Research Challenges in Municipal Solid Waste Logistics Management

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Abstract

During the last two decades, EU legislation has put increasing pressure on member countries to achieve specified recycling targets for municipal household waste. These targets can be obtained in various ways choosing collection methods, separation methods, decentral or central logistic systems etc. This paper compares municipal solid waste (MSW) management practices in various EU countries to identify the characteristics and key issues from a waste management and reverse logistics point of view. Further, we investigate literature on modelling municipal solid waste logistics in general. Comparing issues addressed in literature with the identified issues in practice result in a research agenda for modelling municipal solid waste logistics in Europe. We conclude that waste recycling is a multi-disciplinary problem that needs to be considered at different decision levels simultaneously. A holistic view and taking into account the characteristics of different waste types are necessary when modelling a reverse supply chain for MSW recycling.

Key Words:

Household waste, recycling, reverse logistics, sustainability, review, modelling

1. Introduction

Municipal solid waste (MSW) logistics management is necessary to take care of the growing stream of waste and the need to reuse non-renewable resources. Despite of much legislation and public attention, in 2012 7% of waste in Europe was still landfilled (EUROSTAT 2015). Recycling is among the most common waste treatment options that has the potential for further improvement in Europe. Increased recycling leads to lower environmental impact, lower consumption of energy sources and lower economic costs (Eriksson et al. 2005). There are large differences between countries in terms of their practice and performance in MSW recycling. The statistics from EUROSTAT (2015) show the highest rates for recycling in Germany (64%), Austria (58%), and Belgium (55%). Conversely, collection and recycling are still in their infancy in the new EU Member States with landfill rates ranging between 82% (Estonia) and 98% (Bulgaria). On EU average, still more than 40% of waste going into landfill indicates a potential and need to improve the recycling of MSW.

Municipal solid waste recycling is part of the field of reverse logistics ; the logistics activities all the way from used products no longer required by the user to products again usable in a market (Fleischmann et al., 1997) . It includes strategic and tactical decisions such as logistics network design and collection design. Dealing with all of these aspects is an increasingly complex task that can be supported by Operations Research techniques. Ghiani et al. (2014) give a survey on Operations Research models in strategic and tactical solid waste management. Strategic issues have been modelled using location models taking into account single or multiple periods, single or multiple objectives and uncertainty. Tactical issues have been modelled using flow allocation models, collection models and fleet composition models. However, it is unclear if the available models can cope with key issues in practice, such as the impact of taxations and different recycling targets. Therefore, the objective of this paper is to identify research opportunities for modelling MSW recycling in Europe with a focus on Operations Research models.

2. Research Design

2.1 Research Methodology

We conduct this research using a three-step approach. In the first step, using literature, we identify a general research framework comprising the drivers, the strategic and tactical/operational topics for analysing municipal waste management (section 2.2). The second step is analysing and identifying issues in real life waste management in Europe that need to be addressed (section 3). These issues have a major impact on the performance of the recycling system or show large differences in the practice of various countries. These findings are successively brought together in the research framework. The third step, using the framework, is to survey Operations Research literature on municipal waste management to analyse and evaluate issues that have been addressed and the modelling methods used to address them (Section 4). The research framework is used to categorise the literature review findings and identify major research opportunities for modelling MSW recycling.

2.2 Research Framework

Decisions in MSW management can typically be classified into three levels: strategic, tactical and operational. The combined decisions at inter-related levels are often too complex to be solved at once. A common approach is to cut the total decision making problem into several sub-problems at each level, called decomposition. Ghiani et al. (2014) stated that for planning purpose, a waste management system can be decomposed into two major sub-systems: a regional waste management system, and a collection system. Rubio et al. (2008) suggest examining the design of the reverse logistics network, the analysis of transport routes and internal logistics. Reverse logistics network design belongs to the regional management system which is at the strategic level. Collection planning, transport routes and internal logistics related issues are part of the tactical and operational levels. Accordingly, we partition the decision making into two levels as presented in Figure 1.

Externally, there are drivers and incentives that can influence decision making on the reverse logistics network and processes. Dekker et al. (2004) identified three main drivers that influence reverse logistics, which are economics, legislation and extended responsibility (public, social and economic). From macro-environmental angle, the well-known PESTEL analysis has also identified Political, Economic, Social, Technological, Ecological and Legal factors as key to guide strategic decision-making (Law, 2009). In section 3 specific key external factors for municipal waste recycling will be identified.

Despite the obvious environmental gain from waste recycling, collection and transportation of recovered products have an environmental burden due to greenhouse gas emissions. Minimizing this burden is important in order to increase the total environmental gain from recovery (Tsoulfas and Pappis, 2006). The fast evolution of sustainable development changes the goals in almost every supply chain including reverse logistics for waste management. Sustainable development deals with balancing between ecological, economic and social impacts at the level of society in the long term (Seuring and Muller, 2008). This means that it stresses the importance of key issues closely related to human welfare and the natural environment. To meet the future demand of sustainable development, the output of the decision making on municipal solid waste management is a sustainable performance (see Figure 1).

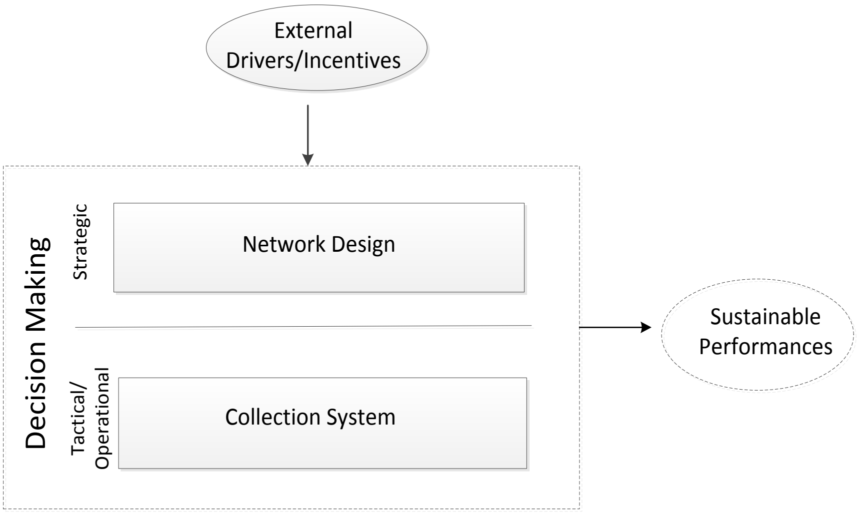

Figure 1: Framework of reverse logistics for household waste recycling

The complexity of waste recycling decisions is determined by external factors, such as EU regulation, rising oil prices, dynamic costs and varying interests of householders, collection companies and municipalities. In order to improve the sustainability of the complex recyling system of household waste, insights into the system is required. Ghiani et al. (2014) states a waste management system can be decomposed into two major sub-systems, (i) a regional waste management system dealing with strategic decisions in network design (e.g. investments for recovery facilities) and (ii) a municipal collection system dealing with tactical and operational decisions such as transport routes and waste flow allocation. Somplak et al. (2014) mention the impact of landfill and incineration tax on the waste flow in a MSW managing system. . In the following section we expand the structure by adding the identified issues derived from the review of recycling practices in various countries. The explicit external factors, the issues to be addressed in the decision process at different levels, as well as the key sustainable performance indicators in the municipal solid waste recycling context will be analysed.

3. Waste recycling practices in Europe

Countries have been chosen based on a combination of two criteria: (i) they vary substantially in their recycling practices and (ii) they have recycling as a substantial waste handling strategy, apart from composting and landfilling. Information on recycling strategies, practices and their performances have been obtained using a triangulation of materials, i.e. (i) Scientific and industrial publications related to waste collection in the countries of interest; Bing et al. (2012) for the Netherlands; Wong (2010) for the UK; Ramos and Oliveira (2011) and Ramos et al. (2014[a], 2014b) and EIMPack (2011) for Portugal and Spain, (ii) Industrial reports: INE (2012), SPV (2011), REA (2011) and APA (2012) for Portugal; ; ; DEFRA (2012) for the UK and Nedvang (2012) for the Netherlands), and publications of EU and national organizations (EU 2012; WRAP 2012) and (iii) Interviews with industry partners and field visits to the waste collection and processing facilities. From these sources the following countries appeared to be interesting according to criterium (i): the Netherlands, Germany, Sweden, UK, Spain and Portugal. Using Eurostat information (2015), these countries also fit criterion (ii): the Netherlands (50%), Germany (65%), Sweden (49%), UK (44%), Spain (30%) and Portugal (26%). Combining the variance in recycling percentages with the variance in recycling practices can explain the differences in waste management in EU countries.

Following the framework we compare the practices in various countries in three parts: (i) the external factors, (ii) strategic and (iii) tactical/operational decision levels. A discussion on what sustainable performance is all about is embedded in each part. For the external factors, an overview of EU regulations is presented, followed by a discussion of incentives as external drivers and actors strategy regarding environmental impact control. At the strategic decision level, the recycling procedures of various waste types and recycling network characteristics are reviewed. At the tactical/operational level an emphasis is given to collection planning. This section ends with a summary of identified issues from practice.

3.1 External Factors

EU regulation on waste treatment is the main driver that puts increasing pressure on member countries to transfer landfilling into recycling and re-use. The European Union Landfill Directive of 1999 was introduced to encourage the diversion of waste treatment away from landfilling. Each Member State is required to build its own disposal capacities by the establishment of a system of national treatment facilities. The European Commission has also defined several specific 'waste streams' for priority attention (packaging waste, end-of-life vehicles, batteries, electrical and electronic waste, etc.), EU Directive 2008/98/EC specified that by 2020, the preparation for reuse and recycling of municipal solid waste shall be increased to a minimum of 50% by weight (EU 2012). The directive not only sets the target for waste recycling, but also specifies the requirements for recycling network design. EU Directive 2008/98/EC states the recycling network shall be designed such that the member states become self-sufficient in waste disposal and recovery, while taking into account geographical circumstances or the need for specialised installations for certain types of waste. It specifies the capacity of the recycling network together with the geographical location of facilities.

To meet the targets set by the regulations, taxation is commonly used as an incentive in many countries for promoting waste recycling and covering the cost of waste collection and treatments. In the Netherlands, to attain a higher recycling rate, a so-called differentiated tariff system (DIFTAR) is used to distinguish the separated and non-separated waste by the tax which householders should pay (10 euros for 240 litre mixed waste versus 2 euros for 240 litre green waste, DIFTAR,2015). Several Swedish municipalities have also introduced a waste management fee based on weight which means that the households pay a charge per kg of waste collected (varying from SEK1.40-3.93 per kg), on top of the basic fee of SEK 313 per person (Avfallsverige, 2014). Germany and Norway have a similar special tax for the waste based on weight/volume of waste. In the UK, commonly, households pay a council tax to the local authority and the tax is used to cover a lot of services including schools, police, street light, and waste/recycling collection (Abbott et al. 2011). There is no special tax for the waste or calculation of tax based on weight/volume of waste (Kipperberg 2007).

Apart from the incentive to push recyclable waste into the recycling channel, demand for recycled materials drives the market. The price paid for recycled materials is very important for the competitiveness of recycling initiatives.. Data from EUROSTAT COMEXT (2015) show that prices of recyclates have varied significantly over time. For example, the price for plastic waste has fluctuated from 250€ /tonne in 2004 to above 350€ in 2008, 230€ in 2009 (financial crisis), to 370€ in 2013. In recent years, an argument on whether exporting waste from Europe to be recycled partly in the Far East should be allowed has raised quite some public attention. On one hand, from an ethical point of view, the social conditions in the Far East are not comparable to European standards and companies can hardly comply with European social standards and working security (Pro-Europe, 2009). On the other hand, waste can be shipped using empty containers, due to the imbalance of trade between Far East countries like China and the European Union. Besides, waste recycling should be operated in a free market and systems are free to choose which end market best suits their needs in terms of price and quality depending on material demand (Pro-Europe 2009).

3.2 Network Design

At the strategic level, decisions are made at the network design of a recycling network which includes the process of collection, separation, sorting and re-processing. We only take into account recycling procedures, thus no remanufacturing procedure for chemistry or electronic products (e.g. batteries, household appliances) are taken into account.

In some cases, the separation of the recyclable waste (paper, metal, plastic, etc.) from other waste is done at the collection point, while in other cases the waste is collected and sent to a separation center for this procedure. After separation, the waste is normally sent to a sorting center, where the further sorting of the material by colour and/or composition is conducted. Cross-docking centers are locations where trans-shipment and baling of waste is done. The sorted waste will be transferred to specialized treatment facilities to be re-melted or transformed for recycling (See Figure 2).

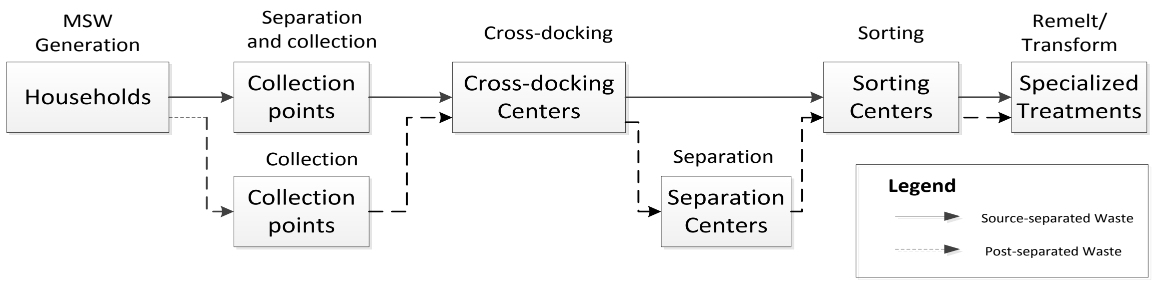

Figure 2: The recycling network flow of municipal solid waste

In practice, separation and sorting processes might take place in different stages for different recyclables. Specifically, the details of some major recyclable waste types regarding the recycling practices in various countries are summarized in Table 1. In the Netherlands (NL), separation and sorting of glass happen all at the collection point. Glass is sorted by color and put in separate containers (often underground containers). Paper is separated at the collection point for a lot of countries such as Sweden (SE), Germany (GE) and Belgium (BE) while aluminium is normally separated in separation centers in countries like Sweden, UK and the Netherlands. For plastics, separation centers exist in the UK, the Netherlands and Portugal (PT).

Table 1: Variation in stages where processes take place in the recycling network in various countries

	Processes	
	Separation	**Sorting**
Collection Point	paper (SE, GE, BE) glass (NL) plastic (UK, NL)	glass (NL)
Separation Center	aluminium (SE, UK, NL) plastic (UK, NL, PT)	

Different waste types go through different treatment processes in the network due to technological variations in the recycling procedure. The network structure to be designed needs to account for these specificities. The capacity and location of facilities also differ. Countries like Germany, UK and Portugal have their domestic material recovery facilities (sorting and other treatments), while small countries like the Netherlands have most of the sorting process done in the facilities of neighbouring countries. Reprocessing, as the specialized treatment for each material, is normally done in facilities all over Europe. For example, the plastic, after sorting to different types and grades in the Netherlands, is sent to specified facilities located in various European countries for further treatment. Some of these materials are exported overseas. Therefore, the recycling network of MSW is in general geographically dispersed from local to global.

The capacity of the processing facilities (separating, sorting, etc.) in various countries also differs. Some facilities in countries with relatively more developed waste recycling system and advanced technology have a problem of over-capacity. UK is at risk of heavily over-investing in residual waste treatment infrastructure. If all of the facilities with planning consent are to be built, UK will have 5 million tonnes more capacity than it requires (Waste Management World 2012). Countries like Germany and Sweden have already a problem with over-capacity, mostly in the sorting plants. To make use of the existing capacity and improve the overall recycling rate to meet the EU recycling target, countries are also cooperating in waste recycling. An incineration plant in Rotterdam, the Netherlands, is planning to process the waste shipped from Naples, Italy. The waste would have been sent to landfill in Italy, but is now going to be converted to energy, saving approximately 160 kg CO_2 emission per tonne of waste (Van Gansewinkel Groep 2012).

To improve the sustainable performance of the recycling network, some countries with good railway and waterway infrastructures have initiated the practice of multi-modal transportation between facilities both domestically and between countries in Europe. For example, in 2004, 172.500 tons of waste was transported by inland waterway in Liege, Belgium, among which 133.000 tons shipped by lorry and 39.500 tons by barge (MONAMI 2005).

3.3 Collection planning

The main issues at the collection planning level are the types of waste to be collected, the organization of collection and the vehicles used. There are in general two types of collection locations for municipal solid waste, either at curbside (curbside collection) or at central collection points where householders have to bring their waste to (drop-off collection). In Spain, mixed waste is usually collected in curbside bins and paper/cardboard, glass and lightweight packaging are deposited at drop-off points (Gallardo et al. 2010). Regarding the collection method, UK municipalities practice three common schemes: i) Curbside-Sort: the recyclables are separated at curbside into different compartments of a specialist collection vehicle ii) Single stream co-mingled: involves the collection of materials in a single compartment vehicle with the sorting of these materials occurring at a MRF (Materials Recovery Facility) and iii) Two-stream co-mingled: householders are provided with two recycling containers and are asked to place different materials in each container, typically paper/card (fibre) in one and plastics, glass and cans (containers) in the other. These materials are kept separate but collected in one vehicle which has two chambers.

The organization of waste collection is often done by municipalities. In the Netherlands, each municipality is responsible for organizing its own waste collection. Some neighbouring municipalities may share the service of the same collection company. In Portugal, the selective collection and sorting of packaging waste are performed by the municipal waste collection companies, so called SMAUTs. There are two types of SMAUTs: (1) municipal and inter-municipal and (2) multi-municipal. Usually, SMAUTs have more than one depot and the municipalities boundaries are respected when defining depot’s service areas and the collection routes.

Different type of vehicles are used in the collection step. Trucks with a pressing function are commonly used in countries like NL, UK, Germany and Portugal. In Portugal, they are used to collect Paper/Cardboard or Plastics/Metal. With pressing function, the vehicle capacity increases about 150% to 200% compared to vehicles without pressing function. In the curbside system, a rear loaded truck is used while the drop-off containers are mainly collected by a top loaded truck, with a single compartment and with no pressing function. However, there are some SMAUTs that have multiple compartment trucks, where Paper/Cardboard and Plastic/Metals are collected together. In Sweden, some collection vehicles are equipped with vacuum pipes to avoid heavy lifting (Afvall Sverige 2014). The same type of vehicles can be used in different collection method for different waste types. In the Netherlands, for example, curbside collection of plastics is conducted by the same truck that collects other waste types. This means that when the truck is used for collecting light weighted waste types, it is less efficiently used. In Portugal, the vehicles used for the curbside collection of Paper/Cardboard and Plastic/Metal are the same as the ones used for the undifferentiated waste.

In the near future, countries will continue aiming for improved efficiency of waste recycling. Some efforts can be made on the collection phase in order to improve the collection efficiency. For example, Portugal aims to increase the curbside collection in urban areas since the amount collected and the quality (low percentage of contaminants) are higher in such a system than in the drop-off system. Moreover, possible synergies and economies of scale are still to be explored further. The Netherlands will combine the separately collected PET bottles (through deposit refund system) with the normal plastic waste to improve the collection efficiency and reduce cost. For the same purpose, efforts are made to optimize routes and decrease the collection frequency in order to collect containers with a high landfill rate. In Portugal, the number of SMAUTs tends to decrease such that collection can be further aggregated.

Additionally, to collect waste in a more sustainable manner, collection companies search for solutions of alternative vehicles. Hybrid trucks start to be applied in waste collection. In 2008, the first hybrid waste collection truck was launched in Gothenburg, Sweden. The advantage of such trucks is in curbside collection, where idling, loading and compacting the waste takes most of the operating time of collection trucks (Helming 2009).

3.4 Summary of identified issues

To summarize, externally driven by the regulations, EU member countries are improving their municipal solid waste recycling towards a more efficient and sustainable direction. By using taxation as an important incentive, waste recycling is promoted in various countries. The reference indicator, to which tax is charged, however, differs in countries. EU regulations also indicate treatment of different waste types according to their specific need in terms of facility and technology needed. The price measurements and valorisation of recycled waste, taking into consideration the demand from the market needs more attention. Therefore, we summarize the external issues derived from the review as: 1) differentiated taxation, 2) differentiated recycling targets, 3) increased recycling targets, and 4) lack of valorisation of recycled waste.

At the strategic decision level, the major differences in the recycling networks are related to where the various materials are separated and sorted. The locations of intermediate facilities (separation, sorting) as well as the quantity and capacities of these facilities differ amongst the different countries in Europe. Due to the composition of municipal solid waste as a mix of materials with diverted characteristics, the recycling network for each material is different, in terms of structure and functionality in various stages. Therefore, it is a multi-commodity problem and the associated network design should be able to fit the specified requirement of each material and handle the different materials together. Locations and capacities of processing plants in different countries also differ a lot. In terms of strategy for improving sustainable performance, the multi-modality transport started to be used in practice for the transportation for waste. Therefore, we summarize the issues from strategic level derived from the review as: 1) facilitate multi-commodity, 2) variability in network configuration 3) facility capacity plan, 4) facility location choice, and 5) sustainable recycling network (e.g. facilitate multi-modality).

With respect to collection practices, the major differences are at the organizing unit of the collection, the allocation of waste types to curbside or drop-off collection points and the type of trucks used. The organizing unit of collection can affect the routing design as well as the collection schedule. The separation method together with the allocation of waste collection locations (which waste types to be put where for collection) are among the important factors that decide which truck types are to be used for collection. Besides, collection trucks with multiple or single compartments can make a difference in the routing and scheduling of waste collection. Therefore, we summarize the issues from operational/tactical level derived from the review as: 1) collection method, 2) collection coordination, 3) collection scheduling, 4) capacity planning (vehicle and bin), 5) vehicle routing, and 6) attention for sustainable collection.

Essentially, municipal solid waste recycling outputs are the recycled materials, together with the emissions of all the processes and transportation and the total cost involved. Thus, the aim of decision making is to deliver a sustainable performance measured by cost, environmental impact and societal impact. The above issues derived from the comparison of recycling practices in various countries will be presented in section 5, but first section 4 identifies issues addressed by modelling waste management problems.

4 Municipal solid waste management models

The search process was carried out with the scientific-technical bibliographic databases Web of Science and Science Direct. We conducted the search by combining the key words of waste recycling (i.e. municipal solid waste, recycling, municipal solid waste) with the three elements of the research framework (network design, collection and routing, sustainability). As the focus is on modelling approaches the scope of the search is set to modelling methods used in Operations Research and Supply Chain Management literature applied to waste management. The most relevant scientific papers of the last 15 years are selected and reviewed in this section.

Apart from specific papers on modelling waste management issues, reviews have been written on sustainable forward supply chains (Brandenburg et al, 2014; Seuring 2013) and sustainable closed loop supply chains (e.g. Fleischmann et al., 1997; Rubio et al. 2008). These reviews will not be discussed here. Govindan et al. (2015) review 382 papers related to reverse logistics and closed-loop supply chain published between 2007 and 2013. Agrawal et al. (2015) provide a literature review in Reverse Logistics, selecting 242 published articles. About 40% of these papers relate to Reverse Logistics networks from secondary markets.

Network design is one of the important strategic issues which may have long term impact on the performance of reverse logistics (section 4.1).

4.1 Network design

The characteristics of a reverse logistics network for waste recycling determine its network configuration. Regarding the network structure, most of reverse logistics networks have a convergent network structure instead of a divergent structure (Fleischmann et al. 1997). Mitropoulos et al. (2009) study the simultaneous design of a distribution network for solid waste with central treatment facilities, transfer stations and sanitary landfills. McLeod and Cherrett (2011) identified the channel structure as the difference between reverse logistics of waste and other return goods. Intermediate points often exist in the reverse supply chain for the consolidation of waste which could be at regional distribution centers, transfer stations, or other locations, before transportation to the final disposal site. Bing et al. (2012) further identified that the availability of intermediate processing plants as the key factor which decides the performances of various channels for collecting the same type of waste, based on a case study on plastic waste recycling. Alshamsi and Diabat (2015) develop a mixed integer linear programming model to select optimal locations for inspection centers and remanufacturing plants with different transportation options to deliver the products across the reverse supply chain.

Quite some research in reverse logistics network design provide decision support for processing capacity design and location allocation problems. The convergent structure from many sources to a few demand locations is also considered in such models. Many studies are conducted with respect to product recall or end-of-use returns. In recycling logistics models, Barros et al. (1998) modelled the network construction for sand waste recycling in the Netherlands. The model determined the optimal number, capacities, and locations of the depots and cleaning facilities. Louwers et al. (1999) designed a recycling network for carpet waste. They proposed a location-allocation model for the collection, pre-processing and re-distribution of carpet waste. Huang et al. (2002) introduces an interval fuzzy capacity expansion integer programming model for the decision support of waste recycling facility capacity expansion. Gomes et al. (2011) modelled the WEEE (Waste Electrical and Electronic Equipment) Portuguese recovery network. A MILP model is proposed where the best locations for collection and sorting centres are chosen simultaneously with network planning. The multiple recycling processes have been taken into account in these models and problems such as location allocation and capacity design have been studied as well. Somplak et al. (2014) introduce a tool for conceptual planning of new waste-to-energy capacities enabling to implement waste management policies through legislation amendments.

Municipal solid waste consists of various waste types, which make the network design also a multi-commodity problem. Lots of studies have been conducted on multi-commodity networks since Geoffrion and Graves (1974), among others, introduced a multi-commodity logistics network model for optimizing product flows. Studying multi-commodity networks in a reverse supply chain setting is relatively new. Ko and Evans (2007) developed a multi-commodity network model that handles forward and reverse flows simultaneously, however not in the context of a reverse supply chain for waste recycling. The specialty of the multi-commodity problem in waste recycling is the process of waste separation throughout the process steps in the chain. This waste separation is similar to a process of product disassembly. Disassembly is a systematic method of separating a product into its constituent parts, components, subassemblies or other groupings (Taleb and Gupta 1997). Waste separation means one “commodity” of mixed waste will be separated to several “commodities” after the process of separation or sorting. Compared to the process of disassembling, the separation of waste materials, as waste is a loose mix, is more dynamic and stochastic than the disassembling process in which components of the objects are fixed (e.g. old cars). The separation will have an impact on the particular distribution channel choice. The point where separation happens could have an impact on the overall performance of the network. Bing et al. (2012) studied such a multi-commodity network for the case of plastic recycling, in which the locations of separation points in the network is analysed.

Regarding the key performances of a supply chain, a lot of recent research has been devoted to improve sustainability in supply chain management, although hardly applied to waste management. Tralhao et al. (2010) describes a multi-objective modelling approach to locate multi-compartment containers for urban-sorted waste. Ramos et al. (2014b) combined a social objective with environmental and economic objective in modelling reverse logistics systems. Lopes Ferri et al. (2015) propose a reverse logistics network involved in the management of MSW to solve the challenge of economically managing these wastes considering the recent legal requirements of Brazilian Waste Management Policy. This study simultaneously involves legal, environmental, economic and social criteria.

To summarize, key issues addressed in network modeling of waste recycling are 1) channel choice (Curb-side or drop-off collection) 2) Network structure 3) Capacity design of facilities 4) Location of recovery facility and transportation links 5) Handle different composition of waste 6) Multi-modality strategy 7) Balance emission and economic concerns.

4.2 Collection planning

When dealing with waste collection, different practices are observed leading to different problems. To solve such problems several approaches have been proposed in the literature where diverse variations of routing problems have been analysed. In particular existing approaches have explored important aspects such as type of collection, number of waste streams collected; collection frequencies and dynamic characteristics of the problems.

MSW collection typically originates from two different routing modelling approaches, an arc-routing or a node-routing approach. At the curbside collection, the problem is frequently modelled as an arc-routing problem, where all arcs in a graph have to be visited so as to allow waste collection in every street of a city. Mora et al. (2013) formulated a waste collection vehicle routing problem as a capacitated arc routing problem (CARP) and proposed a heuristic procedure to solve it. This was applied to the solid waste management in the city of Reggio Emilia (Italy). A waste collection problem was also modelled as an arc-routing problem in the work of Amponsah and Salhi (2004) where characteristics of developing countries were considered. Bautista et al. (2008) also proposed a model for the mixed CARP with turn constraints, where the collection routes take into account forbidden turns due to streets junctions and traffic signals (Spain). On the other hand, at the drop-off collection, all the central spots have to be visited by the vehicle, thus the problem is modelled as a node-routing problem with demand occurs at the nodes. Examples of real-life waste collection problems modelled as a node-routing approach can be found in Baptista et al. (2002) where the collection of recycling paper containers in Almada municipality (Portugal) is solved by a heuristic procedure. Nuortio et al. (2006) develop a guided variable neighbourhood thresholding metaheuristic to solve the mixed waste collection of 3386 bins in Eastern Finland and Karadimas et al. (2007) designs optimal routes by an ant colony algorithm for the MSW collection for the Athens municipality (Greece).

For waste collection systems, one important point to consider is the number of waste streams that are collected in the same route. To deal with this, the problem can be modelled as the classical Capacitated Vehicle Routing Problem (CVRP), where each stream is collected in separated routes (separate collection) or as the Multi-Compartment Vehicle Routing Problem

(MCVRP), where two or more streams are collected simultaneously without commingling them (co-collection). While the CVRP is a widely studied problem and several models have been proposed in the literature (see (Golden, et al. 2008) or (Laporte 2009) for recent surveys), the MCVRP had received limited attention. Muyldermans and Pang (2010) have proposed a local search procedure for the MCVRP and investigate the benefits of co-collection over separate collection based on literature instances. The authors conclude that the improvement over separate collection increases due to different factors. They also point out that imbalances in commodities demand reduce the benefits from co-collection. This brings extra challenges in how the vehicle capacity should be partitioned by the compartments and when each site should be visited since waste streams have different containers' fulfilling rates.

Another feature of the municipal solid waste collection is the variation in collection frequencies from site to site. For instance, in the same network some sites may be visited every day while others may be visited twice a week or three times a week, and so on. This problem is modelled as a Periodic Vehicle Routing Problem (PVRP) since decisions relate to the day when each site will be collected along with the routing visit sequence. Tung and Pinnoi (2000), Angelelli and Speranza (2002), Teixeira et al. (2004) are some examples where PVRP heuristic algorithms were developed and applied to real waste collection systems.

The majority of the works have focused on static routes and only a few have tackled dynamic routing and scheduling aspects, which are present in real time operations. According to Johansson (2006), dynamic routing and scheduling can yield lower operating costs, shorter collection and hauling distances. Faccio et al. (2011) and Anghinolfi et al. (2013) also approached dynamic optimization in waste collection problems, where input data concerning waste generated is updated through sensors in the former work, and through a GIS-based waste generation simulation model in the latter work.

Furthermore, some other waste routing variants have been studied in the literature. Benjamin and Beasley (2010) explored a waste collection problem with multiple disposal facilities and one depot that act only as a vehicle's station. Ramos and Oliveira (2011) studied a recyclable packaging waste collection network with multiple depots, where service areas by depot have also to be defined along with the collection routes. Bektaş and Laporte (2011) proposed the Pollution-Routing Problem (PRP) that accounts not just for the travel distance, but also for the amount of greenhouse emissions, fuel, travel times and their costs in the vehicle routing modeling. Groot et al. (2014) developed a comprehensive collection cost model which includes the emission cost for the estimation of economic and environmental impact of municipal collection of plastic waste. In this study, the impact of differentiated waste taxation alternatives are also analysed, using the proposed model. Ramos et al (2014a) studied the planning of recyclable waste collection systems while accounting for economic and environmental concerns. Service areas and vehicle routes are defined for logistics networks with multiple depots where different products are collected. Also in the collection planning a trend towards sustainability is observed.

To summarize, issues addressed in network modeling literature of waste recycling are 1) Number of waste stream collected 2) Collection frequencies 3) Dynamic routing and scheduling 4) Multi-compartment vehicle 5) Vehicle capacity 6) Road condition 7) Number of depot 8) Differentiated municipal waste tax 9) Balance emission and economic and social concerns.

In the next section, the issues addressed in section 3 (practice) and 4 (models) will be analysed.

5. Results

5.1 Research Gap Analysis

Table 2 addresses the issues derived from practices and models. We make a comparison and identify those issues are not adequately addressed by the current methods in literature. Our first observation is that some issues appear in multiple decision levels. For example, capacity planning is an important issue both at strategic level on facility and network capacity plan and at a very detailed level on collection bin and collection vehicle capacity plans. Differentiating between waste types is a requirement from regulation but also an issue in network design and collection design. Handling waste simultaneously is in line with the vehicle partition problem. Issues can be inter-related with issues from other decision levels. For example, the location of transportation links and capacity of facilities on a strategic level can influence the operational level on the vehicle capacity planning and routing. Waste valorisation and market demand can have a significant impact on network configuration and facility capacity design.

	Issues derived from practice	Issues addressed in the literature	References	Issues not adequately addressed
External	Differentiated Taxiation	Differenciated municipal waste tax	(Groot et al. 2013)	
	Differentiated recycling targets			Differentiated recycling targets
	Increased Reycling Targets	Recycling target (capacity design)	(Gomes et al. 2011)	
	Valorization			Valorization
Strategic	Multi-commodity	Handle different composition of waste	(Bing et al. 2012)	Handle different waste simultaneously
	Network configuration	Network structure	(Fleischmann et al. 1997)	
	Facility capacity plan	Capacity design of facilities	(Barros et al. 1998)	Over-capacity of facilities
	Facility location choice	Location of recovery facility	(Louwers et al. 1999)	
		Location of transportation links	(Krikke et al. 1999))	
	Sustainable recycling network	Multi-modality strategy	(Bing et al. 2013)	
		Balance emission and economic concerns	(Ramos et al. 2014b)	Social concerns
Tactical/Operational	Collection method	Curbside or drop off collection	(Mora et al. 2013)	
	Collection coordination	Number of waste stream collected	(Muyldermans and Pang 2010)	
	Collection scheduling	Collection frequencies	(Tung and Pinnoi 2000)	
		Dynamic routing and scheduling	(Faccio et al. 2011)	
	Capacity planning	Multi-compartment vehicle	(Golden et al. 2008)	Compartment partition
		Vehicle capacity	(Laporte 2009)	Capacity of collection bins
	Vehicle routing	Road condition	(Bautista et al., 2008)	
		Number of depot	(Ramos and Oliveira, 2011)	
		Dynamic routing	(Johansson 2006)	
	Sustainable collection	Balance emission and economic concerns	(Bektas and Laporte 2011)	
		Balance emission and social concerns	(Ramos et al. 2014a)	

Table 2: Research gap analysis Note: Only one reference is given for each category. Matching literature is not limited to those provided.

The models addressed in literature mostly address efficiency issues. To further provide insights for policy makers and address issues like valorisation while including end market demand, researchers and practitioners need to have a broader view on the network of waste recycling; they should take the end market into consideration instead of focusing only on the waste collection and treatment. This holistic view is also necessary for the planning of capacity on a larger scale across borders to solve the problem of over-capacity. In other words, a holistic view is needed to strengthen the applicability of modelling tools for tackling real-life waste recycling problems. This is in line with Ghiani et al. (2014) concluding that a new challenge is represented by modelling a unified framework in which network decisions are combined with multi-commodity waste flow shipping decisions.

In addition to all profound methods already used in addressing problems to increase efficiency, the most promising direction for further improvement is to specify and partition waste flows to be treated differently. Issues such as tailored network design, waste composition and compartment partition should be addressed separately for each waste type, but while taking into account the co-relation in facility sharing with other waste types. This is in congruence with current regulation to treat different types of waste in a tailored way. Current researches often treat municipal waste as a single unit, instead of investigating the distinguishing feature of each waste type. The characteristics of different recyclables are therefore worth further study.

Regarding sustainability issues, the currently modelling methods have been exploring the balance between economic goals and emission control, whereas the societal objectives have only been started to be integrated in the quantitative models. There is a clear need for the definition of concrete social objectives and impact measurements that can be used in modelling. Hutchins and Sutherland (2008) proposed that labor equity, healthcare, safety and philanthropy can be the measurements of social sustainability for supply chain decision making as a starting point. This again calls for the integration of other research disciplines (especially related to social studies) with Operations Research modelling methods. To model the dynamic nature of supply chain operations and include all aspects of the relationships with its environment, modelling techniques that are capable of including the multi-dimensional qualitative and strategic characteristics are needed (Sarkis, 2002).

6.2 Research Opportunities

Based on the discussion of the research gaps above, we propose research opportunities with the following three key perspectives:

- Multiple dimensions

Municipal solid waste management cannot be viewed in a one-dimensional perspective, as a lot of issues from different decision levels are inter-related. The combined decisions on these inter-related issues are often too complex to be solved at once. A possible approach is to decompose the total decision making problem into several sub-problems, which then are solved step by step. However, multidimensional problems often introduce differentiated optimization objectives. Separation of problems and pursuing the objectives on one decision level at a time will result in suboptimal solutions. Global optimal solutions can only be obtained using an integrated approach that takes into account problems at different decision levels simultaneously.

A multiple dimensional perspective on municipal solid waste management indicates an integration of various disciplines in modelling MSW recycling. To improve sustainability performance, especially regarding addressing environmental and social concerns, an integrating of Operations Research modelling methods with methods from other disciplines is needed. For example, the life cycle assessment (LCA) methodology is among the most commonly used methods for assessing sustainable waste recycling systems in literature. Edward and Schelling (1999) conducted an LCA on municipal waste with a special focus on transportation, including a sensitivity analysis on recycling plant capacity. Björklund and

Finnveden (2007) focused their LCA study on the assessment of tax issues regarding national waste policy. The waste LCA model EASEWASTE (Christensen et al., 2007) is a decision support tool for waste management systems. The model can be used for integrated waste management to improve environmental performance. This gives researchers a hint that Operations Research methods have the potential to be integrated with other methods at multiple decision levels.

Other disciplines in technological studies also have the potential to be integrated with OR methods. For example, technology development can bring new parameters into the modelling process, such as new packaging design, RFID technology applied to the measurement of waste quantity, re-processing technology for the application of recycled materials. Such integrated approaches have been used in other sustainability related studies. For example, Vlyssides et al. (2004) have studied the environmental problem caused by olive oil production and used an integrated approach combining waste treatment technology, production processes and the valorisation of by-products. In waste management, the technological development can have impact on the estimation of waste quantity, the recycling channel allocation, the market demand of recycled material and so on. Thus, by taking into account technological development, new opportunities can be found in modelling waste logistics.

- Holistic view

Waste recycling is becoming a global issue with the export of waste between continents. To solve issues like over-capacity and valorisation, to meet the high requirement of waste recycling rates and to satisfy the increasing global demand of the recycled material, a new perspective in research and practice to look into waste recycling is needed. That is, to consider waste recycling as a procedure of retrieving waste as a global resource substitutable to raw material on a regional and a global scope.

A holistic view is necessary as a local “best” solution might not be optimal from the regional or global scale. For example, to measure the cost of waste recycling, it is necessary to take the whole reverse supply chain into account. Taking into account a complete supply chain is also the requirement of developing a sustainable supply chain. Just as economic globalization creates opportunities and poses challenges to supply chains, so does environmental globalization. Furthermore, the existing theories and models of global supply chain can be applied in a waste recycling context for addressing the problem at a global scale. From a modelling perspective, global supply chain constraints, such as tax and trade barriers can be considered in the modelling of reverse logistics network of municipal solid waste. Uncertainties in the global market in terms of the demand of recycled material and currency exchange rates can be integrated in the models too.

- Tailored solution

Externally, the regulation distinguishes recyclables by setting different recycle targets for each material. In practice, some efforts have been made to treat different types of waste in a tailored way. To meet future demands of further improving the efficiency and sustainability of municipal waste recycling, much more should be done to tailor the solution for each waste type.

Understanding characteristics of waste, such as the density (weight to volume ratio) difference, the quantity difference and treatment procedure differences can help to tailor the network design for each type of waste to further improve the recycling efficiency. As some waste shares the facilities at initial stages of the recycling chain, it is interesting to investigate the combined network for several types of waste. On the tactical and operational decision level, only after these different characteristics of each waste type are investigated, we can move on to fill research gaps like the design of combined collection with suitable multi-compartments and channel choices as well as handling different waste differently and simultaneously.

7. Conclusion

To provide guidelines for improving waste recycling in a more efficient and sustainable direction, we reviewed current practices and Operations research modelling methods. This paper took a new angle, by diving into practice first and bringing out issues that are important now and in the future. We started from a comparison of current practices in various EU countries and identified the characteristics and key issues of waste recycling from waste management and reverse logistics point of view. A review regarding the applications of modelling approach was then conducted, such that issues and problems in practice could be linked to the modelling methods used in literature. Comparing practice and models led to identifying research gaps and research opportunities.

Three perspectives of research opportunities were identified to guide the research and practice towards a future sustainable municipal solid waste recycling management; include multiple dimensions, take a holistic view and consider tailored solutions for different waste types. The integration of OR with other disciplines such as LCA in the research can help address issues in a more thorough manner. A holistic view should also be taken, especially when practice has already begun to globalize waste flows. Research with a tailored design for different waste types has the potential to help further improving the efficiency and sustainable performance of waste recycling.

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