AN APPROACHES TO LOCATING DISTANCE DEPENDENT COLLECTION POINTS IN RECYCLING LOGISTICS NETWORKS

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Abstract: The recycling logistics network must be designed in such way that supports the need for efficient collection of the recyclable products from the end user, in terms of adequate quantities since they are input into the recycling process. On the other hand, those products have a low market value and costs related to recycling activities are relatively high. In order to make returned products available for the recycling process, the first step is their efficient collection. So, it is necessary to determine the locations of facilities for the collection of returned products on the first level of the recycling logistics network. This paper describes the problem of designing one part of recycling logistics network, particularly concentrating on review of mathematical modeling approaches used for selecting distance dependent locations of collection points for recyclables in recycling logistics networks.

Keywords: recycling, logistics networks, distance dependent collection points.

1. INTRODUCTION

Municipal solid waste (MSW) is usually defined as “waste from households (household waste), as well as other waste which is similar to waste from households, due to its nature or composition” (Law on Waste Management, 2009). According to the World Bank (2018), an estimated 2.01 billion tonnes of MSW were generated in 2016, and this number is expected to grow to 3.40 billion tonnes by 2050, on a global level. About 37% of these waste quantities are disposed of in some type of landfill, 33% is openly dumped, 19% undergoes materials are recovered through recycling and composting, and 11% is treated through modern incineration (World Bank, 2018). On the other hand, MSW represents a valuable resource of secondary materials which can be used again, that is unused waste represents an economic loss. It is estimated that the materials sent to landfills could have an annual commercial value of around € 5.25 billion (EEA, 2010). So, a number of countries introduced strict environmental regulation, in order to deal with MSW problem.

For example, the European Union (EU) Waste Framework Directive sets a target of 50% of MSW to be prepared for reuse and recycled by 2020 in the EU Member States for at least four categories (i.e. paper, glass, metals, plastics) of waste (EEA, 2018). In the EU during 2018, The Waste Framework Directive, Landfill Directive and Packaging Waste

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Directive, were amended to include a number of new targets and measures beyond 2020, such as (EEA, 2018):

- targets to increase preparing for reuse and recycling of MSW to at least 55% of MSW by 2025, 60% by 2030 and 65% by 2035;
- targets to increase recycling of packaging waste to at least 65% by 31 December 2025 and 70% by 31 December 2030;
- a target to reduce landfill to a maximum of 10% of generated MSW by 2035;
- a ban on landfilling of waste suitable for recycling effective from 2030;
- etc.

Therefore, one solution to the MSW management problem represents recycling by obtaining revenues through the sales of collected materials, ensuring thus an adequate supply of raw materials for manufacturing recycled products and producing important environmental benefits (Vidović et al., 2016).

Recycling, as one of the treatment option for MSW, has been steadily increasing in Europe from 31% in 2004 to 45% in 2016 (EEA, 2018) and as the demand for raw materials is expected to dramatically increase in the upcoming years, the worldwide market for recycling and re-use technologies will offer increasing opportunities (EC, 2013). For example, prices of virgin and recycled materials for different types of packaging materials are presented in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Virgin material (€/t)</th>
<th>Recycled material (€/t)</th>
<th>Price of Recycled material/Virgin material (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>52-59</td>
<td>12.5-34</td>
<td>24-58</td>
</tr>
<tr>
<td>Paper-cardboard</td>
<td>717-776</td>
<td>115-136</td>
<td>16-18</td>
</tr>
<tr>
<td>Aluminium</td>
<td>1719-1774</td>
<td>650-1080</td>
<td>38-61</td>
</tr>
<tr>
<td>Steel</td>
<td>394-630</td>
<td>160-180</td>
<td>41-29</td>
</tr>
<tr>
<td>HDPE Plastics</td>
<td>990-1200</td>
<td>245-280</td>
<td>25-23</td>
</tr>
<tr>
<td>PET Plastic</td>
<td>1550-1700</td>
<td>390-475</td>
<td>25-28</td>
</tr>
</tbody>
</table>

Recycling is defined as any recovery operation by which waste materials are reprocessed into products, materials or substances, whether for the original or other purposes (EEA, 2018). Hence, recycling creates reverse flows of products, materials, parts, etc. comparing to traditional (forward) logistics flows (Figure 1). Reverse logistics system involves the following activities:

- acquisition of returned products, materials, parts, etc.
- collection
- inspection/sorting/testing operations
- choice of disposition, followed by recovery options
- and final disposal if returned products, materials, part, etc., cannot be recovered through any available recovery options.
On the other hand, recycling logistics network (RLN) may include for example secondary markets for recycled products, so the process of redistribution is added to these networks. Hence, reverse logistics networks have different network structure compared to traditional or forward logistics networks due to new activities/processes (i.e. recovery options), facilities (i.e. recycling factories), as well actors in the system. Additionally, when talking about recycling, the value of products, intended for recycling is usually really low and costs related to recycling activities, especially collection can account up to 70% of the entire cost of MSW management (Vidović et al., 2016). Therefore, appropriate RLN must be designed to encompass all recycling activities in order to manage reverse logistics flows in a profitable way. The profitability of RLN is influenced by the efficiency achieved through coordination and integration of all involved participants (Helms and Hervani, 2006).

One of the activities in the recycling process, as can be seen from Figure 1, is collection recyclables from end users, which can been done in different ways. One of the most efficient ways of collecting recyclables is through the separation of MSW into fractions like plastics materials, glass, metal cans, paper, etc. So, an adequate system of collection points (CPs) must be established (set) to encompass all specificities of RLNs. Having in mind that the success of recycling systems lies mostly in end users’ participation, which determines the type and amount of materials to be collected (Gallardo et al., 2010), acceptable walking distance for end users, can be used as a criterion to locating CPs in RLNs. Hence, the emphasis in this paper is on modeling approaches used for selecting distance dependent locations for CPs, as facilities on the first level of the RLNs.

In the last two decades, a number of researchers investigated the problem of designing RLNs. It should be mentioned that there are a number of review papers on reverse logistics systems and design such as Engeland et al. (2018), Rachih et al. (2019), Prajapati et al. (2019), Thierry et al. (1995), Fleischmann et al. (1997), Srivastava (2007), Sasikumar and Kannan (2008a, 2008b, 2009), Rubio et al. (2008), Akçali et al. (2009), Chanimtrakul et al. (2009), Melo et al. (2009), Pokharel and Mutha (2009), Agrawal et al. (2015), Govindan et al. (2015), Govindan and Soleimani (2017). A review paper by Purkayastha et al. (2015) is, to the authors’ best knowledge, the only one of that kind which offers comprehensive insight in location-allocation approaches used for...
locating CPs in waste management systems. Authors stated that only a few studies have been addressing the problem of recycle bin location-allocation problem.

From here, the paper is structured as follows: Recycling processes and designing inputs for a recycling network as well as the relevant literature are addressed in Section 2. Detailed examples of locating distance dependent CPs in RLNs for different types of products are presented in section 3. Finally, concluding remarks are given in section 4.

2. CHARACTERISTICS ON RECYCLING LOGISTICS NETWORKS DESIGN

Generally, to handle returned products in logistics system, a completely new reverse logistics network need to be designed or an existing logistics network must be redesigned (Figure 2). Two main characteristics of reverse logistics flow must be considered when designing reverse logistics networks: convergent structure, where products flow from many sources to few destinations, and uncertainty in quantities of returned products (Melo et al., 2009).

![Figure 2. Forward and reverse logistics flows (Melo et al. 2009)](image)

Designing of RLN falls in the category of strategic network design problems. When designing RLN, two additional distinctive characteristics of RLN must be considered. As mentioned, the economics of the RLN is characterized by low value per volume collected, and high investment costs for specialized equipment and deployed technologies (Bloemhof-Ruwaard et al., 1999). Due to the limited number of recovery options and the fact that material recycling is fairly robust with respect to input quality, a centralized network structure concentrating processing capacities at few locations is a characteristic of RLN (Bloemhof-Ruwaard et al., 1999).

Particularly, strategic design of RLN may include: the selection of locations for collection, inspection, testing or sorting of recyclables as well treatment facilities; the selection of technologies to be deployed in those facilities; determination of capacities of those facilities; allocation of the physical flows between located facilities on the network, etc. Decisions regarding the allocation of the physical flows between located facilities on the network, that is determining transport connections between objects in the RLN, can be made in two ways. Selecting the locations of facilities in the RNL and then defining the vehicles' routes, when problems of locating facilities and finding vehicle routes are
solved independently, or solving these two problems simultaneously. The second approach is referred to in literature as the location-routing problem (LRP).

The design of RNL depends on a number of economic, environmental and social factors such as quantities of generated waste, transport infrastructure, the composition of generated waste, public attitudes towards facilities such as transfer stations, collection points, etc. The general structure of the RLNs can be presented through a number of layers or echelons on the network, or the RLN can be consisted of different levels and facilities (Figure 3). From Figure 3, it can be seen that regardless of the system’s complexity, RNL begin with the end user and finish with the end market (Jahre, 1995b).

Of course, the question who is end user in RLNs plays a vital role when deciding on collection strategies as well as the structure of the network. Generally, all end users as generators of recyclables can be divided into two groups: households and industry and commercial sector. This distinguishing factor is made primarily on the generated quantities of recyclables. Households generate recyclables materials such as packaging materials, household appliances, textiles, furniture, etc., but in much smaller quantities than the industrial and commercial sector. These quantities, with other factors, determine a way of organizing the RLNs. Namely, since the industry and the commercial sector generates larger quantities of recyclable products and materials, the collection is usually organized in a defined time interval when vehicle or vehicles comes to the generator’s location and the recyclables that are generated for a given time period is then transported to the next location in the RLNs. When it comes to the household or individual generators of recyclables, there are several strategies for collecting recyclables, which are encountered in practice and in the literature. These strategies are:

- curbside collection (also referred to as “door-to-door” collection service) - each household has its own container or in case of apartment buildings containers are located in interior courtyards of the building. In both cases, containers are placed outside the household/building on collection days.
- drop-off locations (or bring collection system) - end users are required to bring their recyclables to allocated drop-off points.
- buy-back centers - end users may deliver recyclables to allocated locations as well in drop-off strategy, but in this case, receiving a certain monetary compensation. Also, the number of sites for buy-back centers is significantly lower than the number of locations for drop-off strategy.
• Refill/deposit system - primarily intended for beverage products, nowadays is applied to batteries, tires, etc.

Each of these strategies has its advantages and disadvantages. For example in the case of curbside collection strategy recyclables are collected on a fixed schedule and associated cost are high, but end users have minimal effort in disposing of their recyclables. In the case of drop-off collection strategy, compared to curbside collection strategy costs are lower, due to the smaller number of CPs, but in this case end users have a greater effort compared to curbside collection strategy. Depending on the type of recyclables and available sites for discarding recyclables, end users can decide on what location for generated recyclables is more suitable for them.

In order to make returned products available for the recycling process, the first step is their efficient collection. So, it is necessary to determine the locations of facilities for the collection of returned products on the first level of the network, regardless of the strategy in place. Biehl et al. (2007) point out that CPs are essential elements of any reverse logistics system in order to increase the collection of returned products and reduce transportation costs. Kao and Lin (2002) stated that selecting too many CPs increases the collection cost, while selecting too few may reduce customer satisfaction and probably cause less efficient recyclables process. So, the participation of end users is crucial for a successful recycling program, where the level of participation depends on the convenience associated with accessing recycling CPs (Lin et al., 2011). End users are responsible for sorting products in their homes and delivering recyclables to selected CPs locations. The most common way to encourage the participation of end users in the recycling process in order to collect as large quantities of recyclables is by stimulating them with some incentive (monetary compensation). But when voluntary action is required, personal costs related to the time required for sorting and delivering recyclables to defined CPs locations must be minimized to ensure the greatest possible participation of end users. In many studies (Perrin and Barton 2001, Domina and Koch, 2002; Gonzalez-Torre and Adens-Díaz 2005; Valle et al. 2009) has been shown that proximity and accessibility of CPs location plays a key role for the active participation of end users. One way to reduce the end user's inconvenience is to minimize the distance from the end user to the CP's location. Gonzalez-Torre and Adens-Díaz (2005) confirmed previous researches conducted in Scotland (Speirs and Tucker 2001) and Spain (Domina and Koch 2002), in which authors found that if end users have a greater number of containers for disposal of recyclables which are located closer to their homes, they are more willing to sort and bring recyclables to CP's locations. That is, the amount of collected and sorted recyclables is significantly higher compared to the case when the number of CPs is smaller and farther away from the end user's homes. Those studies also found that the majority of end users who are sorting three or four kinds of products for recycling walk less than five minutes from their homes to the CP's location. Perin and Barton (2001) found that distance to CPs is the main obstacle to effective recycling. Also, González-Torre and Adenso-Díaz (2005) found that the distance to the selective recycling bins affects the number of fractions that end users separate at home.

It should be mentioned that, in the case of some recyclables, allowable distance of end users from CPs can also be specified by legislative measures. For example, this is the case for end-of-life vehicles in Germany and the United Kingdom.

The following section describes mathematical modeling approaches used for selecting distance dependent locations of CPs for recyclables.
3. MODELING APPROACHES FOR LOCATING DISTANCE DEPENDENT COLLECTION POINTS

When talking on recycling, the first association is usually packaging materials such as paper, glass, wood, metal or plastics materials, but vast number of materials and products can be recycled nowadays: electronic and electrical equipment, end-of-life vehicles, furniture, carpets, batteries, medical waste, construction and demolition waste, etc. Hence, researches addressed different types of products when solving the problem of locating CPs in RLNs.

In order to model the influence of the distance between users and CPs on the optimal locations of facilities to be found, Ratkovic et al. (2012), introduced the CP’s catchment area (Figure 4).

![Figure 4. Modeled reverse logistics network (Ratkovic et al., 2012)](image)

Authors presented a multi-level, multi-product facility location model for reverse logistics network design. The proposed model finds effective strategies for the return of discarded products from end users to recycling factories, via CPs, transfer facilities and treatment facilities, with minimal costs. Special emphasis was in analyzing the impact of collection point’s catchments area. The catchment area (Figure 5) models the influence of the distance between end users and CPs in a way that collection service may exist only when end users are within the certain (reasonable) distance from a collection point \( k \). That is, any arbitrary end user \( i \) can be allocated to the CP only if it is located within the CP’s catchment area.

![Figure 5. Collection point’s catchment area (Ratkovic et al., 2012)](image)

For end user \( i \), CP \( k \) and product \( p \), catchment area is formulated as:

\[
(d_{ik} - R)X_{pik} \leq 0, \forall i, p, k
\]  

(1)
where variable $X_{pik}$ represents a fraction of product $p$ transported from end user $i$ to CP $k$, $d_{ik}$ distance between CP $k$ and end user $i$, and $R$ radius of the catchment area. Authors tested the behavior of the system with different values of $R$ in order to examine the impact of $R$ on the collected quantity of recyclables from the one side, and on the logistics network configuration from the other.

Lin et al. (2011) proposed Integer Programming (IP) model to determine convenient CPs in two-shift collection plan on the basis of proximity and then applied Ant Colony Optimization algorithm to determine the most effective routing plan of each shift. Firstly, the authors defined the regions eligible for a two-shift collection schedule and the coverage radius of each recycling CPs. These recycling CPs in the one-shift collection plan are conveniently located for the end users. But, in the two-shift collection plan, end user unable to access their closest CP at the scheduled collection time can dispose of their recyclables at one of the alternative accessible CPs (AACPs) in the second shift. Authors defined the term "coverage radius" representing the maximum distance that end users have to walk from the nearest CP to an AACP. The relationship between a CP (point 1), coverage radius (R), and the AACPs of the observed CP (i.e., points 3 and 4) is presented in Figure 6.

Then, the IP model is formulated to determine the minimal number of CPs required within a predefined coverage radius and to classify the CPs into day and night shifts. Authors used four coverage radii in this study: 50, 75, 100, and 500 m.

![Figure 6. Coverage radius for CPs and AACPs (Lin et al. 2011)](image)

Kim and Lee (2018) proposed two collection network design models: a single-period static model for time-invariant demands and a multi-period restricted-dynamic model for time-variant demands over a planning horizon. Proposed models determine the locations and capacities of CPs as well as the allocations of returned products to the opened CPs. Authors incorporated the maximum allowable distance between CPs and demand points as well as the minimum recovery rates of CPs in the model. Authors incorporated the maximum allowable distance between CPs as well as the minimum recovery rates of CPs in the model. Maximum allowable distance between CPs and demand points is formulated as:

$$d_{ij}x_{ij} \leq S_jy^k_j$$

(2)

where $d_{ij}$ represents the distance between nodes $i$ and $j$ (demand points and potential locations for CPs $i\neq j$), $S_j$ represents the maximum allowable collection distance at the CPs
opened at node \( j \). \( y^k_j \) and \( x_{ij} \) are binary variables. Maximum allowable distances were generated from a discrete uniform distribution with value range (140, 200).

\[
x_{ij} = \begin{cases} 
1, & \text{if the products at node } i \text{ are allocated to CP located at node } j \\
0, & \text{otherwise}
\end{cases} 
\]  \hspace{1cm} (3)

\[
y^k_j = \begin{cases} 
1, & \text{if CP with capacity } k \text{ is opened at node } j \\
0, & \text{otherwise}
\end{cases} 
\]  \hspace{1cm} (4)

Coverage radii, used in these papers, are basically lean on the idea which stands behind formulations of covering location problems introduced by Toregas et al. (1971) and Church and ReVelle (1974). In the context of locating CPs in RLNs, as stated collection service exists only when end users are within the certain (reasonable) distance from a specific CPs. It is clear that defining value of coverage radius strongly influences the design of RLN. Recyclables beyond defined distance are not covered at all, that is not collected. This seems to be an unrealistic modeling assumption in many potential applications (Berman et al., (2003), Eislet and Marianov, (2009)). Hence, Berman et al., (2003), Eislet and Marianov, (2009), Church and Roberts, (1983), Berman and Krass, (2002), suggested that the coverage provided by the facility is assumed to fall off gradually according to some decay function (Figure 7).

![Figure 7. Coverage decay functions (Eislet and Marianov, 2009).](image)

This decay function for selecting optimal locations of CPs was used in Vidovic et al. (2016). Authors presented a mathematical model of a two-echelon LRP in case of recyclables collection with a profit and distance dependent collection rate in the urban environment. Authors modeled the influence of distance between end users and CPs by assuming that the recyclables collection rate, \( f(d) \in [0, 1] \), is a known function of distance. This function models the influence of the distance between end users and CPs, in a way that the collection rate is inversely proportional to the distance (Figure 8). Authors defined two characteristic distances, \( l \) and \( u \) (\( l < u \)), as in Berman et al. (2003), between an end user and CP, where \( l \) represents the lower and \( u \) upper bound of walking distance to a CP for each end user. When the distance from the end user to the closest CP
is $0 \leq d \leq l$, then $f(d) = 1$, while in case when $d \geq u$, $f(d) = 0$. If the distance between the end user and CP is $l \leq d \leq u$, it is assumed that the collection rate corresponds to $f(d) = \frac{u - d}{u - l}$ (Figure 8).

So, the collection rate $Z_{ikb}$ for end user $i$ and CP $k$, in city block $b$, for the distance $d_{ikb}$ is calculated as:

$$Z_{ikb} = \begin{cases} 
1, & \text{when } 0 \leq d_{ikb} \leq l \\
1 - d_{ikb}, & \text{when } l \leq d_{ikb} \leq u \\
0, & \text{when } d_{ikb} > u 
\end{cases}$$

(5)

![Characteristics of $f(d)$](image)

Figure 8. Characteristic distances and shape of function $f(d)$ (Vidovic et al., 2016)

Similar idea was used in the paper by Rahim and Sepil (2014), where authors addressed an LRP in glass recycling. Authors combined maximal covering location problem in the presence of partial coverage and selective traveling salesman problem to determine the location of CPs for glass and the routes of collecting vehicles. They assumed that the rate of recycling of a resident in zone $i$ to a CP located at site $j$, along with the distance between zone $i$ and site $j$ denoted as $d_{ij}$ can be expressed as $q \times k_{ij}$ where:

$q$ is the daily expected amount of recyclable bottles produced per end user, and

$$k_{ij} = \begin{cases} 
1, & \text{if } d_{ij} \leq S \\
1 - \frac{d_{ij} - S}{T - S}, & \text{if } S < d_{ij} \leq T \\
0, & \text{otherwise}
\end{cases}$$

(6)

$S$ and $T$ are parameters representing the linear partial coverage function. Authors stated that the values of $S$ and $T$ parameters, that define the critical distances for full and partial coverage, affect the solutions considerably. After preliminary testing, they set the ratio of $S$ to $T$ as 0.75.

Explained approaches used for selecting locations of CPs, refers to typical recyclables generated by end users like paper, metal cans, plastic bottles, etc., where CP is usually container for collecting returned products. Distance between end users and CP’s location is the distance between the end user’s residency and actual potential location of the container. But in case of, for example, end-of-life vehicles (ELVs) or waste on electric...
and electronic equipment (WEEE), CP is a different type of facility (usually buy-back centers), so slightly different approaches for selecting CP’s location can be used.

In case of end-of-life vehicles (ELVs) as recyclables, classical covering location models used for selecting locations of CPs would aggregate end users in a zip code area by the zip code’s centroid, which allows the problem to be manageable regarding the problem’s size and available data. This kind of approach, although reasonable, introduces errors in solution’s accuracy such as (Vidovic et al., 2011):

- the district that is considered to be covered is actually not. This is the case when the service zone area is only partially covered by the CP, while the service zone’s centroid is covered (the centroid is on the distance smaller than the service radius)
- the service zone that is considered to be uncovered is actually partially covered. This happens when the service zone area is partially covered by the CP, while the service zone’s centroid is not covered (the centroid is on the distance greater than the service radius);
- overlapping of the service zone circles affects the predicted number of ELVs collected. This is the case when the service zone area is partially covered by two or more CPs, while the service zone’s centroid is covered by one or more facilities;

Vidovic et al. (2011) proposed a novel covering approach for locating CPs for ELVs which decreases aggregation error by introducing the concept of multiple service zones.

For allowable distance from end users to CP’s locations, authors used two concepts, found in the UK and Germany ELV legislation. Firstly, the authors proposed a mathematical model for designing RLN based on only one allowable service distance, $R_{fix}$, between the end users and the CPs. This kind of service radius was found in German legislation in which the maximum distance from the end user and a CP should not exceed 50 km. Secondly, the authors proposed a mathematical model for designing RLN based on two allowable service distances, $R_{min}$ and $R_{max}$, between the end users and the CPs. This kind of service radii was found in the UK legislation, which stated that 75% of end users should be within 10 miles on average of the nearest collection facility and no one should be more than 30 miles, in which case free take back is applied.

The proposed approach to decrease of aggregation error was based on an innovative concept aggregation of the service zones centroids. Authors introduced the idea of service zone partitioning to define subzones (subsets of demand locations), which are covered by one or more CPs. Then, the subzones are aggregated into subzone centroids which demand is then calculated as a fraction of the total service zone’s demand (proportional to the covered zone area). In Figure 10 proposed service area partitioning concept for the case of two allowable service distances is illustrated.
As UK legislation stated, the radii of the circles whose centers are located at the same potential location for the CP are denoted as $R_{\min}$ and $R_{\max}$. The smaller and the greater areas of the circles are denoted as $\xi_i^{R_{\max}}$ and $\xi_i^{R_{\min}}$, while the difference between these two values $\xi_i^{R_{\max}} - \xi_i^{R_{\min}}$ represents the ring area. Then, any subzone $k$ of district $j$, with an area $\chi_{kj}$ is expressed as an intersection of district $j$, and an arbitrary number of circles $\xi_i^{R_{\min}}$ and ring areas $\xi_i^{R_{\max}} - \xi_i^{R_{\min}}$. Set $\Omega_{kj}$, representing potential locations of the CPs whose circle or ring areas fully cover the $k$th subzone of district $j$, is divided into two subsets: $\Omega_{kj}'$ and $\Omega_{kj}''$. Set $\Omega_{kj}'$ contains the potential locations that cover the subzone with the circle areas $\xi_i^{R_{\min}}$, while set $\Omega_{kj}''$ contains the potential locations that cover the subzone by the ring areas $\xi_i^{R_{\max}} - \xi_i^{R_{\min}}$. Then, zone partitioning concept for the case of two allowable distances, is expressed as follows:

$$\sum_{i \in \Omega_{kj}} x_i \geq y_{kj}', \forall j, k \quad (7)$$

$$\sum_{i \in \Omega_{kj}} x_i \geq y_{kj}''', \forall j, k \quad (8)$$

$$y_{kj}' + y_{kj}''' \leq 1, \forall j, k \quad (9)$$

where

$$x_i = \begin{cases} 1, \text{if location } i \text{ is selected} \\ 0, \text{otherwise} \end{cases}, \forall i \quad (10)$$

$$y_{kj}' = \begin{cases} 1, \text{if the } k\text{th subzone of the district } j \text{ is served from the distance } R_{\min} \\ 0, \text{otherwise} \end{cases}, \forall j, k \quad (11)$$

$$y_{kj}''' = \begin{cases} 1, \text{if the } k\text{th subzone of the district } j \text{ is served from the distance } R_{\max} \\ 0, \text{otherwise} \end{cases}, \forall j, k \quad (12)$$

Constraints (6) and (7) allow a subzone $k$ of district $j$ to be served from the distances $R_{\min}$ or $R_{\max}$, respectively, only if one or more CPs that cover it within those distances are
opened. The constraints (8) provide that subzone \( k \) of district \( j \) is not counted twice in the objective function when coverage is provided from both distances.

On the other hand, some of the authors studied the problem of locating CPs in RLNs in the case when end users receive an incentive for returned products. Some of the authors argue that the financial incentive offered to the end users must be involved in designing the collection network (Hosseini et al. (2019); Aras and Aksen (2008); Boyacı et al. (2006); Aksen et al. (2009)). Of course, this statement depends on the type of returned products. In the case of recycling process, this fact is valid for the case of ELVs, WEEE, etc. Aras and Aksen (2008) assumed that each end user decides whether or not to return the product, based on both the financial incentive and the proximity to the nearest CP. They formulated a mixed-integer nonlinear facility location-allocation model to determine the optimal locations of the CPs and the optimal incentive values for each return type so as to maximize the profit from the returns. Authors expressed the proportion \( P_{jq} \) (Figure 11) of product holders of type \( q \) located in zone \( j \) who will return a used product, when the company offers incentive \( R_q \) for type \( q \) returns and the distance to the nearest collection center is \( d_j \) as:

\[
P_{jq} = \Pr(R_q - kd_j - R_{0q} > 0) = \min \left\{ 1, \frac{\max\{0, R_q - kd_j - a_q\}}{b_q - a_q} \right\}
\]

(13)

where \( kd_j \) represents the cost of carrying the used product to the collection center with the coefficient \( k \) (the cost per distance traveled), \( a_q \) and \( b_q \) represent the minimum and maximum incentive levels of product holder of type \( q \). Authors assumed that each product holder has a reservation incentive for returning his/her used product denoted as \( R_{0q} \).

![Figure 11. Return proportion \( P_{jq} \) as a function of incentive \( R_q \) (Aras and Aksen, 2008)](image)

Geographic Information Systems (GIS) was used as a tool for selecting CPs in RLNs for modeling distance between end users and CPs locations, in some papers. Gautam and Kumar (2005) proposed a model to analyze the trade-off between the number and capacity of CPs, average walking distance to drop-off CPs, the population covered (recyclables quantities), and the distance traveled by collection vehicles, in a GIS environment. Authors defined two goals: the first was to provide as many CPs as possible within the collection network, and the second to distribute CPs as evenly as possible on the network. In order to achieve these goals, authors formulated the GIS-based programming model with two objectives: maximization of the population served by the recycling CPs, and minimization of total walking distance from household to recycling CPs. Minimal and maximal acceptable walking distance, as input parameters in
the model, were 250 and 500 m, respectively. Gallardo et al. (2015) used GIS for determining number, capacity, and location of CPs for different types of MSW as well as collection strategies. Although, authors didn’t specifically observed RLNs, they proposed a comprehensive methodology to locate the minimum number of MSW CPs in a certain geographic area. Some of located CPs, were intended for collecting recyclables and authors took into account input parameters like the capacity of CPs, the frequency of collection, walking distance for end users in different types of collection strategies, etc. Tralhão et. al (2010) incorporated a multi-objective optimization model in a GIS-based interactive decision support system to determine the number of CPs to be opened, CPs capacities, locations, and the dwellings assigned to each CP. Proposed multi-objective optimization model consists of four objectives. The first objective minimizes the total investment costs; the second one minimizes the average distance from dwellings to CPs; the third objective minimizes the number of individuals too close to any CP, and final objective minimizes the number of dwellings too far from the CP. Authors considered four types of MSW for recycling: glass, plastic, paper and other (mainly organic waste). As an input parameter in the model authors used the assumption that no dwelling may be more than 200 m from an open CP and formulated it as:

\[ d_{ij} x_{ij} \leq D, i \in S, j \in C \]  

where \( d_{ij} \) represents the distance between the sector \( i \in S \) and the candidate site \( j \in C \); \( x_{ij} \) is a binary variable which takes 1 if the sector \( i \in S \) is assigned to the candidate site \( j \in C \) for recyclables deposition, 0 otherwise; and as mentioned \( D = 200 \) m. The second objective function that minimizes the average distance from dwellings to CPs is formulated:

\[ \min \frac{1}{F} \sum_{i \in S} \sum_{j \in C} f_i d_{ij} x_{ij} \]  

where \( F \) is the total number of dwellings, \( f_i \) number of dwellings of sector \( i \in S \), while \( x_{ij} \) and \( d_{ij} \) are previously explained. Due to a large number of dwellings in the observed numerical example, authors aggregated dwellings into linear sectors along the streets.

4. CONCLUSION

In this paper, we presented approaches used for designing one part of RLNs, particularly concentrating on mathematical modeling approaches used for selecting locations of CPs for recyclables collection. Selecting locations for CPs, some authors claim, is a key element of RLNs, since those locations directly influence on the success of recycling process through collected recyclables quantities and associated transportation costs, among others. Namely, since transportation cost associated with the collection of recyclables can be up to 70% of total system costs, location-allocation decisions regarding CPs define the effectiveness of establishing a recycling network as a whole.

A number of factors must be considered when locating CPs conveniently for end users (economic, social and environmental). For end users, distance to CPs is found to be one of the factors that influence on delivering generated recyclables to designated CPs’ locations. An appropriate or optimal, when possible, locations of CPs in RLNs can improve the existing system, through easier accessibility of CPs for every end user in the
observed geographical region, thus influencing on collected recyclables quantities and transportation costs, which is the overall aim of every recycling system. Acceptable walking distance for end users to CPs differs, not only from country to country, region to region, but from city to city, due to different cultural, economic and demographic characteristics. So, research on recycling motives of end users need to include those characteristics and to be input parameters when designing RLNs. Defining functions that model the dependency of distance between end users and CPs on collected recyclables’ quantities, based on aforementioned characteristics of particular cities/regions, could be one of the future researches in this filed. On the other hand, when solving the problems of real size dimensions, it is common practice to aggregate end users in centroids, sectors, etc. which introduces errors in solution’s accuracy. Hence, in this case, future research should be concentrating on approaches which decrease an aggregation error.

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