents the MSW reverse logistics network that is closest to the current conditions in the municipality, in which there is no selective collection in residences, but only the collection by waste pickers in the streets and in some commercial establishments that separate a few types of wastes. MSW costs are still higher in practice because, in the scenario, the MRF_G sort the MSW and oversee the composting of part of the organic material, which does not happen currently. However, even though the real cost is underestimated, the result for this scenario is the only one amongst the proposed scenario that indicates a total cost higher than the revenues generated. The current situation in the municipality of São Mateus is not self-sustaining: that is, the revenue from the sale of the materials does not cover the necessary investments, indicating that the current solution is economically inefficient.

Additionally, this scenario does not meet the legislative requirements. Thus, the environmental costs related to discarding MSW in the dump and the non-reuse of materials that can be recycled must be added to the total cost calculated. Another way of measuring these environmental costs is by comparing the energy consumption required for the production of virgin raw material with that of raw material from recyclable materials (IPEA, 2010). However, this measurement is not part of the scope of this study. Despite the fact that this scenario is not economically or legally viable, it verifies the impact of the changes in other scenarios needed to meet the proposed legal standards.

This analysis is important because the government always argue that modifications burden the MSWM system and that such expenditures must be passed on to the population (SEPLADE, 2014). However, the profitability of the MSWM system increases with an increase in the portion of MSW segregated by selective collection. This occurs when the increase in revenue from the sale of these wastes is higher than the increase in fixed and operational costs required to support this strategy. Thus, it is confirmed that the cost for implementation of selective collection is higher than the cost of conventional collection, which is in agreement with the literature. However, selective collection provides increasing profits in larger proportions than the growth of costs. Fig. 6 illustrates this difference in the evolution of costs with the increase in the percentage of wastes that can be recycled, indicating the viability of implementation of selective collection.

The profitability of this system could be invested in environmental education, a decisive factor for the success of selective collection. This is important because the municipality does not acknowledge the importance and benefits of this permanent programme, primarily due to the limited terms of public officials (Chaves et al., 2014; Correia et al., 2010). The municipality has already been warned by the Public Prosecutor of Espírito Santo, the supervisory body for the implementation of the BSWP at the municipal level (AMUNES, 2014b). Another indirect financial impact related to the implementation of selective collection is a decrease in the materials discarded in sanitary landfills, resulting in a consequent increase in the landfills' useful life and decrease in their operational costs, according to Table 4.

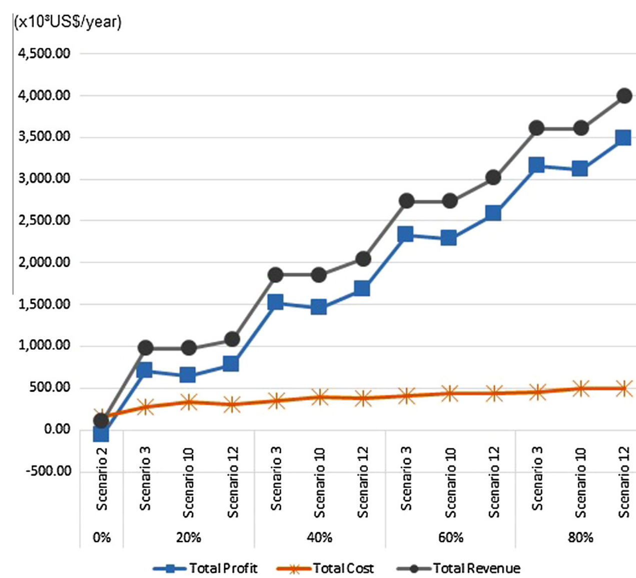

Fig. 6. Pattern of profit, revenue and cost (US$/year).

Table 3
Results for Scenarios 1, 2, 4, 5 and 6.

% SC[a]	Scenarios	Total profit (US$/year)	Total cost (US$/year)	Total revenue (US$/year)	Number of MRF_G	Number of MRF_R
0	Scenario 1	−78008.02	185263.83	107255.82	5	1
20	Scenario 2	695555.70	278720.39	974276.09	5	3
	Scenario 4	637277.36	336998.73	974276.09	5	7
	Scenario 5	372170.04	602106.05	974276.09	1	3
	Scenario 6	771519.14	300184.56	1071703.70	6	3
40	Scenario 2	1509265.23	342458.04	1851723.27	5	4
	Scenario 4	1460735.15	390988.12	1851723.27	5	7
	Scenario 5	1242513.42	609209.85	1851723.27	1	4
	Scenario 6	1667932.42	368963.18	2036895.60	5	5
60	Scenario 2	2328589.00	400587.77	2729176.77	5	6
	Scenario 4	2286238.77	442938.00	2729176.77	5	9
	Scenario 5	2093694.28	635482.49	2729176.77	1	6
	Scenario 6	2569535.72	432558.72	3002094.44	5	7
80	Scenario 2	3152404.13	454218.96	3606623.09	5	7
	Scenario 4	3117871.68	488751.41	3606623.09	5	10
	Scenario 5	2948836.81	657786.27	3606623.09	1	7
	Scenario 6	3471034.02	496251.38	3967285.40	5	8

[a] % SC means the percentage of effectively implemented selective collection.

Table 4
Percentage of reduction of MSW sent to the sanitary landfill.

% of Selective collection implemented	Total amount transported to the sanitary landfill (ton/year)	Amount recovered (ton/year)	Total amount generated (ton/year)	% Reduction[a]
0	40.09	2.17	42.26	5.42
20	37.52	4.74	42.26	1.81
40	34.96	7.30	42.26	18.20
60	32.40	9.86	42.26	24.60
80	29.84	12.42	42.26	30.99

[a] The calculation of the percentage reduction associated with selective collection was based on Scenario 1. For Scenario 1, the reduction was calculated considering the current situation of the municipality, in which there is no MRF.

Scenario 2, considered to be optimal for the compliance of the municipality with the legal requirements, and Scenario 6, considered to be optimal when a projected 10-year population increase is considered, differ by one facility at each stage of evolution (defined by percentage) of the segregation of the solid wastes through effectively implemented selective collection.

The amount of MSW_G collected decreases as selective collection is implemented because waste that can be recycled will not be sent to the landfill. The reduction percentage of sending this waste to the landfill due to the increase of selective collection can be seen in Table 4. In general, however, the number of open facilities is maintained, proving that MRF_G play an important role in the flow of MSW to sanitary landfills. Fig. 7 illustrates the proposal for the allocation of MRF_G and defines the coverage areas for each MRF for Scenarios 2, 4 and 6.

From Table 3, it is evident that the variation in the number of MRF_R required to make the system of collection, screening and sale of these materials feasible is greater than the variation in the number of open MRF_G. Thus, the correct allocation of these facilities leads to a reduction in MSWM costs and indicates the importance of the study of MSW reverse logistics networks made up of facilities that support selective collection. This is important to the extent that the solution proposed by the government of the state of Espírito Santo does not plan reverse consolidation points at the municipal level, only exchange stations in the region served by the sanitary landfill, which must be built according to public consortia solutions. This result shows that these MRF_R can make MSWM economically efficient, as its benefits compensate for the costs of its implementation.

Considering the increase in the population of São Mateus from 2014 to 2024 predicted in Scenario 6, a comparison can be made between the variations in the profit, costs and total revenues of this system relative to those in Scenario 2, which reflects the municipality's compliance with the BSWP. The MRF_R facilities opened at Project Araçá Association (Universitário neighbourhood) and Valdecir Association (Guriri neighbourhood) coexist in both scenarios. The opening of the facility Project Reciclar Association (Vitória neighbourhood) in Scenario 2 (Fig. 8) is not repeated in Scenario 6 (Fig. 9) (population projection), in which three other MRF_R are opened in Primo (Bonsucesso neighbourhood), Vila Nova and Ribeirão Associations.

Scenario 4 includes the opening of an MRF_R in all of the existing associations in the municipality, meeting Goal 6 set in the BSWP, which requires the inclusion and strengthening of waste pickers' organisations (Brazil, 2012). Therefore, considering the social

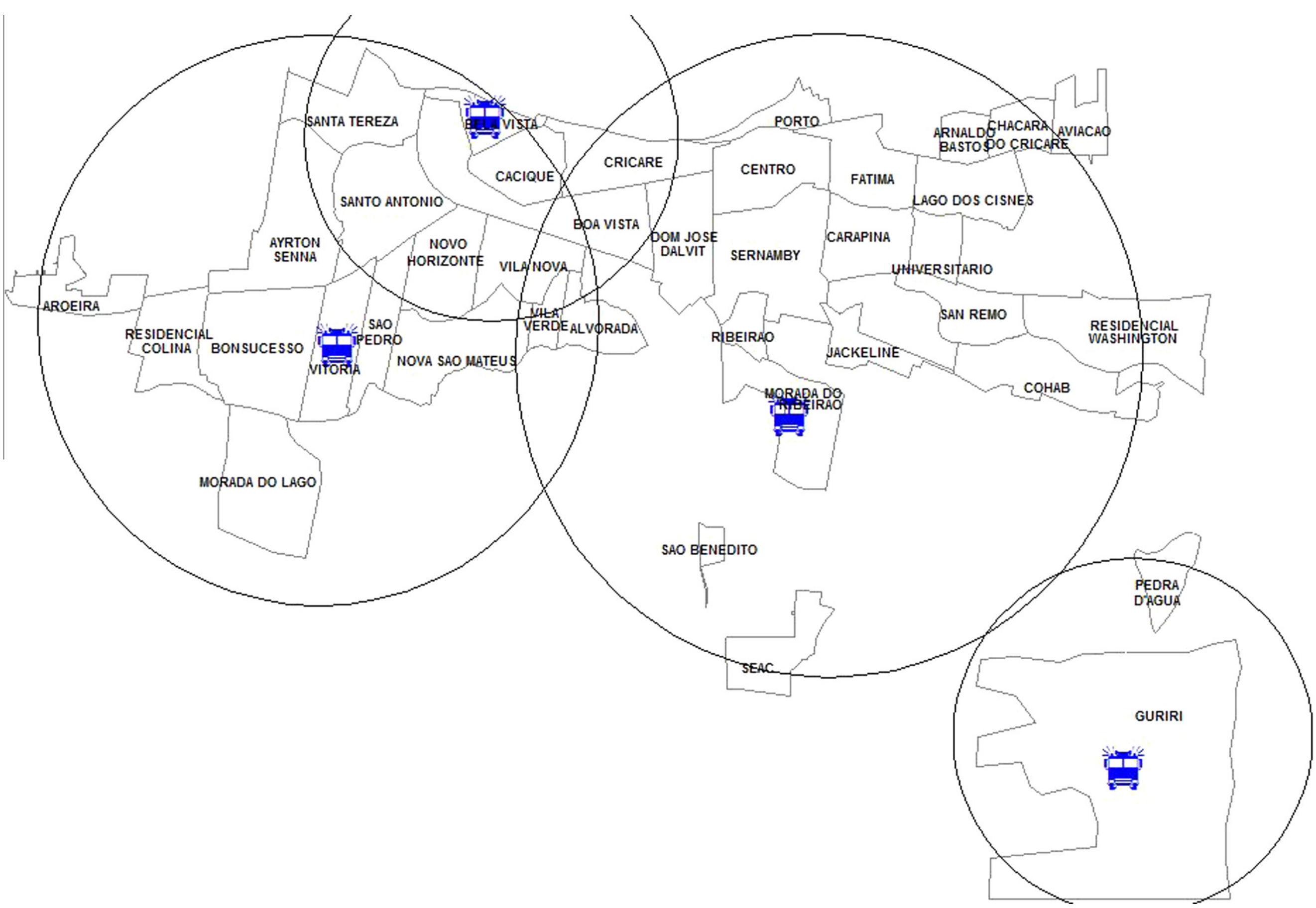

Fig. 7. Coverage area for each MRF_G for Scenarios 2 and 4 (for 20% MSW_R) and Scenario 6 (for 40% MSW_R).

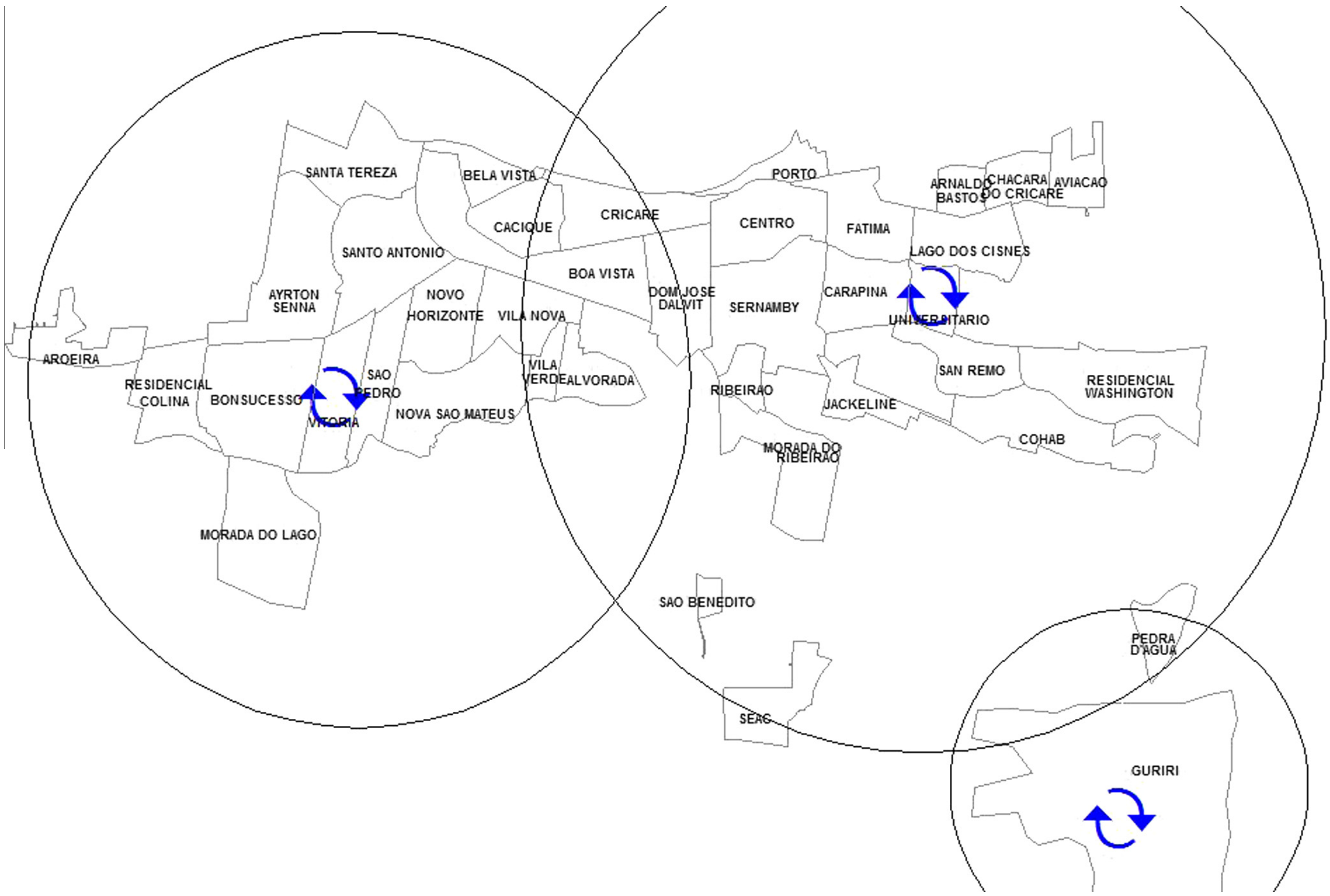

Fig. 8. Coverage area for each MRF_R for Scenario 2 (20% MSW_R).

benefit associated with Scenario 4, the difference between the costs for the implementation of this scenario compared to Scenario 2 becomes irrelevant, given that this solution would be prioritised in the decision-making process regarding the municipality's MSW reverse logistics network. Fig. 10 shows the placement of the MRF_G and MRF_R facilities for Scenario 4 with 20% MSW_R from a different representative manner which highlights the flow of MSW to the MRFs.

The decision-making process leading the selection of the scenario that is best suited to the municipality involves various other factors, including politics. The municipality of São Mateus has a project for the construction of a Municipal Exchange Centre near the border of the city. To implement 20% selective collection, Scenario 5 presents a total cost of implementation almost twice the total cost for Scenario 4 and more them twice Scenario 2. As the total revenue is the same for each level of selective collection, in this case of Scenario 5, the total profit of this solution is reduced.

The results show a geographical displacement with respect to the location of the MRFs. For the MRF_R, this pattern occurred more dramatically with the evolution of the percentage of MSW_R subject to selective collection and amongst the proposed scenarios. A displacement pattern similar to those observed in modelling the maximum coverage of p-medians is observed (Pereira, 2005). There is no correlation between the opening of the different types of MRF because there is no flow of materials between MRF_R and MRF_G.

Additionally, it was found that the variation between the numbers of allocated facilities proposed by Scenario 3 generates different optimal values. Thus, Table 5 presents an analysis of the sensitivity with respect to the total profit of the MSW reverse logistics network.

Scenario 3 is derived from Scenario 2 with 20% of MSW_R. Thus, the highlighted value, referring to the opening of five MRF_G and three MRF_R, represents the optimal solution for Scenario 2. Fig. 11 illustrates the saddle-type pattern of this objective function with the variation in the number of facilities opened for each type of waste. The value highlighted in Table 5 is the global maximum of this illustrated surface.

Considering that, for the Southeast Region, the percentage reduction goal for recyclable wastes disposed in landfills is 30% for 2015 and 42% for 2023 (Brazil, 2012), the results from Scenarios 2 and 4 for 20% selective collection approach viable solutions in the attempt to achieve this goal in a short-term with the proposed network were implemented to support selective collection. Scenario 6 is considered close to the 2023 goal, comprising the reuse of 40% of MSW. Although this study did not analyse the mandatory inclusion of all of the associations in the MSWM, this would be the best solution for the population projection in Scenario 6, as required by the BSWP. Thus, despite the variation between the current proposed scenarios and the future scenario, the use of the pre-existing associations of recyclable materials in the municipality as actors in the MSW reverse logistics network for the municipality of São Mateus is viable and essential to achieve an effective MSWM.

All of the scenarios represented by Figs. 7–10 include the opening of one MRF_G in Guriri neighbourhood and one MRF_R at the Valdecir Association, also in Guriri neighbourhood. This pattern is due to two factors: distance, as Guriri neighbourhood is approximately 15 km from the central area, differing from the others;

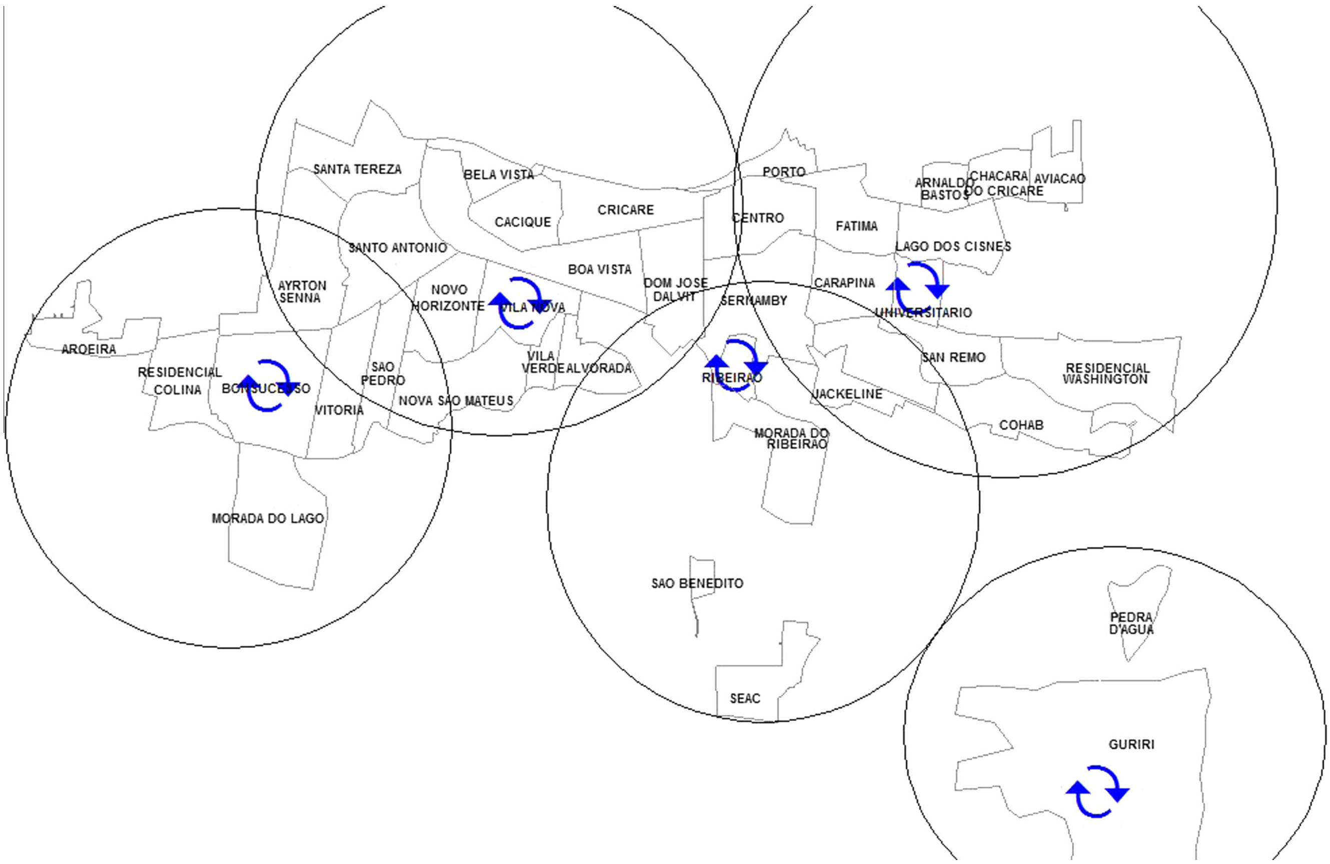

Fig. 9. Coverage area for each MRF_R for Scenario 6 (40% MSW_R).

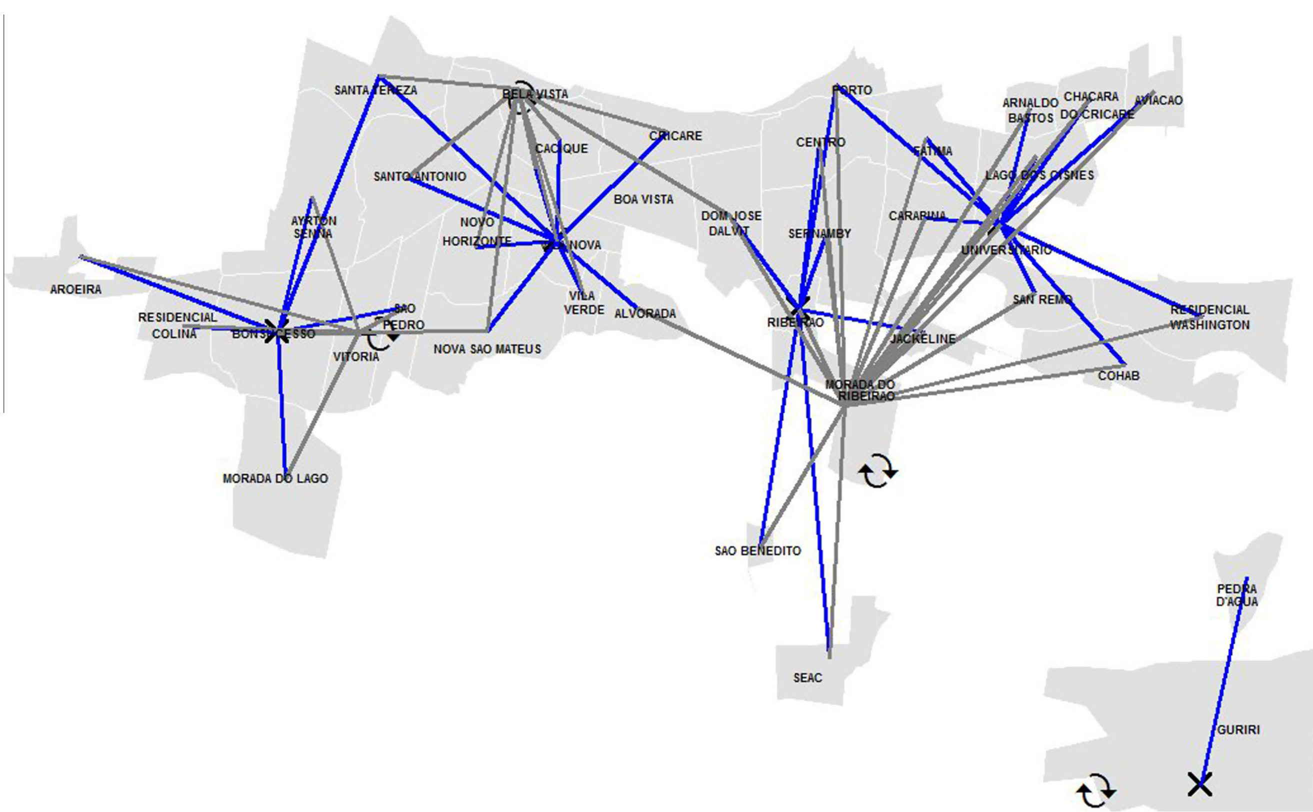

Fig. 10. Placement of the open facilities and their respective flows for Scenario 4 (20% MSW_R).

Table 5
Total profit 10^3 US$/year for Scenario 3.

	Total profit					
	1 MRF_R	2 MRF_R	3 MRF_R[a]	4 MRF_R	5 MRF_R	6 MRF_R
1 MRF_G	476.14	521.71	534.26	523.34	510.16	496.05
2 MRF_G	587.35	632.92	645.47	634.55	621.37	607.26
3 MRF_G	624.92	670.49	683.04	672.12	658.94	644.83
4 MRF_G	632.72	678.29	690.84	679.91	666.74	652.63
5 MRF_G	637.43	683.01	695.56	684.63	671.45	657.34
6 MRF_G	636.76	682.33	694.88	683.96	670.78	656.67

[a]The value highlighted represents the global maximum of the function.

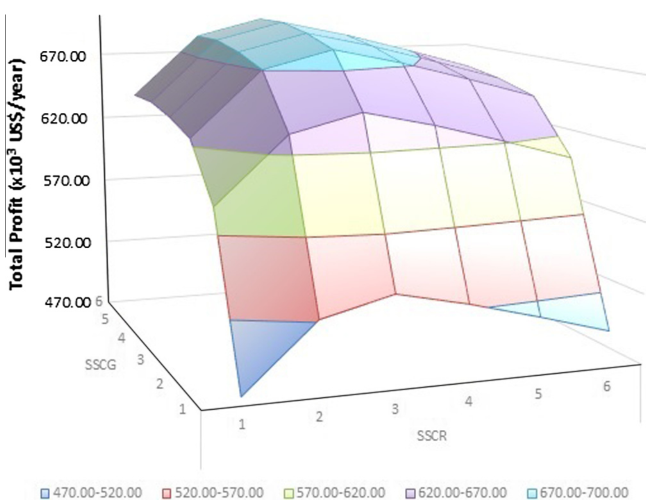

Fig. 11. Pattern of the objective function (maximisation of profit).

and the large population in this neighbourhood, which increases the potential for generation of MSW. These two factors directly affect the logistics costs of the solution. This shows the importance of MRF in minimising the logistics costs of MSWM.

6. Conclusions

This study proposes a model for a MSW reverse logistics network based on a generic mathematical modelling of facility location. The results show that the transport cost of the waste collected door-to-door to the transfer points are quite high. The MRF, intermediate structures proposed in this study, were able to minimise this cost, and allow the waste pickers to participate in the collection of MSW because there was a reduction in the movement area (or coverage area) of these actors, as a larger number of MRF geographically dispersed was proposed. The fixed costs of installation and operation of these MRF were balanced with the reduction of transport costs, allowing the generation of higher income over expenditure with the reverse logistics network.

This modelling approach can be adapted to propose a reverse logistics network for other materials, as well as to represent a logistics network with direct flows. A realistic characteristic of the model is that it allows a given generating location to send MSW to two different facilities. This characteristic directly affects the MSWM, making it possible to predict the quantity of MSW to be received by the MRF and consequently the set capacity for each facility.

The objective of maximising profit can be obtained by minimising the costs for transporting MSW and through the sale of recyclable residues. However, the MSW_R percentages are directly connected to the implementation of a programme of environmental education, on which this proposed MSW network is dependent on, that would support efficient selective collection.

After BSWP, generators are being encouraged to join the network by selective collection (Campos, 2014). For the first time in Brazil, environmental education programmes are being executed, unlike isolated actions as before BSWP. However, it is premature to accurately predict the impact of these programmes in the separation of waste, as they are quite incipient. So, we recognise that a limitation of this study is to consider the adherence of households in the separation of waste. Therefore, a gradual assessment of the accession to the selective collection was tested (20%, 40%, 60% and 80% of participation in selective collection of MSW).

The proposed network was validated for the São Mateus municipality case through the analysis of scenarios. It cannot be stated that one scenario is correct and that another one is incorrect. Instead, certain scenarios are more appropriate than others when considering important aspects of implementation, such as legal, social and economic factors involving the links of this network. This study analyses possibilities for the generation of revenue with the sale of recyclable materials and the total costs for transport, installation and operation of MRF that must be regulated by the government. The results support the hypotheses that recycling of MSW can be economically viable and that the use of MRF can be a potential source of revenue and a better use of MSW.

This study evidences the impact of the involvement of waste pickers in the costs of MSWM. Even with the inclusion of locations where waste pickers are already working with the sorting and storage process of MSW, the increase in the costs of reverse logistics network was unimportant. It was not measured the cost of social assistance programmes needed to ensure this active participation. However, the profit of the MSWM shown by the simulation collection of recyclable waste allows us to conclude that this initial investment in the inclusion of informal sector is recovered in the long term. The social benefits of this action, such as the reduction in expenses with government assistentialist actions also have not been evaluated. More specific studies to investigate other costs of this network are suggested.

We recognise that our proposed model does not consider all elements necessary for the SWM because this involves also institutional, social, financial, economic, technical, and environmental factors. But as stated by Ghiani et al. (2014), no model described in the literature is able to capture all different aspects to be considered and general models have so many variables and constraints that solving them through general-purpose solvers can be very hard and time-consuming.

This proposed network is a planning tool to verify the viability of the network with the inclusion of cooperatives and waste picker but it depends on other actions, such as effective environmental education programmes and selective collection, so that this network can achieve your goal. On the other hand, it is necessary also an effort by the municipal government to provide support for the inclusion of this waste pickers in the SWM process. There are disposals to join the network, but they need to recognise advantages and certainty to participate. In some municipalities in the state of Espírito Santo, where São Mateus is located, several cooperatives already have adhered to the jointly SWM, either through performing the selective collection or in the MRF operation (AMUNES, 2014b). As the public prosecutor has required this integration of the informal sector to MSWM in Brazil, we consider that this reverse logistics network can guide local government in meeting this requirement.

The contribution of this study lies, primarily, in the proposition of a reverse logistics network for MSW simultaneously involving legal, environmental, economic and social criteria, which is a very complex goal. Additionally, the proposed network involves all of

Please cite this article in press as: Ferri, G.L., et al. Reverse logistics network for municipal solid waste management: The inclusion of waste pickers as a Brazilian legal requirement. Waste Management (2015), http://dx.doi.org/10.1016/j.wasman.2015.02.036

the links that are included in the MSWM, that is, the potential waste generators, MRF, sanitary landfills, recycling companies, incinerators and intermediates. The inclusion of waste pickers in the reverse logistics network occurred by considering the associations as potential MRF. Therefore, in addition to the theoretical contribution to the reverse logistics network problem, this study aids in decision making for public managers that have limited technical and administrative capacities for the management of solid wastes.

The results of this study can be used by public managers, as they provide information that aids in decision-making process with regard to the location and capacity ranges of MRF integrated into the selective collection and management of MSW in a manner integrated with social projects involving waste pickers. It is noteworthy that this formal integration of waste pickers to MSWM has been a challenge in Brazil. Although the model incorporates specificities of the municipality of São Mateus, Brazil, this study can be useful to other researchers and managers because the approach can be extended to other sectors or regions.

Although the study was tested to the reality of a Brazilian municipality, as outlined in Subsection 2.1, the challenge of integrating the informal sector to the SWM is also a reality in other developing countries. Therefore, these countries, whose legal framework to deal with this sudden increase of solid waste in cities that quickly increased their populations is recent and has to deal with the presence of waste pickers, can also benefit from this support tool for planning MSW. Since the BSWP was prepared to meet the objectives of Agenda 21, it may be inferred that the present proposal is in agreement with a much broader global policy connected to the precepts of sustainability. This study can guide practices in other countries that have realities similar to those in Brazil of accelerated urbanisation without adequate planning for solid waste management, added to the strong presence of waste pickers who, through the characteristic of social vulnerability, must be included in the system.

The data used for our analysis are adjusted on the Brazilian situation, and therefore results should apply more precisely to the Brazilian cases. While the assumptions concerning urban structure and MSW composition may be specific to the context analysed, the reverse logistics network model is largely independent from that, despite some differences that are country-specific, so as to allow some generalisation of results at least to the developing countries context.

Despite the limitation of having evaluated only one municipality, it is worth emphasising the flexibility of the mathematical model and scenarios used, which can be subjected to alterations whenever necessary, as the volume and characteristics of wastes are in constant changes. This flexibility was implemented for the case of incineration, for example. For future studies, the expansion of the model for the factor of time is suggested, which would make the model more complete and dynamic, but would still represent the reality of MSW management in the studied region.

Although the analysis of scenarios simulates a reality that does not yet exist in the municipality, it is emphasised that the factors involved in the proposal of this reverse logistics network meet all the precepts for economic efficiency and environmental adequacy for a municipal solid waste policy, with the inclusion of waste pickers as required by the BSWP.

Operationally, urban sanitation services, solid waste collection, sweeping and processing facilities management are commonly performed by local government indirectly, being outsourced by granting the service to private companies contracted for this purpose. While outsourcing of urban cleaning services represents a more convenient mechanism for the government, it should be noted a significant questioning that this process gives the implementation of selective collection and shared solid waste management programmes. In general, the subcontractors are paid according to the weight and the volume of collected municipal waste. This form of contracting offers an incentive scheme contrary to waste reduction at the source. In addition, the sorting of recyclable requires the preservation of the collected material, which implies higher transport costs for businesses, as the use of compactor trucks is not recommended for this (IPEA, 2013).

It is noticed that the organisational structure of the recycling chain is very complex, which makes it extremely difficult to establish a single practice to strengthen their industry and for the coordination of selective collection programmes. For this, we must consider the various actors involved in one or more steps of the process of value creation. Additional studies to assess issues relating to the integration of the different actors working in MSWM, often with different objectives and sometimes conflicting, are suggested to qualitatively evaluating the feasibility of MSW networks.

Acknowledgements

This research was partly supported by the National Council for Scientific and Technological Development – CNPq and the Espírito Santo Research Foundation – FAPES. This support is gratefully acknowledged. The authors thank to the three anonymous referees for their valuable comments.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.wasman.2015.02.036.

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Please cite this article in press as: Ferri, G.L., et al. Reverse logistics network for municipal solid waste management: The inclusion of waste pickers as a Brazilian legal requirement. Waste Management (2015), http://dx.doi.org/10.1016/j.wasman.2015.02.036