Article:

Zaharudin, Z.A., Brint, A. orcid.org/0000-0002-8863-407X, Genovese, A. orcid.org/0000-0002-5652-4634 et al. (1 more author) (2021) A spatial interaction model for the representation of user access to household waste recycling centres. Resources, Conservation and Recycling, 168. 105438. ISSN 0921-3449

https://doi.org/10.1016/j.resconrec.2021.105438

A spatial interaction model for the representation of user access to Household Waste Recycling Centres

Zati Aqmar Zaharudin[1,2], Andrew Brint[1], Andrea Genovese[1,*] , Carmela Piccolo[3]

[1]University of Sheffield, Management School, Sheffield (UK)

{a.brint, a.genovese}@shef.ac.uk

[2] Universiti Teknologi MARA, Negeri Sembilan Branch

zati@uitm.edu.my

[3] Department of Industrial Engineering, University of Naples "Federico II", Naples (Italy)

carmela.piccolo@unina.it

Abstract

Managing waste is a crucial challenge for modern societies. By 2020, the UK government target is to recycle 50% of the country's household waste. Household Waste Recycling Centres represent key facilities for achieving this target. However, local authority budgets are under severe strain due to reductions in central government transfers. As such, local councils often need to perform reconfigurations of the recycling centres networks, by reducing the number of sites or their opening hours while still offering adequate service levels. Central to being able to do this, is understanding the spatial patterns of access to such centres. Therefore, this paper develops a spatial interaction model aimed at examining and exploring users' behaviour and preferences when choosing recycling centres. Specifically, an origin-constrained gravity model is developed; through a careful estimation of its attractiveness parameters, the model is capable of describing demand flows from Sheffield City Council districts to Household Waste Recycling Facilities. The results are compared to actual data obtained through a users' survey from an English Local Authority. The high level of correlation between the results provided by the model and actual users' preferences indicates that the model can be a valuable tool in describing users' behaviour in accessing the service. Based on this, the model can be employed in order to estimate the impacts of modifications to the network configuration on users, performing scenario analyses and providing useful suggestions to planners.

Keywords

Waste Management; Gravity Models; Spatial Interaction Models; Household Waste Recycling Centres

---

[*] Corresponding Author

A spatial interaction model for the representation of user access to Household Waste Recycling Centres

Abstract

Managing waste is a crucial challenge for modern societies. By 2020, the UK government target is to recycle 50% of the country's household waste. Household Waste Recycling Centres represent key facilities for achieving this target. However, local authority budgets are under severe strain due to reductions in central government transfers. As such, local councils often need to perform reconfigurations of the recycling centres networks, by reducing the number of sites or their opening hours while still offering adequate service levels. Central to being able to do this, is understanding the spatial patterns of access to such centres. Therefore, this paper develops a spatial interaction model aimed at examining and exploring users' behaviour and preferences when choosing recycling centres. Specifically, an origin-constrained gravity model is developed; through a careful estimation of its attractiveness parameters, the model is capable of describing demand flows from Sheffield City Council districts to Household Waste Recycling Facilities. The results are compared to actual data obtained through a users' survey from an English Local Authority. The high level of correlation between the results provided by the model and actual users' preferences indicates that the model can be a valuable tool in describing users' behaviour in accessing the service. Based on this, the model can be employed in order to estimate the impacts of modifications to the network configuration on users, performing scenario analyses and providing useful suggestions to planners.

1. Introduction

Waste management is a key component in establishing a sustainable environment in order to deal with future challenges such as population growth, increased affluence, and diminishing natural resources. Consequently, British Local Authorities are expected to achieve landfill diversion targets where at least 50% of waste (including paper, plastic, metal, textiles, biodegradable wastes and green wastes) can be re-used and recycled by 2020. The Department of Environment, Food and Rural Affairs (DEFRA) has the overall responsibility for waste management in the UK. At a local level, this responsibility is devolved to each local authority (LA). The waste collected by the LAs is either recycled, sent to landfill or incinerated. Within this context, Household Waste Recycling Centres (HWRCs) (also known as recycling drop-off centres in the USA) represent essential facilities provided by LAs (Speirs and Tucker, 2001; Cherrett et al., 2007). Such facilities ensure the recovery, reuse and recycling of selected materials that are not generally collected through kerbside systems (such as furniture, electric and electronic equipment, garden waste); the provision of such facilities represents then an essential element in order to foster the transition towards a Circular Economy.

However, the severe funding cuts suffered by the public sector over the last ten years mean that LAs are facing increasing challenges in the cost-effective provision of such essential services. Fiscal austerity policies are now a defining feature across many European countries. In the United Kingdom, according to The Institute for Fiscal Studies, the period 2010–2015 saw the Department for Communities and Local Government take a funding cut equivalent to 23.4% per person (Innes and Tetlow, 2015). In many Local Authorities, as a result of the recent regime of austerity, HWRC facilities have been downsized, closed, seen their opening hours reduced, or are under threat of closure.

When considering whether to make changes to the existing network of HWRCs in a given area, LA planners need to ask some of the following questions, in order to devise appropriate actions, solutions and weigh possible risks: (i) "*What makes people visit a particular HWRC?*"; (ii) "*What are the spatial patterns characterising access to HWRCs?*"; (iii) "*What will be the impact on the rest of the recycling network if a particular recycling centre is closed?*". Consequently, there is a need to develop models and tools that could provide LAs and public bodies with an understanding of demand for services offered by HWRCs and of its spatial configuration. This would be a prerequisite for estimating the impacts of possible modifications to their HWRC networks on users' access, and making informed decisions about potential reconfigurations.

In order to address such needs, this study develops an adaptation of a classical Spatial Interaction Model (specifically, a gravity model) for planning purposes and scenario analyses. The model is applied to a real-world scenario focused on a case study from Sheffield City Council. This paper is arranged as follows: Section 2 gives a general overview of the current practice for managing HWRCs, along with contributions from the academic literature; Section 3 provides some generalities about spatial interaction models. Section 4 introduces the case study based on Sheffield's HWRC network. Section 5 applies an adaptation of the spatial interaction model to such a case; Section 6 discusses the results derived from using the spatial interaction model. Finally, some conclusions are drawn in Section 7.

2. Background

The UK government intends to move to a zero-waste *circular economy* (DEFRA, 2015); concepts such as *reduce, re-use and recycle* are central to this intention. In the UK, it is local authorities' statutory duty to collect household waste (DEFRA, 2015; Kirkman and Voulvoulis, 2017). They use three main mechanisms for achieving this: kerbside collections, HWRCs and smaller recycling points, and on-demand specialist (bulky) collection services (Woodard et al., 2005). Besides collection by local authorities, commercial organisations might also collect household waste, for instance as a supplement to local authority collections of special items (e.g., the disposal of a large appliance when a new one is delivered) (Zacho et al., 2018).

2.1 HWRCs: requirements, performance and current issues

HWRCs are viewed as being key to helping LAs achieve their statutory recycling targets (Harder et al., 2008; Maynard et al., 2009; WRAP, 2016). They are particularly important as they can achieve high levels of recycling through the correct sorting of items. Engkvist et al. (2016) notes that "well performing recycling centres, being very early in the recycling chain, are key to the subsequent steps in waste processing". Consequently, it is not unusual for HWRCs to handle a significant percentage of household waste; for instance, in Denmark such centres handle 25% of the total household waste being produced (Edjabou et al., 2019). Previous studies from the UK claimed that around 60% of households regularly use HWRCs as the main route for disposing of bulky items (Curran et al., 2007). Commercial waste is generally banned at HWRCs, as it increases congestion problems, tends to utilise large capacities and potentially disrupts recycling procedures at the sites.

The performance of a HWRC is measured through recycling rates and site-users' satisfaction surveys (Woodard et al., 2004 and 2005; Harder et al., 2008; WRAP, 2016). Recycling rates are influenced by accepted materials, location and layout, along with assistance and service provided by staff (WRAP, 2016; Engkvist et al., 2016). WRAP (2016) noted that a diversified recycling portfolio attracted users to go to specific HWRCs that have user-friendly, split-level designs; these factors can then have a positive impact on recycling rates. Another factor that can boost recycling rates is the presence of ground-level access to containers; also, clear signage with suitable pathway design can increase accessibility and reduce disruption. Cunningham and Conroy (2006) pointed out that vehicle movements and users' permits are major factors that need to be considered in the design of HWRCs.

In terms of the network configuration of HWRCs, accessibility is a key criterion (Harder et al., 2008). WRAP (2016) recommends a maximum catchment radius of three miles for HWRCs in urban areas and seven miles in rural areas, in such a way to cover the great majority of residents. Additionally, WRAP (2016) provides guidance in terms of maximum travel times to HWRCs (respectively, 20 and 30 minutes – by car – in urban and rural areas). Furthermore, recommendations are provided in terms of the maximum population that can be served by a single HWRC.

While the importance of HWRCs is globally acknowledged, in the United Kingdom, due to the continuing cuts in funding to the public sector and local authorities, an increasing number of LAs are facing challenges in terms of cost-effective provision of essential services (Widdowson et al., 2015; Smith & Bolton, 2018). The result is that in many LAs, HWRCs are facing the risk of closure. See, for example, reports about closures in Oxfordshire (reported by Sproule, 2015) and

Hampshire (reported by Neal, 2016) and the reduction in opening hours in North Yorkshire (reported by Prest, 2016), Buckinghamshire (Marino, 2018) and Warwickshire (WRAP, 2016). In 2016, Cheshire East Council proposed to close six sites whereas Hampshire County Council planned to reduce the operating hours of its HWRCs (WRAP, 2016). The impact of such network downsizing can be very detrimental on the environmental performance of LAs, as it has been reported that an insufficient number of recycling facilities is one of the main reasons for the increase in the number of fly-tipping cases, i.e. the illegal dumping of waste (Evans, 2013; WRAP, 2016). This can cause environmental pollution and often results in the LAs needing to cover clean-up costs. As such, LAs are under pressure to find more efficient ways to manage their HWRCs, while the public is increasingly expecting higher service levels in terms of a broader range of recycling materials, well-trained staff and a more enjoyable site service (WRAP, 2016).

2.2 Modelling approaches for dealing with the organisation of HWRC networks

Academic literature has been devoting sporadic attention to the issues related to the planning of services offered by HWRCs. Woodard et al. (2004) monitored a HWRC in the English county of Sussex. The authors observed the operation of the sites for one week, monitoring 969 site users, identifying users' behaviour and providing recommendations for the layout optimisation of the site. Williams and Taylor (2004) carried out a telephone survey amongst HWRC attendants in an English Local Authority, in order to establish the effects of site improvements on customer satisfaction and investigating methods that would assist customers in maximising the amount of recycling at HWRCs.

Maynard et al. (2009) proposed a modelling approach to investigate the significance of key factors (vehicle type, compaction type, site design, temporal effects) in influencing the variability in observed bin weights produced by HWRCs, in order to optimise performance of the centres.

Sundin et al. (2011) applied lean production principles for designing and managing recycling centre operations, in order to improve layout choices. Such research was aimed at improving the performance of 16 Swedish HWRCs that had experienced a variety of problems such as queues of visitors, overloading of material and improper sorting. A similar approach was followed by Engkvist et al. (2016).

Using an English Local Authority as a case study, Ongondo et al. (2011) discussed the estimated impacts of the so-called digital switchover (which took place in 2012) on British HWRCs, estimating the impact that this would have had in terms of material flows and capacity of the centres. With reference to Danish HWRCs, Edjabou et al. (2019) performed an analysis of seasonal and geographical variations in waste collection, drawing interesting implications in terms of service provision.

Consequently, while some of the reported contributions focused on layout optimisation and on the analysis of material flows (mainly at the single centre level), it appears that demand issues have not been specifically investigated, especially according to a spatial pattern within the context of a network composed of multiple HWRCs. As such, the current literature does not provide LAs and public bodies with tools that can be utilised in order to gain an understanding of the determinants underlying the demand for services offered by HWRCs and the spatial distribution of such demand. Such understanding would be a prerequisite for estimating the impacts of possible modifications to HWRC networks on users' access. For this reason, the remainder of the paper develops an adaptation of a classical Spatial Interaction Model for HWRC networks.

3. Spatial Interaction Models: Generalities

General location theory reports that while distance is one of the influencing factors for users' selection of facilities (Eiselt et al., 1993; Newing et al., 2015), such a choice might also be based on other factors such as the physical condition of a facility, its ease of use, the services it provides and also the distance of the facility from other facilities (Eklund et al., 2010). Clearly, such concepts also apply to HWRC facilities (Struk, 2017). Spatial interaction models allow such features to be considered (Haynes and Fotheringham, 1984); as such, this class of models could be ideal to describe the process governing the selection of the HWRC facility to be visited by a user.

The left hand side of Figure 1 illustrates a situation in which demand from a generic customer *i* is always assigned to its nearest facility *j*. The right hand side of Figure 1 shows the situation that occurs in practice where, although customers take into account distance as one of the main factors in selecting the facility to visit, customers' preferences might mean that they do not automatically go to the nearest facility. These situations are indicated by the green dashed lines in Figure 1.

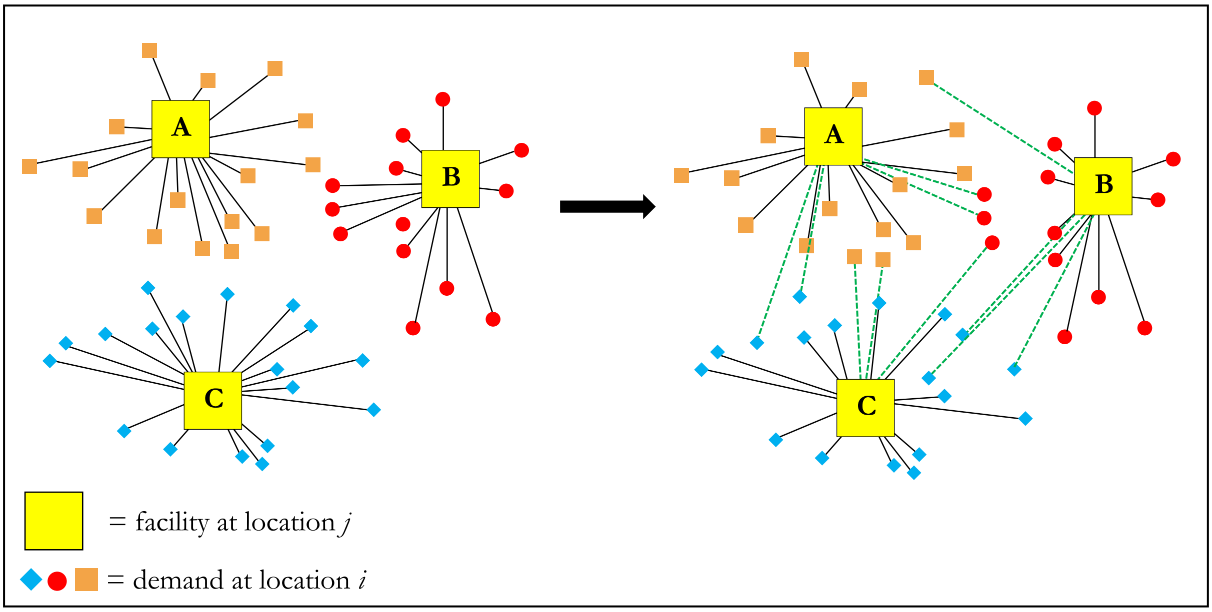

Figure 1: Nearest Facility (left) vs Spatial Interaction (right) allocation models

Spatial Interaction models describe spatial flows (of people, goods, or information) resulting from decision-making processes. Such a class of models, and its variants, has been applied in various sectors, including education, tourism, trade, health related studies, social network and transportation (See Table 1), in order to predict flows between regions and understand the determinants of such flows (Fotheringham, 1983; Tong et al., 2018).

Flows between territorial units are estimated through an assessment of their characteristics, as well as the distance between them (Black, 1972). Bröcker (1989) demonstrated that trade flows inspired by spatial interaction models provide results that, besides being empirically sound, are consistent with the ones derived from classical spatial equilibrium models (Samuelson 1952).

Sector	Application Context	Authors (year)
Education	Student mobility flows	Bruno & Genovese, (2012)
Tourism	Estimation of tourist flows	Morley et al., (2014); Patuelli et al., (2014, 2016); Galli et al., (2016)
Trade	Analysis of the impact of international trade policies	De Benedictis and Taglioni, (2011)
Health-Related Studies	Hospital patient flows	Congdon, (2001); Teow et al., (2018)
Social Networks	Online social interaction	Lee et al., (2011); Wang et al., (2018)
Transportation	Trip distribution for regional railway systems; freight transport flows estimation	Cordera et al., (2018); Holguín-Veras et al., (2015)

Table 1 - Example applications of spatial interaction models

The general formulation and description of spatial interaction models is discussed, amongst others, by Wilson (1971), Beaumont (1980), Fotheringham (1983), Fotheringham and O'Kelly (1989), Sen and Smith (1995) and Roy and Thill (2004). In general, a mathematical expression is used to represent the consumers' choice among a set of available alternatives (Bruno and Genovese, 2012). A spatial interaction model is constructed by first considering a set I of origin nodes (where the customers are located) and a set J of destination nodes (the locations of single facilities). In general, the model assumes the probability that customer i chooses a facility j is based on j's attractiveness value and is inversely proportional to a power of the distance between the user and the facility. This distance can be an actual distance (e.g. in kilometres), but it could also be a travel time.

Various forms of spatial interaction models have been applied in aggregate analysis, most commonly the so-called gravity model (Wilson, 1971). The gravity model incorporates two basic factors that affect the level of flow between places: a measure of potential for flow, and the distance between them (Giuliano et al., 2015). This can be described through a gravity equation, which has strong analogies with Newton's Law of Gravity:

$$G_{ij} = k_{ij} \cdot (P_i)^{\alpha_i} \cdot (Q_j)^{\beta_j} \cdot f(d_{ij})$$

where G_{ij} is the flow from origin *i* to destination *j* which depends on: (i) a generation factor (P_i) associated with the origin *i*; (ii) an attractiveness factor (Q_j) due to the features of the destination *j*; (iii) the "impedance" between *i* and *j* measured as a function $f(d_{ij})$ of the distance from *i* to *j*. In the above expression, k_{ij}, α_i and β_j represent calibration parameters. In the literature, the deterrence (or distance decay or impedance) function $f(d_{ij})$ is usually assumed to be an exponential or a power function (Fotheringham and O'Kelly, 1989; Chen, 2015). According to Chen (2015), power-law decay functions are more suitable for analysing large, complex, and scale-free regional and urban systems. A frequently used expression for the power form of the impedance function is:

$$f(d_{ij}) = (d_{ij})^{-n}$$

In most cases, $1 \leq n \leq 3$ (Huff, 1964; Haynes and Fotheringham, 1984). The meaning of the factors P_i and Q_j can vary. Their magnitudes can be affected by various attributes; in practice $P_i = P_i(p_{1i}, p_{2i}, \ldots, p_{pi})$ and $Q_j = Q_j(q_{1j}, q_{2j}, \ldots, q_{qj})$ where $p_{1i}, p_{2i}, \ldots, p_{pi}$ and $q_{1j}, q_{2j}, \ldots, q_{qj}$ are attributes linked to the nodes.

In many versions of the model it is assumed that $\alpha_j = \beta_j = 1\ \forall j$, $k_{ij} = k_{ji} = k\ \forall i, j$ and, hence, the flow G_{ij} is equal to:

$$G_{ij} = k \cdot P_i \cdot Q_j \cdot (d_{ij})^{-n}$$

The definition of the attractiveness factors of each facility *j* (Q_j), of the distances d_{ij} (*i, j*=1,.., *N*) between customers and facilities, and of the calibration parameters of the model (k_{ij}, α_j, β_j, *n*) are necessary for the implementation of this model (Bruno and Genovese, 2012). The attractiveness factors of each facility *j* should represent its capability of attracting demand.

Wilson (1969, 1971) noted that from this simple *Newtonian* formulation (based on an entropy maximisation principle; see also Batty, 2010), which was employed originally to describe the connection strength between two places (rather than to predict spatial flows from a place to another), a whole family of spatial interaction models could be generated as extensions of the traditional gravity model. In particular, in some cases, there are constraints about the sum of the total flow emanating from customers (origins) or entering at facilities (destinations). If the total flows emanating from origins (O_i) are known, the model is called "origin constrained" and:

$$\sum_j G_{ij} = k \cdot P_i \cdot \sum_j (Q_j \cdot (d_{ij})^{-n}) = O_i$$

Dividing the two last expressions, we obtain:

$$\frac{G_{ij}}{\sum_j G_{ij}} = \frac{Q_j \cdot (d_{ij})^{-n}}{\sum_j (Q_j \cdot (d_{ij})^{-n})}$$

From which derives:

$$G_{ij} = O_i \cdot \frac{Q_j \cdot (d_{ij})^{-n}}{\sum_j (Q_j \cdot (d_{ij})^{-n})}$$

This expression is the core of the implemented model that will be described in the next sections, with the aim of quantifying user flows in accessing HWRCs in a given urban area.

4. Case Study: Sheffield HWRCs system

Sheffield is an English city with a population of 556,000 spread between 230,000 households (Office for National Statistics, 2016); the city is part of the county of South Yorkshire. Sheffield City Council currently provides and manages five HWRCs. Sheffield's case is very representative of the tensions experienced by LAs in waste management services, due to the financial pressures experienced by the Council, and to the contentious relationship between the council itself and the contractor managing the entire waste management cycle (Cole, 2017). This relationship has resulted in service disruptions and labour disputes (BBC, 2016) which have damaged the reputation of the contractor and resulted in inconveniences for citizens. Also, regarding the HWRC network, the Council has been experiencing several issues. On the one hand, constant cuts to the Council budget have posed a serious challenge to the operations of the centre; on the other hand, the current HWRC system experiences very high levels of demand and frequent queueing problems (Let's Recycle, 2020). As such, the Council has been constantly reviewing the performance of the HWRC network, with the aim of better understanding demand patterns and considering alternative configurations.

4.1 Sheffield HWRC system generalities

Locations of the centres are shown in Figure 2 (Longley Avenue, Beighton Road, Blackstock Road, Deepcar and Greaves Lane), along with the partition of the city in to 28 electoral wards. These 28 electoral wards are then partitioned into 206 districts (see Figure 3 for an example of a partitioning of a ward into districts).

It can be seen from Figure 2 that the Longley Avenue facility is located near the centre of the council's territory, while all of the other four HWRCs are positioned near to the council's border. In particular, Greaves Lane and Beighton Road sites are near to the edge of the council's area and both are easily accessible by residents who live outside Sheffield City Council area. For example, some of the districts in the neighbouring local authority of Barnsley (which is still part of the county of South Yorkshire) are just 4 minutes away by car from Greaves Lane. Likewise, Beighton Road's HWRC is easily accessible by non-Sheffield City Council districts such as the Swallownest ward, which again is only 4 minutes away, despite being located in the Rotherham Metropolitan Borough Council area (part of South Yorkshire).

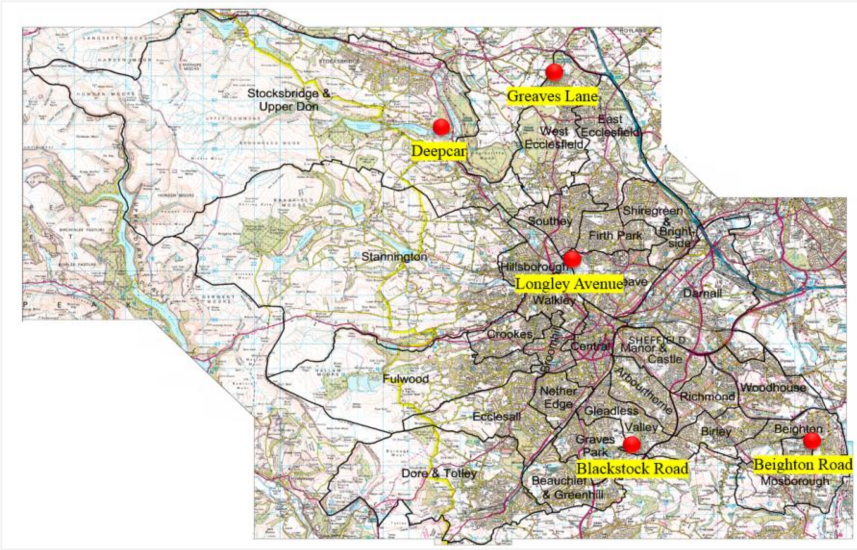

Figure 2 - A map of Sheffield City Council's electoral wards and HWRC locations

The opening days for each HWRC vary, while the operational hours depend on the season. Table 2 indicates opening days for each facility. Longley Avenue operates 7 days a week, Blackstock Road and Beighton Road are opened six days a week, while Greaves Lane and Deepcar are functioning five days a week. As shown in Table 2, the schedule ensures that for each day, users can find at least two centres that are operational. The operating hours for all centres are from 10.00 a.m. until 6.00 p.m. during the summer, and from 10.00 a.m. until 4.00 p.m. during the winter.

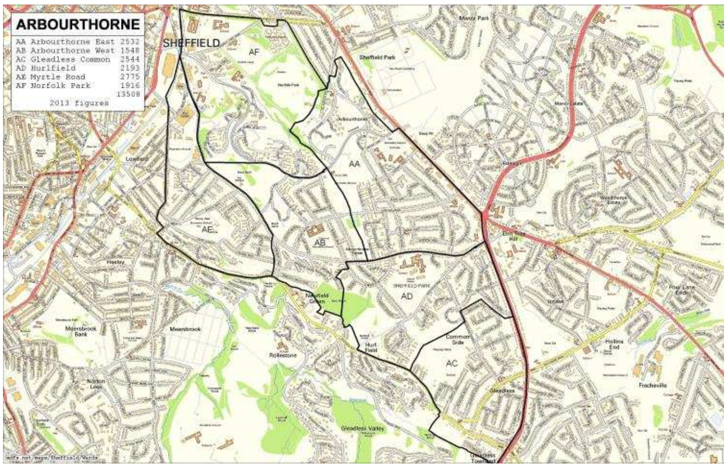

Figure 3 – Partitioning of Electoral Wards into Districts – Arbourthorne ward

The recyclable items that can be received by each HWRC vary. For example, the only centre that can receive household chemicals (such as residuals of painting products) is Longley

Avenue, but this centre does not accept materials containing asbestos. The number of accepted materials categories varies across the five HWRCs (see Table 2). These figures show that even though Longley Avenue is operated seven days a week, the range of recyclable items it accepts is quite limited compared to the other HWRCs.

			Opening Days						
HWRCs	**Accepted Materials**	**Number of Containers**	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**
Beighton Road	23	11	☑		☑	☑	☑	☑	☑
Blackstock Road	26	12	☑	☑		☑	☑	☑	☑
Deepcar	23	6	☑			☑	☑	☑	☑
Greaves Lane	24	7	☑	☑			☑	☑	☑
Longley Avenue	22	10	☑	☑	☑	☑	☑	☑	☑

Table 2 – Accepted materials, number of containers and opening days for each HWRC.

The average composition of materials deposited at Sheffield's HWRCs in a typical year is illustrated in Figure 4. The highest proportion of waste being recycled is represented by green waste (38.59%), followed by mixed woods (28.25%), whilst other recyclable materials being deposited account for less than 10% of the total. This is probably because the other materials besides greens and mixed woods, are collected through the kerbside scheme operated by the council or disposed of at local recycling points, hence explaining the small amount deposited in all HWRCs.

Figure 5 shows the proportions of customers who access HWRCs at different times during the week. The lowest number of users is reported on a Wednesday (also due to the fact that there are only two HWRCs open on this day). Meanwhile, the highest number of users is on Sunday. The preferred time for users to visit the HWRCs is during the morning session, and this figure reduces slowly towards noon, but slightly increases after 2.00 – 3.00 p.m. On a daily basis, the number of users starts to decrease from 3.00 p.m. until the HWRCs are closed. It must be noted that access to these HWRCs is only allowed by car, for disposing household waste that cannot be disposed of at kerbside. Visiting the HWRCs without a car is not only unpractical (generally very large and bulky items are disposed of at HWRCs) but also forbidden (due to the organisation of the centres, for safety reasons). Special vehicles (such as vans and pick-ups) are just allowed based on an ad-hoc permit system.

Table 3 reports the list of Sheffield wards, including their population and travel times from the centroid of each ward to each of the HWRCs. Estimated travel times between the centre of each district (the sub-divisions of the wards) to each HWRC were provided by Sheffield City Council. Histograms of the distances between each HWRC and the 206 districts are shown in Figure 6. The mean of these travelling times is greatest for Deepcar and lowest for Longley Avenue.

While the distance and travel time data might be useful for understanding spatial patterns, these might not be the only reason behind the decision-making process for choosing a particular HWRC to visit. Consequently, a survey was carried out in order to discover the preferred HWRCs for households in each ward, and the main factors that guide the choice process; the findings are reported in the next sub-section.

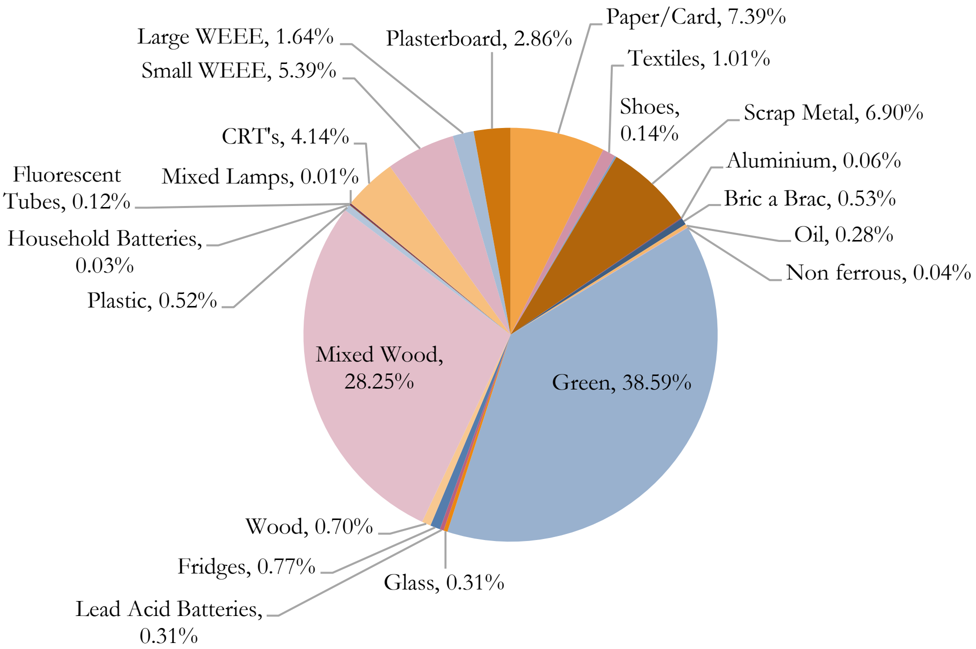

Figure 4: Composition of waste (in weight) received by Sheffield HWRCs

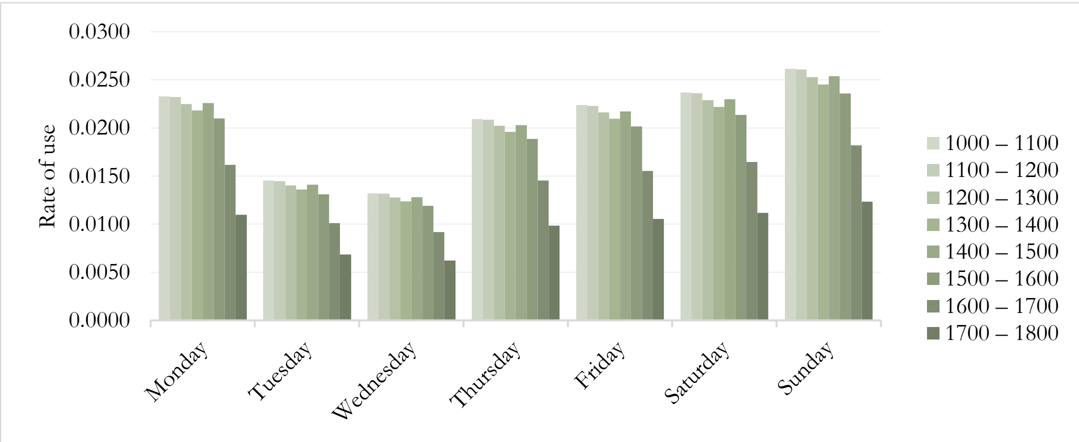

Figure 5 - Proportion of users according to days and hours (Source: Sheffield City Council)

		Travel times to HWRCs (minutes)				
Wards	**Households**	**Beighton Road**	**Blackstock Road**	**Deepcar**	**Greaves Lane**	**Longley Avenue**
Arbourthone	13508	12	3	25	23	15
Beauchief	13867	20	10	29	30	20
Beighton	13385	3	16	30	26	20
Birley	12976	8	8	28	24	18
Broomhill	13311	17	12	19	19	10
Burngreave	16055	13	13	19	19	5
Central	20855	15	10	23	23	13
Crookes	14099	19	14	19	21	11
Darnall	16000	13	14	20	16	13
Dore and Totley	13615	22	13	30	30	21
East Ecclesfield	14573	21	24	12	6	12
Ecclesall	14994	23	16	27	27	18
Firth Park	14498	21	22	19	14	7
Fulwood	14365	22	16	24	24	14
Gleadless Valley	14667	15	2	27	28	18
Graves Park	13634	19	10	27	28	18
Hillsborough	14103	21	18	11	14	7
Manor e Castle	13507	11	11	24	21	14
Mosborough	13821	8	13	34	30	23
Nether Edge	13645	19	12	23	24	14
Richmond	13455	5	11	23	19	12
Shiregreen	14721	20	21	19	15	9
Southey	13882	20	18	15	11	2
Stannington	14486	24	22	18	20	12
Stocksbridge	14701	32	33	6	12	20
Walkley	14926	19	14	16	17	9
West Ecclesfield	14376	23	21	10	6	8
Woodhouse	13572	3	13	27	22	18

Table 3 – Sheffield Wards; population data and travel times from HWRCs (minutes)

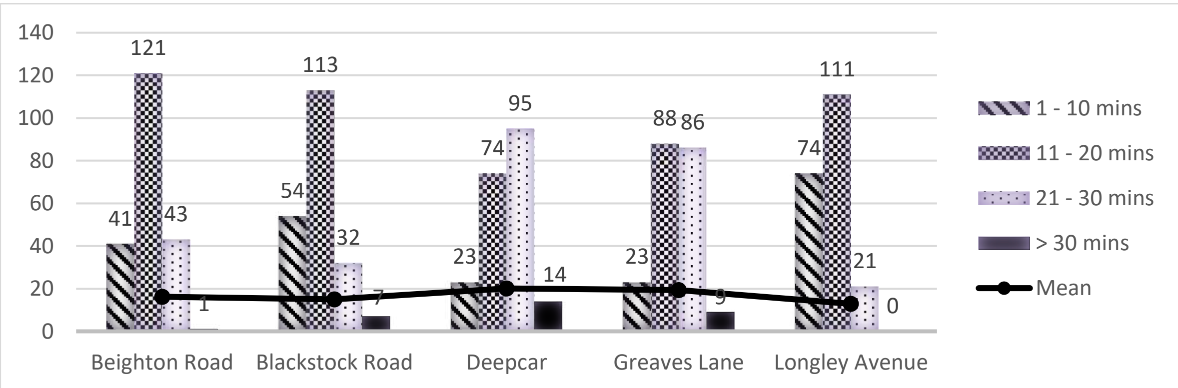

Figure 6 - Frequency of travel times (in minutes) from a district to a specified HWRC

4.2 HWRC user preferences survey

An online survey was conducted to assess the users' preferences with respect to HWRC access. The survey focussed on the satisfaction level of users with their experience in using the recycling points and centres. The target respondents were approached using email through the volunteer list of the University of Sheffield. There were 504 respondents to the survey. Anonymous respondents were asked to state their electoral ward of residence. The results showed that almost 90% use a HWRC at least once a year, with no significant difference across wards. Respondents were asked their preferences for the available HWRCs, ranking them from the most preferred to the least preferred one. This ranking was then converted into estimated probabilities of the respondent using each of the HWRCs by multiplying by the weights in Table 4. It was assumed that the probability of using the respondent's 4^{th} and 5^{th} choices was zero, given that these two choices had a negative correlation, being presented as "less preferred" and "least preferred".

Preferences	Weights
1 - most preferred	60%
2 - preferred	30%
3 - average	10%
4 - less preferred	0%
5 - least preferred	0%

Table 4 - Assumption on weights for each preference level

The resulting preference scores are shown in Table 5. On average, the most preferred centre is Blackstock Road, with 29.9%, followed by Longley Avenue (26.5%), Beighton Road (22.9%), Greaves Lane (11.3%) and lastly, Deepcar (9.5%). Out of the 28 wards, users from 10 wards choose Longley Avenue to be their preferred place to dispose their waste. This was followed by users from 9 wards choosing Blackstock Road, 6 wards choosing Beighton Road and only 2 wards choosing Greaves Lane. The least preferred HWRC is Deepcar, with Stockbridge and Upper Don being the only ward to choose this HWRC as the most preferred one. Also, users where asked to rate the main factors causing their choice of HWRC centres, by using a 5-point Likert Scale (with 1 meaning "not important at all" and 5 meaning "very important"). Proximity, recycling portfolio of the centre and centre organisation were found to be the most prominent factors, having all scoring average values larger than 4. Other factors (such as centre opening hours and recycling efficiency of the centre) were found to be less prominent, with averages lower than 3.00. Proximity is part of the general equation of the proposed spatial interaction model; hence, the two remaining prominent factors should be represented in the attractiveness function of the spatial interaction model that is going to be introduced in the next section. In addition to this, participants were also asked to state the main route by means of which they access HWRCs; Table 7 shows that almost the totality of surveyed users access HWRCs through on-purpose trips; furthermore, almost 90% of the users do not wish to travel more than 20 minutes for accessing a HWRC.

		Preferences				
Wards	**Households**	**Beighton Road**	**Blackstock Road**	**Deepcar**	**Greaves Lane**	**Longley Avenue**
Arbourthone	13508	22.4%	56.3%	11.3%	1.2%	8.8%
Beauchief	13867	27.9%	55.7%	4.3%	1.4%	10.7%
Beighton	13385	51.1%	30.0%	5.6%	1.1%	12.2%
Birley	12976	50.0%	38.3%	1.7%	0.0%	10.0%
Broomhill	13311	16.1%	32.6%	9.1%	5.7%	36.5%
Burngreave	16055	0.1%	13.3%	3.3%	23.3%	60.0%
Central	20855	29.1%	45.4%	8.2%	5.5%	11.8%
Crookes	14099	14.3%	16.1%	9.6%	9.3%	50.7%
Darnall	16000	54.0%	26.0%	2.0%	2.0%	16.0%
Dore and Totley	13615	32.2%	56.7%	6.1%	2.8%	2.2%
East Ecclesfield	14573	1.2%	0.0%	13.7%	53.8%	31.3%
Ecclesall	14994	20.3%	53.4%	3.4%	2.9%	20.0%
Firth Park	14498	8.0%	8.0%	6.0%	18.0%	60.0%
Fulwood	14365	19.3%	25.7%	7.0%	8.3%	39.7%
Gleadless Valley	14667	24.3%	60.0%	2.8%	5.0%	7.9%
Graves Park	13634	21.2%	53.7%	3.8%	12.5%	8.8%
Hillsborough	14103	11.5%	8.9%	20.0%	12.3%	47.3%
Manor and Castle	13507	16.7%	50.0%	3.3%	0.0%	30.0%
Mosborough	13821	59.9%	30.0%	6.3%	1.3%	2.5%
Nether Edge	13645	17.0%	53.5%	11.0%	6.5%	12.0%
Richmond	13455	54.0%	36.0%	2.0%	2.0%	6.0%
Shiregreen	14721	16.7%	16.7%	7.8%	12.2%	46.6%
Southey	13882	6.0%	24.0%	8.0%	14.0%	48.0%
Stannington	14486	2.2%	2.2%	18.9%	23.3%	53.4%
Stocksbridge	14701	2.7%	0.9%	60.0%	20.0%	16.4%
Walkley	14926	15.0%	19.0%	10.0%	10.0%	46.0%
West Ecclesfield	14376	0.0%	0.0%	16.0%	54.0%	30.0%
Woodhouse	13572	55.1%	25.0%	3.3%	3.3%	13.3%
Total (%)	100.0%	22.9%	29.8%	9.5%	11.3%	26.5%
Total	403686	92588	120176	38353	45519	107050

Table 5 - The estimated split of each ward's customers to HWRCs

HWRC	Frequency
Longley Avenue	10
Blackstock Rd	9
Beighton Rd	6
Greaves Lane	2
Deepcar	1

Table 6 - Frequency of a HWRC being the first choice of a ward

Route	Frequency
Home-HWRC-Home	93.01%
Home-HWRC-Work	2.59%
Work-HWRC-Home	2.07%
Home-HWRC-Other	2.07%
Work-HWRC-Other	0.26%
Work-HWRC-Work	0.00%

Availability to Travel	Frequency
Less than 5 mins	2.86%
5 - 10 mins	22.14%
11 - 15 mins	38.33%
16 - 20 mins	25.24%
21 - 25 mins	7.38%
More than 25 mins	4.05%

Table 7 – Preferred routes for accessing HWRCs (left); availability to travel for accessing HWRCs (right)

5. Model Description

We propose a mathematical model for the description of demand flows from Sheffield City Council districts to Household Waste Recycling Facilities. In particular, we adopt the origin constrained model presented in Section 3. The adaptation of the parameters is shown in Table 8 and described in the following.

As regards the zoning of the model, the centroids of the 206 districts into which the Sheffield City Council area (and its 28 electoral wards) is partitioned, are assumed as origins. Such origins are indicated with the index i ($i \in I$; $|I| = 206$). The destinations are represented by the index *j*, and can be identified with the five HWRCs managed by Sheffield City Council ($j \in J$; $|J| = 5$).

As described in Table 8, flows emanating from the origins (O_i) are represented by the number of households in each district. The attractiveness of a generic HWRC (Q_j) is based on several factors, hence let $Q_j = f(q_{kj})$ where q_{kj} is the generic attractiveness factor $\in K$. In the specific case of Sheffield HWRCs, as mentioned above, the survey found that the main factors ruling the choice of HWRC centres are proximity to the potential user, recycling portfolio and centre organisation. Proximity is part of the gravity model, hence only two further factors have been considered; specifically, the number of containers at each centre has been considered as a proxy of the centre organisation, while the number of materials which are accepted at each centre measures the recycling portfolio (see Table 9; normalised values of the figures introduced in Table 2 are employed). A weighted average formula is used to compute Q_j:

$$Q_j = wq_{1j} + (1 - w)q_{2j} \qquad \forall j \in J$$

where w represents the weight of the first attractiveness factor (with $0 \leq w \leq 1$) .

Finally, the travel times d_{ij} between the centre of each district i and each HWRC j were provided by Sheffield City Council.

Parameters	Implementation
i	Sheffield City Council Districts $(i \in I; \lvert I \rvert = 206)$
j	Household Waste Recycling Centres $(j \in J; \lvert J \rvert = 5)$
G_{ij}	Demand Flow from each district i to each HWRC j
O_i	Number of households in each district i, intended as potential users of the HWRCs
Q_j	Attractiveness factor for each HWRC, computed as $Q_j = wq_{1j} + (1-w)q_{2j}$. q_{1j} represents the number of containers at the centre; q_{2j} represents the number of materials accepted at the centre; w is the parameter defining the weight of the two factors
d_{ij}	Distance between each district i and each HWRC j.
n	Calibration parameter

Table 8 - Notation adopted for the model implementation

HWRC (j)	q_{kj}	
	Number of containers (k = 1)	**Recyclable materials (k = 2)**
Beighton Road	0.92	0.88
Blackstock Road	1.00	1.00
Deepcar	0.50	0.88
Greaves Lane	0.58	0.92
Longley Avenue	0.83	0.85

Table 9 - Attractiveness score for each recycling centre

6. Results

Parameters n and w were subject to a calibration procedure. The value of n was varied from 1.00 to 3.00 using steps of size 0.01; similarly, the value of w was varied between 0.00 and 1.00 using steps of size 0.01. In order to calibrate the model, the absolute difference between the actual distribution of users per HWRC (estimated through the survey) and the one produced by the model was adopted as the objective function of a minimisation problem, with n and w being the decision making variables. For n = 1.46 and w = 0.84, the average absolute difference of the users' distribution provided by the model compared to the actual distribution is 0.23% (see Table 10) achieving the minimum value (as can be seen in Figure 7).

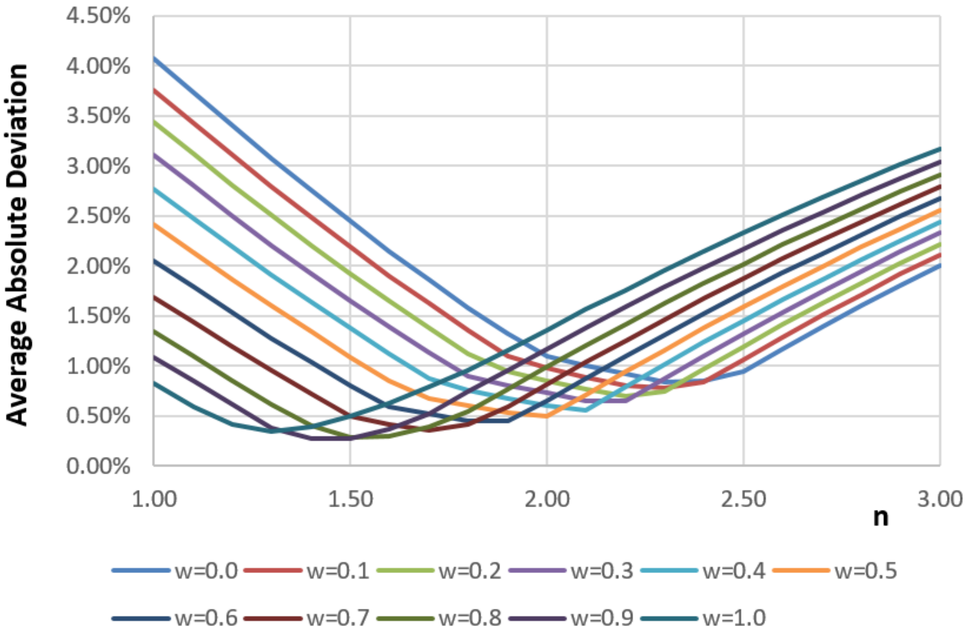

Figure 7 - The change of absolute difference of users' distribution per ward *i* of the survey and the estimated with variation of *n* values

6.1 Model Accuracy Estimate

For $n = 1.46$ and $w = 0.84$, the distribution of users from each district towards each HWRC was determined. Table 10 and Figure 8 compare the estimated percentage of users at each HWRC with the actual percentages from the survey. The spatial interaction model slightly overestimates users at Longley Avenue and Greaves Lane; the model slightly underestimates the user share of Blackstock Road; however, such deviations are very small, both in absolute and percentage terms. The spatial interaction model perfectly predicts the user share of Deepcar and Beighton Road centres; the Mean Absolute Percentage Error (MAPE) is 1.19%.

It can be seen that the results provided by the Spatial Interaction model are much better than the ones that would be provided by a simple allocation model which would assign users from each ward to the nearest facility, according to the behaviour presented in Figure 1 (see Table 11). In this case, indeed, the Mean Absolute Percentage Error (MAPE) would be much higher (33.78%); this clearly represents the fact that the process ruling the choice of the HWRC facility by users is not based just on distance considerations.

HWRC	Actual percentage distribution of users (A)	Predicted percentage distribution of users (B)	Absolute Error $\lvert B - A \rvert$	Absolute Percentage Error $100 \times \lvert B - A \rvert / A$
Beighton Rd	22.94%	22.94%	0.00%	0.00%
Blackstock Rd	29.77%	29.19%	0.58%	1.96%
Deepcar	9.50%	9.50%	0.00%	0.00%
Greaves Lane	11.28%	11.62%	0.35%	3.09%
Longley Avenue	26.52%	26.75%	0.24%	0.89%
Mean Absolute Percentage Error (MAPE) =				**1.19%**

Table 10 – Users' distribution provided by the Spatial Interaction Model; comparison with Survey Results

HWRC	Actual percentage distribution of users (A)	Nearest Facility percentage distribution of users (B)	Absolute Error $\lvert B - A \rvert$	Absolute Percentage Error $100 \times \lvert B - A \rvert / A$
Beighton Rd	22.94%	18.70%	4.24%	18.48%
Blackstock Rd	29.77%	32.71%	2.94%	9.88%
Deepcar	9.50%	3.64%	5.86%	61.68%
Greaves Lane	11.28%	7.17%	4.11%	36.44%
Longley Avenue	26.52%	37.77%	11.25%	42.42%
Mean Absolute Percentage Error (MAPE) =				**33.78%**

Table 11 – Users' distribution provided by a Closest Facility allocation; comparison with Survey Results

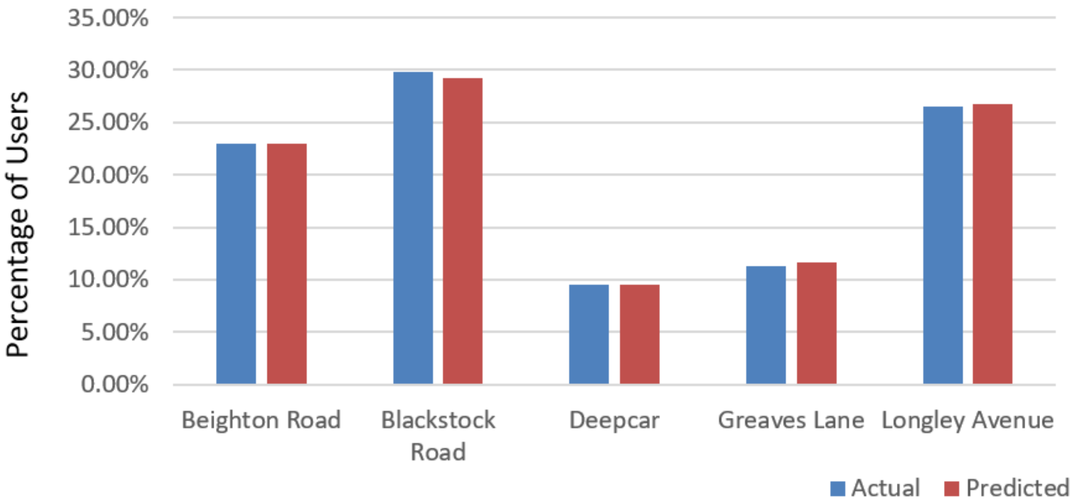

Figure 8 - Distribution of users in each HWRC, based on actual (survey) and the predicted profiles

As an example, Figure 9 shows the results for Beighton Road HWRC. For this facility, most of the users are from Beighton (10.96%), followed by Woodhouse (10.02%) and Mosborough (9.16%).

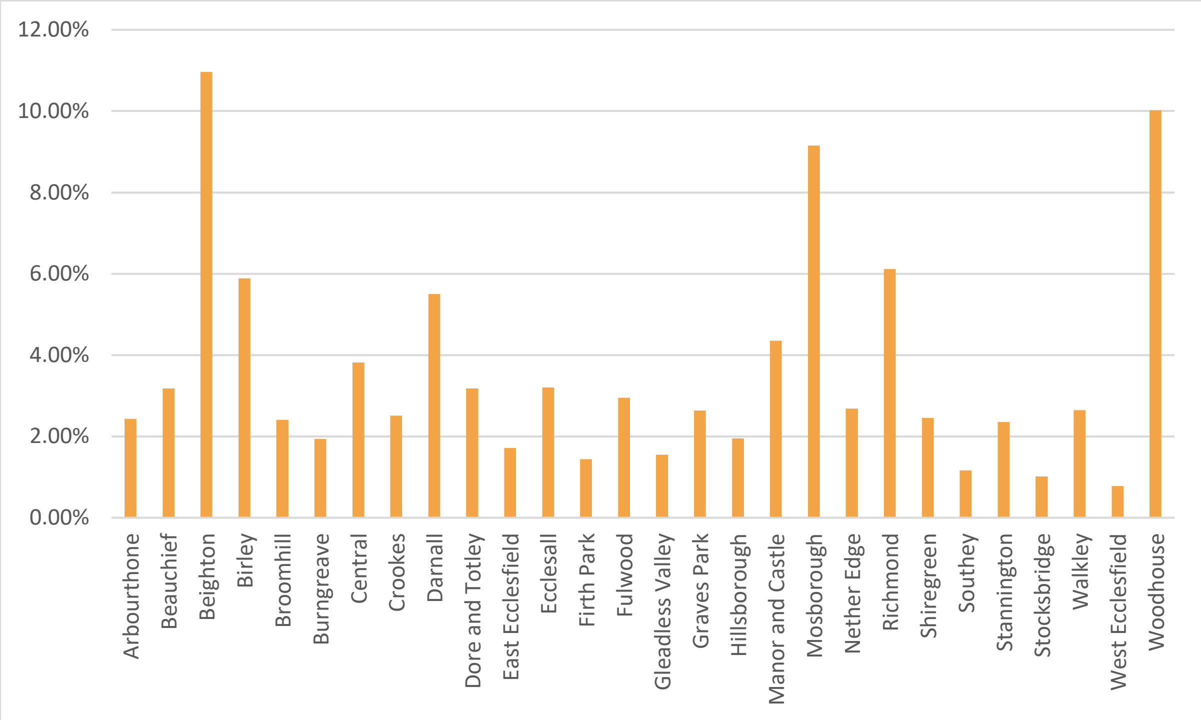

Figure 9 - Predicted breakdown of Beighton Rd users by ward

The difference between the prediction and expressed preference for each ward at each HWRC is shown in Figure 10.

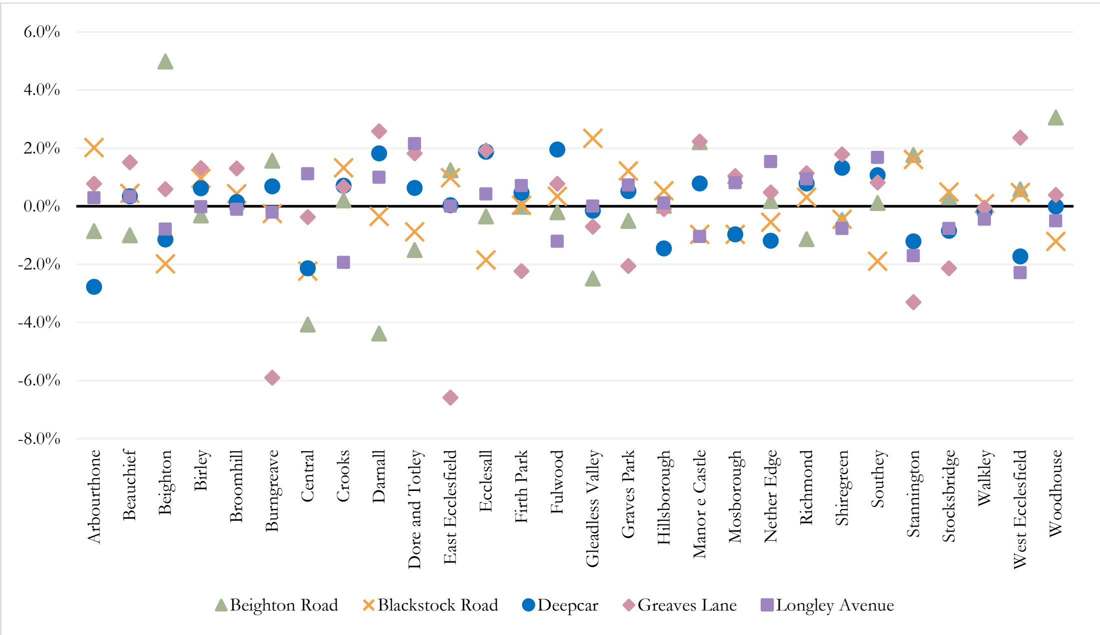

Figure 10 - Difference between actual and predicted preference at all five HWRCs

Figure 11 shows the detail of the predicted versus actual allocation of flows from one of the 28 electoral wards (Broomhill) towards the five HWRCs, highlighting the capability of the model to reproduce actual results to a very reasonable extent.

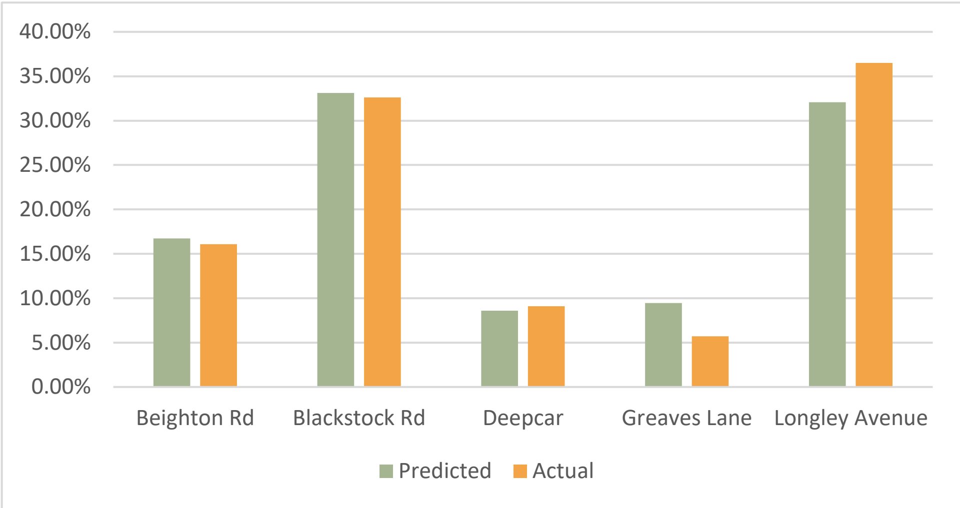

Figure 11 - Difference between actual and predicted allocations for Broomhill ward

6.2 Scenario Analysis

Given the high reliability in reproducing user behaviour for the access to HWRCs, the model can also be employed to understand the impact on the rest of the recycling network if a particular HWRC is closed. For instance, based on the results shown in the previous section, it can be understood that Deepcar HWRC is clearly the least utilised site, attracting the lowest amount of demand. Within a scenario of budget restrictions, Sheffield City Council could be interested in understanding the impact of the closure of this centre on the rest of the network. Table 12 below shows the effect of the reallocation of users following the closure of Deepcar HWRC.

HWRC	Initial User Distribution	Modified User Distribution (Deepcar HWRC closure)
Beighton Rd	22.94%	24.77%
Blackstock Rd	29.19%	31.53%
Deepcar	9.50%	0.00%
Greaves Lane	11.62%	13.77%
Longley Avenue	26.75%	29.93%

Table 12 – Modified user's distribution closing Deepcar HWRC

It can be seen that, from a capacity point of view, the increase in the demand of remaining centres would be modest; with a simple expansion of the workforce at the four remaining HWRCs (which could be obtained by relocating workers from the closed HWRC) the system could cope with the closure of one centre.

The relatively modest impact of the closure of Deepcar HWRC might trigger the evaluation of the scenario related to the closure of the next least utilised site (Greaves Lane). However, Table 13 shows that, in this case, the increase in the demand for the three remaining sites would start to become significant, thus discouraging further consolidation.

HWRC	Initial User Distribution	Modified User Distribution (Deepcar HWRC closure)	Modified User Distribution (Deepcar and Greaves Lane HWRC closure)
Beighton Rd	22.94%	24.77%	28.16%
Blackstock Rd	29.19%	31.53%	35.53%
Deepcar	9.50%	0.00%	0.00%
Greaves Lane	11.62%	13.77%	0.00%
Longley Avenue	26.75%	29.93%	36.31%

Table 13 – Modified user's distribution closing Deepcar and Greaves Lane HWRCs

The same approach could be adopted also to simulate the effect produced by the downgrading of services at single HWRCs, i.e. in terms of recycling portfolio and number of containers. Indeed, in this case, it would be sufficient to modify the values of the attractiveness factors considered in the model. For instance, by halving both the number of containers and the type of recycled items at Deepcar and Greaves Lane HWRCs, flows can be modified as shown in Table 14.

HWRC	Initial User Distribution	Modified User Distribution (downsizing of Deepcar and Greaves Lane HWRCs)
Beighton Rd	22.94%	24.85%
Blackstock Rd	29.19%	31.63%
Deepcar	9.50%	6.02%
Greaves Lane	11.62%	7.39%
Longley Avenue	26.75%	30.12%

Table 14 – Modified user's distribution closing Deepcar and Greaves Lane HWRCs

6.3 Policy Implications

The previous section has shown that the model could provide LAs and public bodies with an understanding of the demand for services offered by HWRCs and of their spatial configuration, also providing a first estimate of the impacts of possible modifications to their HWRC networks on users' access. Local Authorities could employ the model for understanding the effects of closures, downsizing and expansion of their HWRC network.

As specified by WRAP (2016), British Local Authorities must provide 'reasonably accessible' HWRCs that are 'available at all reasonable time' for residents to dispose of their household waste.

At the same time, HWRC operations are often carried out by third party contractors; this can lead to challenging situations in a context of cuts to public expenditure and contentious relationships with contractors. Local Authorities are under pressure to achieve efficiency savings, while providing accessible and effective services, which can meet policy objectives in terms of landfill diversion. Also, waste services, being highly visible, often act as a tangible indicators of the efficiency of Council services in a given area.

Recently, many Local Authorities have needed to perform changes to their HWRC networks (WRAP, 2016). Such modifications could be quite contentious, as HWRC provision and recycling yields seem to be quite linked; also, closure and downsizing HWRCs can increase the pressure on the remaining sites. This has been clearly shown in the previous sub-section, thanks to the scenarios tested in the sensitivity analysis.

It is therefore imperative that Local Authorities adopt adequate decision support systems for performing such reorganization actions. The model introduced in this paper provides a first step towards this objective, and allows an understanding of the spatial dynamics underlying access to the services provided by HWRCs, which could also be embedded into mathematical programming frameworks aimed at optimising the performance of the network against a given objective and subject to pre-determined budget constraints.

7. Conclusions

Managing waste is a crucial challenge for modern societies. By 2020, the UK government target is to recycle 50% of the country's household waste; Household Waste Recycling Centres represent key facilities for achieving this target. However, local authority budgets are under severe strain due to reductions in central government transfers. Consequently, it is very important that funds for operating and managing household waste recycling centres are used as efficiently as possible. Central to being able to do this, is understanding spatial patterns of access to such centres.

Within this context, this paper has developed a spatial interaction model aimed at examining and exploring users' behaviour and preferences when choosing recycling centres. The recycling portfolio and the number of recycling containers were used as attractiveness factors in the spatial interaction model. The deviation between the actual and the estimated (i.e., produced by the model) distribution of users was very low. These figures show that the allocation provided by the spatial interaction model is accurate and able to present the flow of users in using recycling services. As such, the spatial interaction model can be a valuable tool in evaluating the attractiveness of the HWRC system and estimating demand flows and spatial patterns.

The research reported in this study can be extended in a number of directions to further assist LAs in the reorganisation of their HWRCs. In particular, the developed spatial interaction model could be integrated in a mathematical programming approach aimed at providing recommendations to Local Authorities on the optimal planning of HWRC facilities. Such a tool could determine the best location and opening hours for HWRCs in a context of budget restrictions. Also, further empirical research could be aimed at performing further calibration of the spatial interaction model, in order to get a better estimation of its parameters. Furthermore, it could be interesting to apply the proposed spatial interaction model to different national contexts.

Acknowledgements

The Authors also gratefully acknowledge the support from the projects "Realising the Transition towards the Circular Economy: Models, Methods and Applications (ReTraCE)", funded by the H2020-MSCA-ITN-2018 programme (Grant Number: 814247) and “Promoting Circular Economy in the Food Supply Chain (ProCEedS)”, funded by European Union’s Horizon 2020 Marie Skłodowska-Curie European Research and Innovation programme (Grant Number: 823967).

References

Batty, M. (2010). Space, scale, and scaling in entropy maximizing. *Geographical Analysis*, 42(4), 395-421.

BBC (2015). Sheffield bin workers walk out in 24-hour strike action over pay. Available online at: https://www.bbc.com/news/uk-england-south-yorkshire-37560271 (Last accessed on the 21st of December 2020).

Beaumont, R.J. (1980). Spatial interaction models and the location-allocation problem, *Journal of Regional Science*, *20*(1), 37-50.

Black, W.R. (1972). Interregional commodity flows: some experiments with the gravity model. *Journal of Regional Science*, 12, 107–118.

Bröcker, J. (1989). Partial equilibrium theory of interregional trade and the gravity model. *Papers in Regional Science*, 66, 7–18.

Bruno, G. and Genovese, A. (2012). A Spatial Interaction Model for the Representation of the Mobility of University Students on the Italian Territory. *Networks and Spatial Economics*, *12*(1), 41–57.

Chen, Y. (2015). The distance-decay function of geographical gravity model: power law or exponential law? *Chaos, Solitons & Fractals*, 77, 174-189

Cherrett, T., Hickford, A. and Maynard, S. (2007). Potential for local "bring sites" to reduce householder recycling mileage. *Transportation Research Record: Journal of the Transportation Research Board*, *2011*, 201-209.

Church, R.L. and ReVelle C. (1974). The maximal covering location problem, *Papers of the Regional Science Association*, *32*, 101-118.

Cole, R. (2017). Veolia hits back over Sheffield recycling to incinerator allegations. Available online at: https://resource.co/article/veolia-hits-back-over-sheffield-recycling-incinerator-allegations-11988 (Last Accessed on the 9th of June 2020)

Congdon, P. (2001). The development of gravity models for hospital patient flows under system change: a Bayesian modelling approach. *Health Care Management Science*, *4*(4), 289-304.

Cordera, R., Sañudo, R., dell'Olio, L., & Ibeas, Á. (2018). Trip distribution model for regional railway services considering spatial effects between stations. *Transport Policy*, *67*, 77-84.

Curran, A., Williams, I. D., & Heaven, S. (2007). Management of household bulky waste in England. *Resources, Conservation and Recycling*, *51*(1), 78-92.

De Benedictis, L., & Taglioni, D. (2011). The gravity model in international trade. In *The trade impact of European Union preferential policies* (pp. 55-89). Springer, Berlin, Heidelberg.

DEFRA (2015). UK Statistics on Waste. Department for Environment, Food and Rural Affairs. Retrieved from www.defra.gov.uk

Edjabou, M.E., Faraca, G., Boldrin, A. and Astrup, T.F. (2019). Temporal and geographical patterns of solid waste collected at recycling centres. *Journal of Environmental Management*, *245*, 384-397.

Eiselt, H.A., Laporte, G. and Thisse, J.F. (1993). Competitive Location Models: A Framework and Bibliography. *Transportation Science*, *27*(1), 1526-5447.

Eklund, J., Kihlstedt, A. and Engkvist, I.L. (2010). Sorting and disposing of waste at recycling centres – A users perspective. *Applied Ergonomics 41*, 355-361.

Engkvist, I.L., Eklund, J., Krook, J., Björkman, M. and Sundin, E. (2016). Perspectives on recycling centres and future developments. *Applied Ergonomics 57*, 17-27.

Evans, J. (2013). Two Blaenau Gwent recycling centres set to close down, Closing recycle centres in Blaina and the Silent Valley site in Ebbw Vale 'will lead to more fly-tipping'. *Wales Online*. Available online at: https://www.walesonline.co.uk/news/local-news/two-blaenau-gwent-recycling-centres-6160487 (Last Accessed on the 6th of November 2019).

Fleischmann, M., Bloemhofruwaard, J.M., Dekker, R. and Vanderlaan, E. (1997). Quantitative models for reverse logistics: A review. *European Journal of Operational Research*, *103*(1), 1-17.

Fotheringham, A.S. (1983). A New Set of Spatial Interaction Models: The Theory of Competing Destinations. *Environment and Planning A*, *15*, 15–36.

Fotheringham, A.S. and O'Kelly, M.E. (1989). Spatial interaction models: formulation and applications. Netherlands, Springer.

Gamba, R.J. and Oskamp, S. (1994). Factors influencing community residents' participation in commingled curbside recycling programs. *Environment and Behavior*, *26*(5), 587-612.

Galli, P., Fraga, C., & de Sequeira Santos, M. P. (2016). Gravitational force exerted by Brazilian tourist destinations on foreign air travelers. *Journal of Air Transport Management*, *55*, 76-83.

Giuliano, G., Chakrabarti, S., & Rhoads, M. (2015). Transportation geography. Elsevier

Innes, D., & G. Tetlow. 2015. *Central Cuts, Local Decision-Making: Changes in Local Government Spending and Revenues in England*, *2009-10 to 2014-15*. IFS Briefing Note BN166. London: Institute for Fiscal Studies.

Harder, M. K., Stantzos, N., Woodard, R., & Read, A. (2008). Development of a new quality fair access best value performance indicator (BVPI) for recycling services. *Waste management*, *28*(2), 299-309.

Haynes, K.E. and Fotheringham, A.S. (1984). Gravity and spatial interaction models, Sage Publications, Beverly Hills.

Holguín-Veras, J., Xu, N., Jaller, M., & Mitchell, J. (2015). A Dynamic Spatial Price Equilibrium Model of Integrated Urban Production-Transportation Operations Considering Freight Delivery Tours. *Transportation Science*, *50*(2), 489-519.

Huff, D.L. (1964). Defining and Estimating a Trading Area. *Journal of Marketing*, *28*(3),34–38.

Kirkman, R., & Voulvoulis, N. (2017). The role of public communication in decision making for waste management infrastructure. *Journal of environmental management*, *203*, 640-647.

Krook, J. and Eklund, J. (2010). The strategic role of recycling centres for environmental performance of waste management systems. *Applied Ergonomics 41*, 362-367.

Lee, C., Scherngell, T., & Barber, M. J. (2011). Investigating an online social network using spatial interaction models. *Social Networks*, *33*(2), 129-133.

Let's Recycle (2020). Sheffield implements fines for HWRC queues. Available online at: https://www.letsrecycle.com/news/latest-news/sheffield-implements-fines-for-hwrc-queues/ (Last Accessed on the 20th of December 2020).

Lowndes, V., and L. Pratchett. 2012. Local Governance under the Coalition Government: Austerity, Localism and the 'Big Society'. *Local Government Studies* 38 (1): 21–40.

Marino, D. (2018). Funding cuts prompt recycling centre closure proposals. Available online at: https://www.mrw.co.uk/latest/funding-cuts-prompt-recycling-centre-closure-proposals/10034664.article (Last Accessed on the 6th of November 2019).

Maynard, S., Cherrett, T. and Waterson, B. (2009). Monitoring household waste recycling centres performance using mean bin weight analyses. *Waste Management*, *29*(2), 614-620.

Morley, C., Rosselló, J., & Santana-Gallego, M. (2014). Gravity models for tourism demand: theory and use. *Annals of Tourism Research*, *48*, 1-10.

Neal, C. (2016). Recycling centres in Rushmoor and Hart could close due to Hampshire County Council cuts. Available online at: http://www.gethampshire.co.uk/news/local-news/recycling-centres-rushmoor-hart-could-11094023. (Last Accessed on the 6th of November 2019).

Newing, A., Clarke, G.P. and Clarke, M. (2015). Developing and applying a disaggregated retail location model with extended retail demand estimations. *Geographical Analysis*, *47*(3), 219-239.

Office for National Statistics (2019). Population Estimates. Avalilable online at: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates (Last Accessed on 30 September 2019)

Ongondo, F. O., Williams, I. D., & Keynes, S. (2011). Estimating the impact of the "digital switchover" on disposal of WEEE at household waste recycling centres in England. *Waste Management*, *31*(4), 743-753.

Patuelli, R., Mussoni, M., & Candela, G. (2014). Cultural offer and distance in a spatial interaction model for tourism. *Economics and Business Letters*, *3*(2).

Prest, V. (2016). Opening times to be cut next week at 20 local waste centres. *The Press*. Available online at: http://www.yorkpress.co.uk/news/14373260.Opening_times_to_be_cut_next_week_at_20_local_waste_centres/?ref=mac (Last Accessed on the 6th of November 2019)

Public Health Act (1936). Her Majesty's Stationery Office, London.

Roy, J.R. and Thill, J. (2004). Spatial interaction modelling. *Papers of the Regional Science*, *83* (1–2), 339–361.

Samuelson, P. A. (1952). Spatial price equilibrium and linear programming. *The American economic review*, *42*(3), 283-303.

Sen, A. and Smith, T.E. (1995). Gravity models of spatial interaction behaviour. Springer-Verlag, Berlin.

Smith, L., & Bolton, P. (2018). *Briefing Paper: Household recycling in the UK.* Available online at: https://researchbriefings.parliament.uk/ResearchBriefing/Summary/CBP-7285 (Last Accessed on the 6th of November 2019).

Speirs, D., & Tucker, P. (2001). A profile of recyclers making special trips to recycle. *Journal of Environmental Management*, *62*(2), 201-220.

Sproule, L. (2015). All change at the tips with fewer hours and closures on the cards. *Oxford Mail.* Available online at: http://www.oxfordmail.co.uk/news/13586305.All_change_at_the_tips_with_fewer_hours_and_closures_on_the_cards/?ref=mr&lp=8 (Last Accessed on the 6th of November 2019).

Struk, M. (2017). Distance and incentives matter: The separation of recyclable municipal waste. *Resources, Conservation and Recycling*, *122*, 155-162.

Sundin, E., Björkman, M., Eklund, M., Eklund, J., & Engkvist, I. L. (2011). Improving the layout of recycling centres by use of lean production principles. *Waste Management*, *31*(6), 1121-1132.

Teow, K. L., Tan, K. B., Phua, H. P., & Zhu, Z. (2018). Applying Gravity model to predict demand of public hospital beds. *Operations Research for Health Care*, *17*, 65-70.

Toregas, C., Swain, R., ReVelle, C., and Bergman, L. (1971). The location of emergency service facilities. *Operations Research*, *19*(6), 1363–1373.

Waite, R. (1995). Household Waste Recycling, Earthscan Publications, London.

The Waste (England and Wales) Regulations 2011. Retrieved from http://www.legislation.gov.uk/uksi/2011/988/contents/made

Tong, X., Wang, T., Chen, Y., and Wang, Y. (2018). Towards an inclusive circular economy: Quantifying the spatial flows of e-waste through the informal sector in China. *Resources, Conservation and Recycling*, *135*, 163-171.

Wang, Z., Ye, X., Lee, J., Chang, X., Liu, H., & Li, Q. (2018). A spatial econometric modeling of online social interactions using microblogs. *Computers, Environment and Urban Systems*, *70*, 53-58.

Widdowson, S., Sankey, H., & McElearney, R. (2015). *Waste on the Front Line – Challenges and Innovations*. England.

Wilson, A. G. (1969). The use of entropy maximising models, in the theory of trip distribution, mode split and route split. *Journal of transport economics and policy*, 108-126.

Wilson, A.G. (1971). A family of spatial interaction models, and associated developments. *Environment and Planning*, *3*(1), 1–32.

Williams, I. D., & Taylor, C. (2004). Maximising household waste recycling at civic amenity sites in Lancashire, England. *Waste Management*, *24*(9), 861-874.

Woodard, R., Bench, M., Harder, M. K., & Stantzos, N. (2004). The optimisation of household waste recycling centres for increased recycling—a case study in Sussex, UK. *Resources, Conservation and Recycling*, *43*(1), 75-93.

Woodard, R., Bench, M., & Harder, M. K. (2005). The development of a UK kerbside scheme using known practice. *Journal of Environmental Management*, *75*(2), 115-127.

WRAP. (2016). *Household Waste Recycling Centre (HWRC) Guide*. Available online at: http://www.wrap.org.uk/sites/files/wrap/HWRC_Guidance_2018_4.pdf (Last Accessed on the 6th of November 2019).

Zacho, K. O., Bundgaard, A. M., & Mosgaard, M. A. (2018). Constraints and opportunities for integrating preparation for reuse in the Danish WEEE management system. *Resources, Conservation and Recycling*, *138*, 13-23.