Urban material cycle closing – assessment of industrial waste management in Lisbon region

João Patrício a, *, Inês Costa b, Samuel Niza a

* IN+i – Center for Innovation, Technology and Policy Research, Instituto Superior Técnico – Campus Taguspark, Av. Prof. Doutor Aníbal Cavaco Silva, 2744-016 Oeiras, Portugal
b 3 Drivers-Engineering, Innovation, Environment, Av. 5 de Outubro, 124, 4º Floor, 1050-061 Lisbon, Portugal

ARTICLE INFO

Article history:
Received 25 November 2013
Received in revised form 17 July 2014
Accepted 21 August 2014
Available online 3 September 2014

Keywords:
Industrial symbiosis
Industrial waste
Waste management
Resource recovery

ABSTRACT

Promoting the recovery of waste produced by companies in urban areas through Inter-firm relations such as Industrial Symbiosis, Resource Recovery or In-House Reuse can be seen as good approaches to achieve materials loop closure and foster self-reliance (resilience), by decreasing dependence of external sources. In this article the industrial waste produced in the Lisbon Metropolitan Area (LMA) during 2008 is assessed. By applying a Material Flow Analysis methodology, the research identifies the amount of waste that was recovered as well as the Recovery Networks that each transaction is integrated in. Additionally, it was performed an identification of the composition of the waste disposed and the results were computed against a database of waste recovery cases worldwide. Possible recovery solutions of the disposed waste were identified and proposals of improvement of the recovery network are advanced. Results show that a high amount of waste produced by the companies located in the LMA was recovered (791,086 tonnes from the 1,000,091 tonnes of generated waste). The Resource Recovery process processed 43% of the wastes, In-house reuse, 34%, and Industrial Symbiosis, 23%. The recovery solutions identified for the disposal waste show that at least 68% of the 209,005 tonnes disposed could also be recovered, increasing the total amount for Industrial waste recovered from 79% to 94%. The performance of the waste recovery network in this region supports the results of previous researches and uncovers new behavioural characteristics, namely when comparing Industrial Symbiosis and Resource Recovery.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

The reintegration of wastes and by-products back in the economy, thus fostering a roundput system (Korhonen and Snäkin, 2005) strongly lies on the notion of waste as a stock of secondary raw materials. In particular, the promotion of inter-firm linkages to assist such solution may improve cohesion through tacit knowledge exchange and stimulate growth and innovation, resulting in an enhanced adaptive capacity (Korhonen and Seager, 2008). In other words, the resilience of companies, and of the urban system they are embedded in, can be improved by pursuing such material loop closing strategies.

Literature on a systematic approach to IS identification at the regional level, by using data pools on waste material flow analysis compiled at the national level, is scarce and seldom goes insofar as to detail the data nomenclature or the methodologies used. Therefore, this paper aims contributing to fill this gap while characterizing an industrial waste management case study at a Portuguese region.

This paper has the following objectives: 1) identify and analyse more than 3 thousand waste exchanges between companies occurred in the Lisbon Metropolitan Area (LMA) in 2008 and 2) identify potential new exchanges and recovery solutions for the 200 thousand tons of waste that is currently disposed in the region. Therefore, the research conducted in this paper aims to identify if it is possible to improve the region resource efficiency by avoiding and reducing the disposal of industrial waste and improving the material loop closing.

Research held is partially built on previous work developed by Costa and Ferraõ (2010) for the year 2003 but providing higher detail on the types of wastes recovered and also, identifying potential recovery solutions for the waste that has been disposed. This study runs in parallel with other research that is being developed

http://dx.doi.org/10.1016/j.jclepro.2014.08.069
0959-6526/© 2014 Elsevier Ltd. All rights reserved.
for the Region, towards identifying strategies to promote its resilience (Niza et al., 2009; Rosado et al., 2014; Marteleira et al., 2014).

2. Theory

In order for economic systems to move towards a circular flow of materials as opposed to a linear flow, there are two main approaches to inter-firm relation: Industrial Symbiosis (IS) and Resource Recovery (RR) (Costa and Ferrao, 2010). Several authors also consider the reuse of by-products within the same organization - In-House Reuse – as a form of IS (Bain et al., 2010; Chertow, 2000; Zhu et al., 2007), a common practice in large industries. In this article we consider that IS implies the involvement of independent companies, and that In-House reuse may be considered part of the manufacturing process, and not an exchange of materials.

In the natural system, detritivores act as organisms that break down matter into simple nutrients which can, then, be used by consumers and producers. Resource Recovery Networks perform, in industrial environments, the same type of tasks that detritivores do in Nature. Their main industrial activities are to recover recyclable materials from waste flows, disassemble products into their material components, followed by remanufacture or recycling (Costa and Ferrao, 2010). They may be companies that are specialized in collecting specific materials, or they can be embedded in nation-wide waste management networks, dealing with the dismantling of wastes into different materials.

One of the best known examples of resource recovery, and inter-firm relations, was observed for the particular case of Kanluborg, Denmark (Ehrenfeld and Gertler, 1997). This case was described as an isolated phenomenon, where a number of companies have coincidentally been locked into a web of waste, water, and energy exchanges based on contractual dependency. The basic philosophy developed aimed at enhancing the emergence of an industrial system relying on co-operation between the actors involved, in which they use each other’s waste material and energy as resources, and minimize the system virgin material and energy input, as well as the waste and emission output (Korhonen, 2001). According to Domenech and Davies (2011), Kalundborg’s annual waste saving approaches translate into $15 million (US) in savings and revenues, with investments around $78.5 million (US). Total accumulated savings up to 2011 were estimated around $310 million (US). Some of the environmental savings include 3.9 million cubic meters of water, gypsum savings are estimated around 170,000 tons, and sulfur dioxide waste avoidance is estimated around 53 tons.

Self-organizing symbiosis emerges from decisions by private actors motivated to exchange resources to meet goals such as cost reduction, revenue enhancement, or business expansion (Chertow, 2007). Beyond the previous aspects, there are several other factors that can be seen as important drivers in order to promote a symbiotic relationship between two industries. First, and according with Ehrenfeld and Gertler (1997), the proximity of the enterprises seems to be an important driver; much more if material exchanged is not a high-value by-product. According to the same authors, also the symbiosis may work better when industries produce large quantities of by-products.

Current European Union (EU) waste management policies aim to reduce the environmental and health impacts of waste and contribute to improve EU’s resource efficiency. This is achieved by a continuous effort on removing barriers namely for recycling activities in the EU market and reviewing existing prevention, re-use, recycling, recovery and landfill diversion targets (European Council, 2013). For instance according to the Portuguese Decree-Law n° 73/2011, recovered materials must be forwarded to different industries that will use them in their process either by i) reusing them directly; ii) recycling and processing them into secondary raw materials; or, iii) burning for energy recovery.

EU-28 generated 2505 million tonnes of waste in 2010 (European Commission, 2013) of which manufacturing waste, the main target of this paper accounted for 276 million tonnes and an 11 % share. The remaining activities that generated wastes were construction, with 860 million tonnes (34 % share of the total) and mining and quarrying with 672 million tonnes (27%). Households made up 9% of the total and contributed 219 million tonnes. Almost half (49%) of this waste was recovered (other than energy recovery) and 45% was subject to disposal operations other than incineration (mostly landfilling, but also mining waste disposed in and around mining sites and waste discharges into water bodies) (European Commission, 2013). The remaining waste was incinerated with energy recovery (4%) and without energy recovery (2%).

In Portugal, manufacturing waste represents a higher share, 25%, with 9766 thousand tonnes (European Commission, 2013) of the total produced wastes (38,340 thousand tonnes (INE, 2014)), as compared to the EU-28 average. The remaining activities produced the following amounts of waste: Construction — 11,017 thousand tonnes (29%); Household wastes — 5464 thousand tonnes (14%); Mining and Quarrying — 1206 thousand tonnes (3%). Disposal was the treatment held for 49% of the wastes, while recovery (other than energy recovery) only comprehended 38% of the wastes. The remaining was incinerated with energy recovery (11%) and without energy recovery (2%).

3. Methods

The Lisbon Metropolitan Area (LMA) is an association of 18 municipalities, located around the Portuguese Capital, Lisbon. It comprehends approximately 3.3% of the Portuguese Territory (2998 km²) and about one quarter of the Portuguese population (3 million). Moreover, around 30% of the Portuguese economic activities are concentrated in the LMA and, as presented ahead around 80% of its wastes were recovered, a very good performance under the national standards. Therefore this region represents a good case study to perform the proposed assessment. There are commonly two groups of approaches to identify potential synergies across a given region or development. The first refers to discovery tools to identify potential partners, although their application is limited (Bossilkov et al., 2005). This approach is based on input—output matching operation; users introduce data for raw materials, wastes and by-products, organized by type of industry. The outputs (wastes, by-products) are paired with inputs (raw materials), mostly based on material description, from which the potential partners are then identified.

The second set of tools are discovery tools (Chertow, 2007), by which research teams are usually assembled to track resource flows associated to industries with a higher probability of being involved in waste/by-product exchanges. This typically involves data collection of waste material flows between organizations in a given region, in order to identify kernels of symbiosis, from which to foster additional synergies.

In the present paper, the methodology used combines both approaches: in terms of discovery, the database provided by the APA for the latest stable year (2008) contains data on 31,612 waste flow transactions between organizations at the national level, which allows the authors to uncover instances of symbiosis. The discovery tool, named DISC — Database on IS case studies — is a database compiled by Costa et al. (2011a) that codifies IS synergies published in the literature, by economic activities involved, waste
exchanged and raw material substitution. The particularities of the juxtaposition of both tools are now described.

The data used in this research and collected by APA arises from the Portuguese regulation Decree-Law n° 73/2011, which mandates companies and operators demonstrating information on a yearly basis regarding waste transfers. This includes companies that: 1) have more than 10 workers, or; 2) produce more than 1100 L of Municipal Solid Waste on a daily basis, or 3) produce hazardous waste. Companies are allowed to send the waste to another manufacturing company, a municipal waste transfer site, a waste management operator, or a dedicated waste management operator, which handles specific waste flows (e.g. tires, batteries, etc.).

According to the legislation, there are no restrictions for companies to receive wastes and use them as raw material substitutes, provided that they are licensed to do so by the Portuguese Environmental Agency (APA). However there is an exception, wherein no licence is required. Forest and agricultural biomass from agriculture or forestry activities are not considered a waste (as long as they are not contaminated with hazardous materials). For instance, wood shavings from a sawmill company can be used as bedding materials, by a poultry farming company, and the exchange does not need to be licensed.

A transaction can be defined as a reallocation of a waste or by-product from a producer to a receiver. The methodology held in the present study consists of three sequential phases (Fig. 1).

First, the economic activities from the LMA region involved in waste reallocation were identified and classified according to the European Economic Activities Nomenclature (NACE). The wastes transferred were also subject to classification, according to their typology — using the European Waste Catalogue (EWC) — their quantity and final destination (recovery or disposal).

Secondly, each waste transfer sent for recovery was classified as one of the three sub-types of networks mentioned in the previous section — IS, RR or In-House. If it was integrated in the industrial process of other company, and used as a by-product, it was classified as an IS connection. If it was collected by specialized companies, that recover and collect wastes, in order to treat or transform them into secondary raw materials, it was classified as RR connection. Finally, if the by-product was recovered within the company in which it was produced, it was classified as In-House recovery.

Thirdly, for the waste sent for disposal, each particular transfer was analysed in order to assess its recovery potential. This was accomplished by cross-comparing material and energy transfers data on company-to-company basis occurring in recovery case studies. For the purpose it was used the database compiled by Costa et al. (2011a). This database was updated in the aim of the current research with new cases published between 2008 and 2011 raising the number of comparable exchanges from 818 to 1095. It was then possible to quantify the amount of materials with recovery potential as well as finding potential solutions for them.

4. Results

4.1. Waste generation and treatment in the LMA

According to the data assessed, a total of 1,000,091 tonnes of industrial wastes were generated in the LMA in 2008. Recovered
waste totalled 791,086 tonnes (79.1%), corresponding to 3373 transactions (Fig. 2) of which 92.8% (734,000 tonnes) were recovered within the region. The remaining 7.2% were recovered outside the LMA, most of it within the neighbouring municipalities (approximately 60%). In this context, it is possible to state that proximity is important in keeping the recovery rate in a higher level.

The data also shows that there is still a fair amount of waste — 209,000 tonnes (20.9%) — being disposed, while it still contains material which has potential to be recovered, as it will be demonstrated in Section 4.3. Landfill was the primary disposal destination (163,000 tonnes), followed by specially engineered landfill, physical—chemical treatment, incineration without energy recovery and other sources of elimination.

Furthermore, there are significant differences in the recovery/disposal shares when the origin of the waste (urban solid waste or industrial waste) is compared. According to the National Statistics Institute (INE), in 2008, 2,128,327 tonnes of municipal solid waste were produced in the LMA. Of this amount, 1,222,314 tonnes were landfilled, and the remaining, 906,013 was recovered. Therefore, 42.6% of the total amount of municipal solid waste was recovered, contrasting to the 79.1% of the total amount of waste produced by companies that was recovered. It is admissible to state, then, that companies are contributing more to the resource use efficiency of the region, than municipalities.

4.2. Main economic activities involved in waste management in the LMA

The economic activities that contributed most to the waste production (Fig. 3) were: 1) Manufacturing (NACE Sector C) with 632,180 tonnes, 2) Wholesale and Retail trade/repair of motor vehicles and motorcycles (NACE Sector G) with 165,836 tonnes, and 3) Construction (NACE Sector F) with 97,662 tonnes. These results are aligned with Eurostat data for the waste generated by economic activities in 2008 in Portugal (Eurostat, 2012). In the particular case of the Construction sector, the majority of the wastes, such as road construction waste or demolition waste, were disposed in sand extraction sites and landfills (87.6%).

Although in some LMA municipalities there is still considerable activity in the Primary Sector, the share of waste from agriculture, forestry and fishery (NACE Sector A) was low, probably due to most of these wastes being considered as by-products, and therefore being reused by other companies. It is also plausible that such type of activities — particularly small and medium sized businesses — do not have to register their waste production, since they do not fulfill the specifications demanded by the legislation. As stated before, according to the Portuguese legislation, exchanges of forest and agricultural biomass from agriculture or forestry activities may be established without licensing.

Considering recovery and disposal waste receivers in the LMA (Fig. 4), the main activities identified were: 1) Manufacturing (NACE Sector C), and 2) Water Supply/Sewerage - Waste Management and Remediation Activities (NACE Sector E), with 424,976 tonnes and 382,736 tonnes respectively. In Sector C large amounts of wastes were directly used as by-products in its processes. In the case of Sector E, transactions were diversified in the type of waste received; usually in small amounts (half of the transactions have less than 1 ton). Approximately half of these transactions were classified as hazardous waste, which suggests that these wastes had to be recovered by specialized companies. The Mining and Quarrying sector is the next largest receiver, with 84,696 tonnes, most of which waste from the Construction Sector. It is plausible that the objective is to use inert materials for landscape rehabilitation.

The wholesale waste and scrap sector (NACE Sector G) was the fourth main receiver. This Sector includes companies that usually collect waste that do not require any pre-treatment (e.g. packaging wastes, paper and cardboard, wood, etc.) and then sell it to recycling companies.

As mentioned previously, one of the objectives of the present research is characterizing the LMA waste management network, given the types of exchanges conducted for the total amount of waste sent for recovery. As shown in Fig. 5, each transaction was classified according to the type of company receiving the waste. In the following sub-sections each network will be more thoroughly characterized.

4.3. Waste management network in the LMA

4.3.1. Industrial Symbiosis

According to Chertow (2007), companies usually pursue symbiosis in response to regulatory pressure, requiring industrial operators to increase the efficiency of resource use, reduce emissions or eliminate waste. These factors could be a precursor of some IS connections in the LMA. In fact, one of the main promoters of innovation in companies identified in Portugal was pollution prevention/control (Costa et al., 2011b). Since there are no formal IS promotion programs for companies in Portugal we may assume that the uncovered connections were self-organizing.

From the database it was possible to uncover 39 connections which can be characterized as IS. These involve 44 different companies in the LMA, for a total 171,671 tonnes of wastes (around 20% of the wastes recovered in the region).

Companies involved in this network are typically large industries (mainly receivers). They usually have advanced technologies, which is an important factor to obtain the necessary permits to use the by-products in substitution of raw-materials. Forward and Morgan (1999) state that the trigger for adopting and extending symbiosis is the existence of one successful material exchange, sometimes referred to as green twinning. In the case of the identified IS connections, there are companies that are integrated in more than one connection, and cases where two companies exchange more than one by-product. Furthermore, there are companies that increased the number of by-products exchanged between 2003 (as in Costa and Ferrão, 2010) and 2008. For instance, a logging company received 3 different by-products in 2008, while just 1 in 2003 and a cement factory received 10 by-products in 2008 instead of the 6 registered in 2003. These

Fig. 2. Destination of the waste produced by economic activities in the Lisbon Metropolitan Area, 2008 (own calculation).
Linkages seem to confirm that once a company realizes the benefit of one first connection, it will try to find new partnerships, either as producer or as receiver.

Moreover, since the data assessed concerns a period of one year, the transactions may not have been sporadic, and in fact occurred several times during the entire year. Table 1 presents the main IS connections identified.

Results show that providers have a wider variety of activities compared to the receivers. It is also possible to confirm that the industries defined as “Usual Suspects” by Chertow (2000), which are large companies that typically have continuous process waste streams, have more incidence in the network, due to their large amount of output materials. For example, the Manufacture of Paper Pulp provides several types of wastes and by-products such as wood, rubber and plastics, used as fuel or filler for cement production, or sludge and ashes which are used as fertilizers. The Cement Industry also plays a central role in the network, receiving several types of wastes used in substitution of fuel or raw materials for cement production.

Twenty nine different types of by-products were exchanged in the IS Network (Fig. 6). Sand blasting is the main material exchanged (in weight), a by-product usually used as an iron source for cement manufacturing. It can also be noticed that several by-products reused in symbiotic connections are materials to which is difficult to apply recovery solutions, such as the cases of sludge’s, blasting wastes, or ash. In addition to these solutions, the use of by-products for energy recovery is a common practice in IS, as for instance the case of the waste bark and wood.
Activities linked to the maintenance and sales of motor vehicles produce, on a daily basis, hazardous waste (e.g. used oils), and for this reason are required to record all the waste they produce, regardless of the number of workers the company has.

Certain companies are engaged to the collection of specific wastes, while others receive a more diverse set of materials. One example of the later is a company from Sector E (NACE 3832), that received 173 transactions of 51 different types of wastes, of which 97.7% were stored. This seems to indicate that these companies work as transfer stations for the wastes, which are afterwards forwarded to another specialized company dedicated to recycling. These are designated as “brokers” by the UK Environment Agency (2012): companies that make arrangements, on the behalf of others, to recover or dispose waste, regardless of whether or not they handle the waste themselves.

In the LMA case it is also observed that companies that produce more than one type of waste usually send it to the minimum receivers as possible, particularly if the amounts are small and/or hazardous. Understandably, even if in some cases the solutions may not be the best from an environmental perspective it is much easier (less bureaucracy) and economically advantageous for a company to provide a set of different wastes to one company than to find a recycler for each type of waste. This can also be explained by the local offer of companies whose main activity is managing the wastes produced by other companies leading producers not to expend time looking for other solutions farther.

Analysing the types of industrial wastes recovered in the RR network (Fig. 7), it is possible to observe that a great amount are managed by Producer Responsibility Organizations (PRO) under the extended producer responsibility framework (Niza et al., 2014), such as tyres, paper and cardboard, or packaging materials. Additionally this network integrates other end-of life materials, which are not included in these dedicated circuits, but have traditionally good potential to be recycled, as is the case of metals (e.g. aluminium) or wood. The resource recovery network includes also wastes that require special treatment, usually hazardous waste like wastes containing oil, sludge or oily water.

Usually, the amount of industrial waste exchanged per transaction in this network is much smaller than the industrial waste per transaction in the IS network since it is produced in smaller amounts, especially in the case of hazardous wastes. For instance the 168 transactions of used engine oils (EWC-130208) totalled only 0.8 tonnes. This waste, due to its potential hazardousness but also its economic value is also managed by a PRO (Niza et al., 2014).

In geographic terms, 19 of the IS connections occurred between companies of the same municipality. In weight, this represents 97.3% of the total waste exchanged. Industries and manufacturers usually try to find a potential receiver in their neighbourhood, especially if the amount of materials is high. Even if the main driver is economic (cost of transport), it is also possible that proximity renders companies more familiarized with each other, thus contributing for this behaviour.

### 4.3.2. Resource recovery

In the case of the RR network, it was possible to identify 2493 transactions between 575 companies, in a total of 313,381 tonnes of waste exchanged. First, and as expected, there were a wider variety of economic activities associated with the providers (161), than with the receivers (31). Most of the waste receivers are companies that work in the management and/or treatment of waste (e.g. consulting companies and wholesale of waste and scrap; treatment of hazardous and non-hazardous waste; dismantling of wastes; and companies specialized in waste recycling/reuse). Table 2 shows part of the activities involved in this network, and the frequency of transactions.

The second main receivers are the freight transport companies which work as intermediate carriers between the producers and the waste management or treatment companies.

<table>
<thead>
<tr>
<th>Producer</th>
<th>By-product</th>
<th>Receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>NACE</td>
<td>Description</td>
<td>EWC</td>
</tr>
<tr>
<td>1 C17.1.1</td>
<td>Manufacturer of pulp</td>
<td>030301 Waste bark and wood</td>
</tr>
<tr>
<td>2 C17.1.1</td>
<td>Manufacturer of pulp</td>
<td>100101 Bottom ash, slag and boiler dust</td>
</tr>
<tr>
<td>3 C17.1.1</td>
<td>Manufacturer of pulp</td>
<td>191204 Plastic and rubber</td>
</tr>
<tr>
<td>4 C17.1.1</td>
<td>Manufacturer of pulp</td>
<td>030301 Waste bark and wood</td>
</tr>
<tr>
<td>5 C33.1.5</td>
<td>Repair and maintenance of ships and boats</td>
<td>120117 Waste blasting material</td>
</tr>
<tr>
<td>6 F42.1.2</td>
<td>Const. of railways and underground railways</td>
<td>170201 Wood</td>
</tr>
<tr>
<td>7 G46.7.7</td>
<td>Wholesale of waste and scrap</td>
<td>191201 Paper and cardboard</td>
</tr>
<tr>
<td>8 C25.1.2</td>
<td>Manufacturer of doors and windows of metal</td>
<td>170402 Aluminium</td>
</tr>
<tr>
<td>9 C25.1.2</td>
<td>Manufacturer of doors and windows of metal</td>
<td>200139 Plastics</td>
</tr>
<tr>
<td>10 C25.9.9</td>
<td>Manufacturer of other fabricated metal products n.e.c.</td>
<td>191202 Ferrous metal</td>
</tr>
<tr>
<td>11 C23.1.2</td>
<td>Shaping and processing of flat glass</td>
<td>101112 Waste glass</td>
</tr>
</tbody>
</table>
4.3.3. In-house reuse

Data describes 10 cases where recovery operations were performed within the company, totalling 248,559 tonnes of by-products. Activities involved are dominated by a paper mill, which reused 247,697 tonnes of wood as fuel in its production. Table 3 presents an excerpt of the identified in-house reuse exchanges corresponding in weight to 99.7% of the total recovered by-products.

When compared to the results of the previous networks, it may be concluded that in-house reuse highly contributes to industrial waste recovery (33.9% of the total waste recovered within the LMA). However the biggest fraction of it was used as fuel.

4.4. LMA’s waste management structure

Fig. 8 presents part of the waste management network in the LMA, illustrating how the various sub-networks (IS, RR and In-House) intertwine in one integrated, larger network. In particular, the diagram presents 27 resource recovery exchanges between companies operating in the LMA. Each dark grey diamond is a receiver company involved in the RR Network, while each light grey box corresponds to waste producing activities, integrated in both RR and IS Network. The white boxes are receiver companies from IS Network.

Each arrow indicates the amount and type of material exchanged, and each box represents a different company.

Table 2

Main Receivers/Providers of the waste exchanged in the Resource Recovery Network, Lisbon Metropolitan Area, 2008 (Excerpt).

<table>
<thead>
<tr>
<th>Receivers</th>
<th>Providers</th>
</tr>
</thead>
<tbody>
<tr>
<td>NACE</td>
<td>Description</td>
</tr>
<tr>
<td>E38.3.2</td>
<td>Recovery of sorted materials</td>
</tr>
<tr>
<td>H49.4.1</td>
<td>Freight transport by road</td>
</tr>
<tr>
<td>E38.1.2</td>
<td>Collection of hazardous waste</td>
</tr>
<tr>
<td>E38.1.1</td>
<td>Collection of non-hazardous waste</td>
</tr>
<tr>
<td>E38.2.2</td>
<td>Treatment and disposal of hazardous waste</td>
</tr>
<tr>
<td>G46.7.7</td>
<td>Wholesale of waste and scrap</td>
</tr>
<tr>
<td>E38.2.1</td>
<td>Treatment and disposal of non-hazardous waste</td>
</tr>
<tr>
<td>E38.3.1</td>
<td>Dismantling of wrecks</td>
</tr>
<tr>
<td>M71.1.2</td>
<td>Engineering activities and related technical consultancy</td>
</tr>
<tr>
<td>G46.9.0</td>
<td>Non-specialised wholesale trade</td>
</tr>
</tbody>
</table>
(excluding both of the manufacture of pulp, which are only one company). The Manufacture of Cement and the Manufacture of Pulp are the “usual suspects” as designated before.

Many companies do not exchange by-products and wastes exclusively within one network. E.g. the ships and boats repairing company send its wastes to both RR and IS receiver companies. The preference for one or the other will probably depend on the type and amount of waste and the proximity of a potential licensed receiver company.

In resume, when comparing RR and IS networks it is possible to characterize them by the following:

- RR connections are typically related to smaller companies that produce waste sporadically; produce small amounts of waste; or produce hazardous waste. A large part of these transactions are paid services.
- IS connections are more related to large industries that produce large amounts of a single type of waste.

4.5. Disposal

In 2008, 249 different types of industrial waste were disposed, totalling 209,005 tonnes. Hazardous waste is the most frequent transaction between the producers and the disposal facilities, although the exchanged amount is very low (6.9% of the total waste sent for disposal).

Most of the disposed wastes are inert materials (approximately 97,000 tonnes), such as stone and concrete, mainly produced by Sector F (Construction) even though it has a high recovery potential, according to the database updated in phase 3 of the methodology: 1) as structural materials (for buildings, roads, etc.); or 2) as raw materials in the production of construction materials (e.g. bricks, cement).

A low landfill tax in Portugal (2.5 € per tonne of inert waste in 2008) together with the cost of transportation of heavy loads surely contributes to this scenario. According to several authors (Costa et al., 2010; Tojo et al., 2011; Niza et al., 2014), countries that have higher landfill taxes, in combination with other initiatives such as separation at source, specific recycling targets or a landfill ban, have greater recovery values for such type of waste. The application of this mix of measures could potentially decrease the amount of wastes currently being disposed, thus contributing for materials cycle closing.

In order to evaluate the recovery potential of the disposed waste in the LMA, the authors developed a multiple case comparison between the type of waste being disposed and the information associated to recovery cases gathered from literature (Table 4). For some cases it was not possible to suggest a proper solution, mainly because of the ambiguous description of some of the EWC codes; while some classes are well defined, there are others that cover a set of very different types of waste.

Table 3

<table>
<thead>
<tr>
<th>Economic activity</th>
<th>NACE Description</th>
<th>EWC</th>
<th>Waste reused</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C26.7.0 Manufacture of optical instruments and photographic equipment</td>
<td>150104</td>
<td>metallic packaging</td>
</tr>
<tr>
<td>2</td>
<td>C22.1.1 Manufacture of rubber tyres and tubes; retreading and rebuilding of rubber tyres</td>
<td>160103</td>
<td>end-of-life tyres</td>
</tr>
<tr>
<td>3</td>
<td>C10.4.1 Manufacture of oils and fats</td>
<td>190801</td>
<td>screenings</td>
</tr>
<tr>
<td>4</td>
<td>C29.3.2 Manufacture of other parts and accessories for motor vehicles</td>
<td>120105</td>
<td>plastics shavings and turnings waste bark and wood</td>
</tr>
<tr>
<td>5</td>
<td>C17.1.1 Manufacture of pulp</td>
<td>030301</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7. Types of wastes exchanged in the Resources Recovery Network, Lisbon Metropolitan Area, 2008 (own calculations).
5. Conclusions

The research described in the paper contributes to demonstrate the importance for resource efficiency of economies of promoting the development of systems to record and describe exchanges of residual materials and energy among companies. The detail achieved in the paper was only possible, on the one hand because the Portuguese legislation and the Portuguese Environmental Authority (APA) mandates companies and operators disclosing information on a yearly basis regarding waste transfers and, on the other hand, because there was a hard effort in developing an important database on international IS case studies (as described in Costa et al., 2011a). This allowed picturing the resource recovery network per type of material and operation for a whole region, instead of a case by case study, as usual in the literature.

Additionally, the paper indirectly evidences the added value for state institutions, as APA in this case, of allowing researchers to process and assess data collected by them (e.g. for inspection purposes). Information gets an additional value than the one it was previously intended for. In this case instead of only a control purpose, information may be used to promote resource use efficiency in the industrial sector of the country.

The paper describes the waste exchanges between companies occurred in the Lisbon Metropolitan Area (LMA) in 2008 and identifies potential new exchanges and recovery solutions for the waste that is currently disposed in the region, therefore identifying potential improvements for the region resource efficiency.

Results show that 79.1% of the total industrial waste produced in 2008 within the Lisbon Metropolitan Area was recovered. This is a significant value, if compared to the rate of the Municipal Solid Waste recovered in the LMA for the same year (42.6%). This suggests that LMA companies are making higher efforts than municipalities fostering resource use efficiency by promoting the closure of material loops. Furthermore, most of the recovered waste (94%) was managed within the LMA or in neighbour municipalities, keeping economic and material benefits within the region.

The industrial waste recovery networks approached in this paper (Industrial Symbiosis, Resource Recovery, and In-House Reuse), which revealed to be connected and intertwined in one larger integrated network, were crucial to this recovery rate. Resource Recovery network processed 43% of the wastes, In-house reuse 34% and Industrial Symbiosis 23%.

The performance of the system in this region supports the results of previous researches and uncovers new behavioural characteristics. This performance may be resumed as in the following paragraphs.

Pollution prevention regulation could be a precursor of some IS connections in the LMA but it may be assumed that connections were self-organizing. On the other hand, self-organizing symbiotic connections were driven by:

- The proximity of the enterprises. Not only because it avoids large transportation costs, but also because companies are more familiarized with each other;
- The amount of by-products available to be exchanged. This can be one of the reasons why the companies defined as “usual suspects” (large companies), can be seen as the main catalysts of symbiotic connections due to their large amount of output materials.

When comparing RR and IS networks the main differences are the following:

- IS connections are more related to large industries that produce large amounts of a single type of waste.
- RR connections are typically related to smaller companies that produce waste sporadically; produce small amounts of waste; or produce hazardous waste.

A great amount of industrial wastes recovered in the RR network are managed by Producer Responsibility Organizations (PRO) under the extended producer responsibility framework. Also, in the RR...
network, companies that produce more than one type of waste usually send it to the minimum receivers as possible, particularly if the amounts are small and/or hazardous.

Finally, as demonstrated in this paper, although a large amount of industrial waste is already being recovered, it is still possible to improve resources efficiency. The analysis of the waste that is currently being disposed revealed that at least 67.9% of the 209,005 tonnes have still potential of being re-circulated back into the local economy. This would increase the total amount of industrial waste recovered in the LMA from 791,086 tonnes to approximately 936,000 tonnes, corresponding to 93.6% of the total industrial waste produced. However, several EWC codes associated to waste materials are not specific enough about their composition, hampering the identification of recovery solutions for some materials.

Research presented in this paper contributes to further advancing innovative strategies to improve urban resilience in the particular case of the LMA. By providing a blueprint on existing connections between industries within this region, it will be possible to evaluate this urban area capacity to withstand material or energy provision fluctuations. Additionally it allows extrapolating the need for further connections taking into consideration material and energy availability and providing a dynamic unfolding of potential future scenarios for sources, movements and sinks of materials (Rui et al., 2011).

Life Cycle Assessment (LCA) and cost-benefit analysis of these networks should be developed not only to assist decision makers on the best management option for different types of wastes, but also to evaluate the network’s impact in the regional economy. This would contribute to the development, promotion and strengthening of waste recovery networks in the LMA, and make the benefits explicit, which may go beyond resource use efficiency and include new added value, new products and consequently new jobs (Girard et al., 2011; Behera et al., 2012; Meneghetti and Nardin, 2012).

### Table 4

<table>
<thead>
<tr>
<th>Waste EWC description</th>
<th>Potential solution</th>
<th>Description</th>
<th>Reference</th>
<th>% Of the total waste disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>170204 – bottom ash, slag and boiler dust (excluding boiler dust mentioned in 10 01 04)</td>
<td>C23.3.2 – Manufacture of bricks, tiles and construction products, in baked clay C23.6.1 – Manufacture of concrete products for construction purposes C23.5.1 – Manufacture of cement</td>
<td>Structural fill for building, stabilizing ramps, drainage, road constructions Used as raw material in the production of bricks Used as raw material in cement production</td>
<td>(Bain et al., 2010) (Bain et al., 2010) (Curtin University of Technology (2007))</td>
<td>5.71</td>
</tr>
<tr>
<td>170504 – soil and stones other than those mentioned in 17 05 03</td>
<td>E38.2.1 – Treatment and disposal of non-hazardous waste</td>
<td>Used in industrial composting process</td>
<td>(NISPM, 2009)</td>
<td>6.79</td>
</tr>
<tr>
<td>030302 – green liquor sludge (from recovery of cooking liquor)</td>
<td>C17.1.1 – Manufacture of pulp E38.2.1 – Treatment and disposal of non-hazardous waste A1.5 – Mixed farming</td>
<td>Neutralization of acidic wastewaters Used in Industrial composting process Agricultural schemes (soil improvement)</td>
<td>(Nurmnesieni et al., 2004) (Zambrano et al., 2010) (Bain et al., 2010)</td>
<td>6.64</td>
</tr>
<tr>
<td>100101 – bottom ash, slag and boiler dust (excluding boiler dust mentioned in 10 01 04)</td>
<td>C23.3.2 – Manufacture of bricks, tiles and construction products, in baked clay</td>
<td>Agricultural schemes (soil improvement)</td>
<td>(Bain et al., 2010)</td>
<td>6.79</td>
</tr>
<tr>
<td>100413 – wastes from stone cutting and sawing other than those mentioned in 01 04 07</td>
<td>C23.6.1 – Manufacture of concrete products for construction purposes C23.5.1 – Manufacture of cement</td>
<td>Used as raw material in cement production</td>
<td>(Curtin University of Technology (2007))</td>
<td>5.71</td>
</tr>
<tr>
<td>170904 – mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03</td>
<td>C23.3.2 – Manufacture of bricks, tiles and construction products, in baked clay</td>
<td>Structural fill for building, stabilizing ramps, drainage, road constructions Used as raw material in the production of bricks Vermicomposting — turn organic waste into nutrient-rich fertilizer (using worms) Anaerobic digestion — Production of energy and compost</td>
<td>(Carpenter and Gardner, 2008) (Beers, 2008) (NISPM, 2008)</td>
<td>3.62</td>
</tr>
<tr>
<td>200108 – biodegradable kitchen and canteen waste</td>
<td>C23.6.1 – Collection of organic waste</td>
<td>Structural fill for building, stabilizing ramps, drainage, road constructions</td>
<td>(Carpenter and Gardner, 2008)</td>
<td>6.24</td>
</tr>
<tr>
<td>200109 – biodegradable waste</td>
<td>E38.2.1 – Treatment and disposal of non-hazardous waste</td>
<td>Vermicomposting — turn organic waste into nutrient-rich fertilizer (using worms) Anaerobic digestion — Production of energy and compost</td>
<td>(NISPM, 2008)</td>
<td>5.71</td>
</tr>
<tr>
<td>191209 – waste gravel and crushed rocks other than those mentioned in 01 04 07</td>
<td>F42.1.3 – Site preparation</td>
<td>Structural fill for building, stabilizing ramps, drainage, road constructions</td>
<td>(Environment Agency, 2010)</td>
<td>6.79</td>
</tr>
<tr>
<td>191208 – waste gravel and crushed rocks other than those mentioned in 01 04 07</td>
<td>F43.1.2 – Construction of roads and motorways</td>
<td>Structural fill for building, stabilizing ramps, drainage, road constructions</td>
<td>(Carpenter and Gardner, 2008)</td>
<td>3.62</td>
</tr>
<tr>
<td>170201 – waste gravel and crushed rocks other than those mentioned in 01 04 07</td>
<td>A1.5 – Mixed farming</td>
<td>Agricultural schemes (soil improvement)</td>
<td>(Environment Agency, 2010)</td>
<td>6.24</td>
</tr>
<tr>
<td>170101 – concrete</td>
<td>A1.5 – Mixed farming</td>
<td>Agricultural schemes (soil improvement)</td>
<td>(Environment Agency, 2010)</td>
<td>0.51</td>
</tr>
<tr>
<td>170107 – mixtures of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06</td>
<td>C29.3.2 – Manufacture of other parts and accessories for motor vehicles</td>
<td>Reused as secondary raw material</td>
<td>Recovery identified in the studied database</td>
<td>0.20</td>
</tr>
<tr>
<td>190082 – waste from desanding</td>
<td>C29.3.2 – Manufacture of other parts and accessories for motor vehicles</td>
<td>Reused as secondary raw material</td>
<td>Recovery identified in the studied database</td>
<td>0.20</td>
</tr>
<tr>
<td>120105 – plastics shavings and turnings</td>
<td>E38.2.1 – Recovery of sorted materials</td>
<td>Speared to be used as raw material</td>
<td>Recovery identified in the studied database</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Acknowledgements
The authors would like to acknowledge the Portuguese Science and Technology Foundation (FCT) for its financial support in the aim of projects ResiSt (Reference: PTDC/SEN-ENR/103044/2008) and MeSuR (Reference: PTDC/SEN-ENR/111710/2009).

Appendix A. Supplementary data
Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2014.08.069.

References