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A multi-period model for reorganising urban household waste recycling networks

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ABSTRACT

Managing waste is a crucial challenge for modern societies. Within the UK government's ambitious environmental targets, municipal Household Waste Recycling Centres represent key facilities. However, local authority budgets are under severe strain due to reductions in central government funding. Therefore, local councils often need to perform reconfigurations of the recycling centres networks, by reducing the number of sites or their opening hours while still ensuring adequate service levels. This paper describes a novel multi-period mathematical programming model for optimising reorganisational actions within Household Waste Recycling Centre networks. The model is tested on a case study based on an English local authority, in order to demonstrate its applicability to a real-world scenario, and its role in supporting decision-makers in deciding the best way to reorganise Household Waste Recycling Centres.

1. Introduction

Waste management is a key component in the transition towards more sustainable societies. British local authorities (LAs) are expected to achieve stringent landfill diversion targets where at least 50% of waste (including paper, plastic, metal, textiles, biodegradable and green wastes) can be re-used and recycled, avoiding landfill and incineration options. Within this context, Household Waste Recycling Centres (HWRCs) (also known as recycling drop-off centres in other geographical contexts) represent essential facilities provided by LAs ensuring the recovery, reuse and recycling of selected materials not generally collected through kerbside systems (such as furniture, electrical and electronic equipment, garden waste) [1,2]. The proper management of HWRCs is crucial in achieving high levels of reuse and recycling, through the correct sorting and separation of items, thus assisting in the transition towards a Circular Economy [3–5]. Engkvist et al. [6] notes that "well performing recycling centres, being very early in the recycling chain, are key to the subsequent steps in waste processing". HWRCs handle significant percentages of household waste [7]; Curran et al. [8] claimed that, in the UK, around 60% of households regularly use HWRCs for disposing of bulky items. Commercial waste is generally banned at HWRCs as it could increase congestion problems.

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 essential services [9,10]. In the UK, 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% [11]. In many LAs, as a result of the recent regime of austerity, HWRC facilities have been downsized, seen their opening hours reduced, or are under threat of closure [10]. Even though efficiencies can be sought, as highlighted by Ref. [5]; there are nevertheless some authorities who are being forced to close HWRCs due to financial pressures. See, for example, reports about closures in Oxfordshire [12] and Hampshire [13] and the reduction in opening hours in North Yorkshire [14], Buckinghamshire [15] and Warwickshire [5]; in 2016, Cheshire East Council proposed to close six sites [5].

In England, as reported by WRAP [16], in 2010/11, there were 734 sites; this number was reduced to 697 in 2013/14 [5]. Still in 2018, several local councils planned to reduce operating hours or completely close some of the available recycling sites, even though such sites were well used by the population [15]. Waste being deposited at HWRCs sites in the UK continuously increased between 2013 (1503 tonnes) and 2016 (1747 tonnes), but slightly reduced in 2017 (1715 tonnes), also as a result of the cuts to available facilities [17]. The increase in government debt due to the Covid-19 pandemic, and the associated extraordinary measures, will mean that the financial pressure on local government

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spending is likely to continue for many years to come.

Furthermore, the insufficient number of recycling facilities has been linked to the increase of cases of illegal dumping of waste (also known as *fly-tipping*), which indirectly results in an increased cost of disposing of waste in landfills and other environmental pollution problems [5,18,19]. Fly-tipping has increased considerably over the years and the major contributor here is household waste (about 67%) [20]. In 2016/17, DEFRA reported that the estimated total cost related to the clearance of such incidents was £57.7 million (with an average of £58 per incident), with a total enforcement cost of £16 million (with an average of £33.75 per enforcement) [21].

Due to the financial pressure caused by budget cuts, LAs need to find more efficient ways to manage their HWRCs. This includes managing centres with a suitable number of staff and the creation of an optimal schedule. Failure to properly manage HWRCs within budgetary constraints could lead to permanent site closures. It is apparent that, in most cases, LAs lack adequate planning tools in order to identify rationalisation plans that, if implemented, could return some financial savings without compromising the ability of the HWRC system to provide an adequate service level to users. Therefore, in order to bridge this gap and provide a valuable tool to assist LAs with decision-making, this paper presents a multi-period mathematical model aimed at reorganising HWRCs operations within budgetary constraints. The driver for the model is to cope with reorganisational problems arising in a context of supply reduction while minimising possible risks. Due to reorganisational actions, the network size might be reduced. Hence, this study is also concerned with the effect of the reorganisation, i.e. the congestion problems which might derive from the changes imposed on the network.

The reminder of this paper is organised as follows. Section 2 provides an overview of past studies related to the organisation of HWRC networks, pointing out current gaps and highlighting related literature streams which could be useful for developing modelling approaches. Drawing upon this literature, Section 3 proposes a multi-period model for reorganising HWRCs operations. Section 4 illustrates the adaptation of the model to the real-world case of the HWRC network in the City of Sheffield (UK), along with a sensitivity analysis of the results. Section 5 provides some conclusions and avenues for future work.

2. Literature review

While the management of HWRC networks represents a problem of high practical relevance, the academic literature has been devoting sporadic attention to the issues related to the planning of services offered by these facilities. The following two sub-sections will present, in detail, modelling approaches which have been developed for dealing with the organisation of HWRCs; also, the literature concerned with reorganisation problems related to facility networks will be presented, in order to evaluate its suitability to the HWRC context.

2.1. Modelling approaches for dealing with the organisation of HWRC networks

A seminal study in the context of HWRC services was performed by Woodard et al. [22], who observed the operation of the HWRCs in the English county of Sussex for one week, monitoring users' behaviour and providing recommendations for the optimal layout of the site. Williams and Taylor [23] carried out a survey amongst HWRC attendants in an English LA, in order to establish the effects of site improvements on customer satisfaction and investigate methods that would assist customers in maximising the amount of recycling at HWRCs.

The performance of a HWRC is generally measured through recycling rates and by satisfaction surveys of site users [3,5,22]; these are influenced by the materials accepted, the location and the layout, along with the assistance and service provided by the staff [5,6]. Cunningham and Conroy [24] pointed out that vehicle movements, ground-level access and user permits are major factors that need to be considered in the design of HWRCs. WRAP [5] noted that a more diversified recycling portfolio attracted users to go to specific HWRCs; also, the presence of user-friendly and split-level designs can play a role.

Maynard et al. [4] proposed a modelling approach to study 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 the performance of the centres. Sundin et al. [25] applied lean production principles for designing and managing recycling centre operations, in order to improve the performance of 16 Swedish HWRCs that had experienced queuing and congestion problems. A similar approach was followed by Engkvist et al. (2016).

Using an English LA as a case study, Ongondoet al. (2011) estimated the 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. Edjabou et al. [7] performed an analysis of seasonal and geographical variations in waste collection at Danish HWRCs, drawing interesting implications for service provision.

Consequently, while some of the reported contributions focussed on layout optimisation and on the analysis of material flows (mainly at the single centre level), it appears that network optimisation issues have not been specifically investigated, especially according to a spatial pattern within systems composed of multiple HWRCs. The few available studies stress that, in terms of network configuration of HWRCs, accessibility is a key criterion [3]. In order to ensure adequate coverage of the population, WRAP [5] recommends a maximum catchment radius of three miles for HWRCs in urban areas and seven miles in rural areas. Additionally, WRAP [5] provides guidance on the maximum travel times to HWRCs (respectively, 20 and 30 minutes by car in urban and rural areas) for the most disadvantaged users. However, such recommendations developed by practitioner bodies have not been corroborated by academic studies, especially in the recent context of funding reduction experienced by Local Authorities; 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 reorganisation actions that should be performed.

For this reason, the next subsection provides some insights about general-purpose models from the location modelling literature, which have dealt with network restructuring. These models could be adapted to deal with reorganisation problems involving HWRC networks.

2.2. Reorganisation problems in the facility location literature

There is only a relatively small number of studies focusing on reorganising facility networks in the literature. In general, traditional location models can be repurposed to choose which existing facilities are to be closed [26], with some modification in the definition of variables and constraints. Closure and downsizing actions are part of the reorganisation process.

Focusing on opening new facilities and closing existing ones [27], created a model that uses price-sensitive demand as a variable. However, the model does not consider the capacity of the facilities. Min [28] used fuzzy goal programming in a multi-period setting to reorganise public libraries taking into account their capacity restrictions. In contrast, Shulman [29] introduced flexible capacities that depended on the type of facilities. Canel et al. [30] considered opening, re-opening and closing of a capacitated facility over time, with penalty costs that are incurred when re-openings and closures occur.

Wang et al. [31] and Monteiro and Fontes [32] dealt with the restructuring of bank branches under financial curbs. In particular, Wang et al. [31] concentrated on the possibility of redirecting clients of closed facilities to branches with spare capacity. Dias, Captivo and Clímaco [33] analysed the possibility of temporary and permanent facility closures, also introducing multi-period planning. ReVelle et al. [26], developed a set of models for dealing with companies needing to shrink their service network, with the aim of minimising their market share loss; such models were adapted to both competitive and non-competitive contexts. A similar problem was tackled by Bhaumik [34]. Melo et al. [35,36] designed a dynamic, multi-commodity model for reconfiguring facilities in supply network in order to react to changes in demand [37]. discussed the relocation of facilities including the temporary closure option.

[38] tackled a facility network reorganisation problem dealing with uncertainty in demand and budget constraints [39]. designed a model for reorganising a school system in Chile's rural areas, due to insufficient numbers of students (demand) and teachers (supply), aiming at facilities consolidation and better utilisation of the resources. Similarly [40], dealt with a non-competitive service, the higher education system in Italy. They focus on the downsizing and the closure of facilities that could minimise the system operational cost by reallocating demands; a similar approach is presented in Ref. [41] for the downsizing of a postal collection network, due to declining volumes.

It has to be acknowledged that when networks are reorganised, and facilities closed, users' accessibility can be affected, and service quality reduced [40]. A side effect of closing facilities is represented by the fact that congestion problems might arise at the remaining sites. Traditionally, most studies dealt with congestion issues by expanding the network size (such as [42–47]. However, due to budget restrictions, this might not be an option in contexts where reorganisational actions need to be performed.

Recent work on reorganisational studies has been presented by Refs. [41,48,49]. All studies focused on capacity reorganisation by using mathematical programming approaches, looking at the possibility of transferring capacities within a network of facilities [49]. focused on a specific aspect of reorganisation actions, by allowing the transfer of unused capacities between cooperative capacitated facilities within the same network. This is accomplished by assuming that facilities with surplus capacity can cooperate with those facing a shortage by transferring part of this capacity; while such a transfer can generate costs, these can nonetheless be compensated by savings both in installation and distribution costs. Meanwhile [41,48], focused on redistributing healthcare capacity (respectively in terms of blood processing centres and hospital beds) within a network of facilities, in order to increase patients' accessibility and availability. In both studies, spatial analyses of users' accessibility are also employed in order to inform the reorganisational approach, and provide a comparison to the status quo across key metrics. Mathematical programming models aiming at redistributing healthcare capacities (e.g., beds) seeking to maximize users' accessibility were then formulated and solved.

Both the recent studies from Refs. [41,49] demonstrate the importance of ensuring maximum facility utilisation and users' accessibility while minimising extra costs. It is important to notice that these are also practical issues faced by LA planners when needing to redesign HWRC networks due to budget constraints.

However, to the best of our knowledge, no attempt has been developed in the literature to formulate models aimed at reorganising an existing HWRC network (or similar services) in terms of opening schedules, demand allocation, capacity resizing and, if needed, closure of facilities. The combination of strategic and tactical elements in this type of problem might suggest the adoption of a multi-period model, as advised by Ref. [50]; who developed a similar framework to deal with location and dynamic capacity planning. It is important to notice that multi-period models have been previously employed, in a successful manner, to deal with planning issues arising in waste management systems (see, for instance, Ref. [51]. As such, in this paper we present a multi-period model for a network of HWRC facilities which might be characterised by funding restrictions and related congestion problems. Details of the proposed model are illustrated in the next section.

3. A multi-period model for reorganising HWRCs' operations

The model assumes the presence of a network of HWRC facilities within a given territory. The model explicitly considers demand for the service, which is spatially distributed across the considered territory. Also, the model considers a given time horizon, the initial opening schedule of each facility, its capacity in terms of users that can be processed within each time period. The model is capable of determining a revised operational schedules for the HWRC facilities, in order to optimise a cost-based objective function and ensure a required service level. The explicit representation of the time dimension of the demand dynamics, along with the reproduction of real-life options for demand (such as the possibility, for users, to move to other facilities or to leave the system) differentiates the proposed model from any existing studies in the field of facility reorganisation.

In the model, it was assumed that users turning up at a HWRC facility have no knowledge of the queue length. We also assumed that demand at HWRCs can be served within the same period, stay in a queue to be served in subsequent periods, move to a different facility, or leave the system without being served. Additionally, in order to resemble a real-life situation (where users are not allowed to queue at a centre overnight), it is assumed that at the end of a day (conceptualised in the model as a macro-period), there will be no users allowed to wait in a queue. This is illustrated in Figs. 1 and 2, and explained in the following.

Let the time horizon, T, be divided into periods and macro-periods. Fig. 1 illustrates this concept, where the macro-periods represent the days of the week, and the periods represents the multiple 1-h long operational intervals per day. In Fig. 1, we report a typical week of operations at an HWRC (seven days; and eight 1-h periods per day). A generalisation of this situation is shown in Fig. 2. Let W be the set of macro-periods, indexed by $w = \{1 \ldots W\}$, and H be the number of periods per macro-period. It is assumed that the length of each macro-period is identical. The general concept of macro-periods and periods is presented in Fig. 2.

The sets, parameters, and decision variables for the model are as follows.

Sets		
J	=	set of existing HWRC facility locations, indexed by j (and k), where $j \in J$
T	=	set of time-periods, indexed by t, where $t \in T$
W	=	set of macro-periods (see Figs. 1 and 2), indexed by w, where $w \in W$
Parameters		
K_j	=	activation cost for facility j across the whole time horizon
C_{jt}	=	cost of operating a facility j for a single period t
ε_1	=	cost to the facility owner of serving one unit of demand
ε_2	=	unit *holding* cost to the facility's user for one unit of demand waiting in a queue at the end of period t (which will be assumed constant across facilities and time periods)
ε_3	=	unit penalty cost to the facility owner of losing one unit of demand
ε_{4j}	=	cost to the facility's user when a unit of demand moves from facility j to facility k, $k \neq j$
x_{jt}	=	amount of demand assigned to facility j at time t through the spatial interaction model
δ_j	=	maximum operating periods for facility j per week
δ_{minj}	=	minimum number of operational periods per facility j per week
δ_{jw}	=	number of operational periods per facility j per day (indexed by $w \in W$)
δ_{minjw}	=	minimum number of operational periods per facility j per day (indexed by $w \in W$)
u_{jkt}	=	predetermined binary value which indicates the possibility for demand to move from facility j to facility k during period t based on travel distance.
τ_{jt}	=	capacity level of facility at location j during a period t
B	=	upper bound for the amount of demand leaving system
H	=	number of periods per macro-period (see Figs. 1 and 2)

(*continued on next page*)

(*continued*)

Decision variables		
v_j	=	$\begin{cases} 1 \text{ if facility } j \text{ is activated across the whole time horizon} \\ 0 \quad \text{otherwise} \end{cases}$
y_{jt}	=	$\begin{cases} 1 \text{ if facility } j \text{ is operating during a period } t \\ 0 \quad \text{otherwise} \end{cases}$
s_{jt}	=	non-negative decision variable representing the amount of unserved demand (users) transferred to the next period at a facility at location j at the end of a period t
r_{jkt}	=	amount of unserved demand (users) transferred (relocated) between facility j and facility k during a period t
l_{jt}	=	amount of unserved demand (users choosing to leave at each facility at a location j during a period t
q_{jt}	=	amount of demand (users) served at each facility at a location j during a period t

The following multi-period model can be introduced:

$$Min\ (Z_1 + Z_2) \tag{1}$$

subject to:

$$x_{jt} + s_{jt-1} + \sum_{k,\ k\neq j} r_{kjt}u_{kjt} = s_{jt} + \sum_{k,\ k\neq j} r_{jkt}u_{jkt} + q_{jt} + l_{jt};\ \forall j \in J,\ \forall t \in T \tag{2}$$

$$\sum_j \sum_t x_{jt} = \sum_j \sum_t (q_{jt} + l_{jt}); \tag{3}$$

$$\sum_j \sum_t l_{jt} \leq B\left(\sum_j \sum_t x_{jt}\right); \tag{4}$$

$$q_{jt} \leq \tau_{jt} y_{jt}\ ;\forall j \in J,\ \forall t \in T \tag{5}$$

$$s_{jt} \leq x_{jt}\ y_{jt+1}\ ;\forall j \in J,\ \forall t \in T \tag{6}$$

$$r_{jkt}u_{jkt} \leq x_{jt}y_{kt}\ ;\forall j \in J,\ \forall t \in T \tag{7}$$

$$\delta_{minj}v_j \leq \sum_t y_{jt} \leq \delta_j v_j;\ \forall j \in J \tag{8}$$

$$\delta_{minjw}v_j \leq \sum_{t=1+H(w-1)}^{Hw} y_{jt} \leq \delta_{jw}v_j;\ \forall j \in J,\ \forall w \in W \tag{9}$$

$$y_{jt-1} \geq y_{jt}; \forall j \in J,\ \forall t = (1 + H(w-1), Hw] \tag{10}$$

$$s_{jt} = 0; \forall j \in J, \forall t = (1 + H(w-1), Hw] \tag{11}$$

$$q_{jt},\ l_{jt},\ s_{jt},\ r_{jkt} \geq 0; \forall t \in T,\ \forall j \in J \tag{12}$$

$$y_{jt} \in \{0,\ 1\}; \forall t \in T,\ \forall j \in J \tag{13}$$

The objective function (1) indicates the total operational costs for the entire system, including costs on both the provider's and the users' side. The cost on the provider's side, Z_1, consists of the operational costs (C_j), the cost to serve a unit of demand (ε_1) and of the cost faced when a unit of demand leaves the system (ε_3). It is assumed that the cost on the demand side, faced by the users, Z_2, consists of the *holding* cost (ε_2) and the cost when a unit of demand moves from the preferred facility j to an alternative facility k (ε_{4j}). It is worth to note that it is assumed that the movement of a unit of demand from facility j to k is based on the fact that

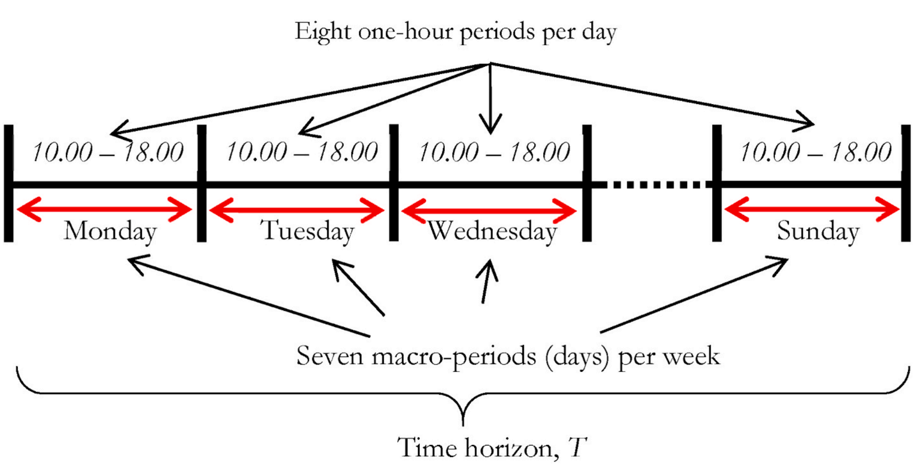

Fig. 1. Illustration of periods and macro-periods.

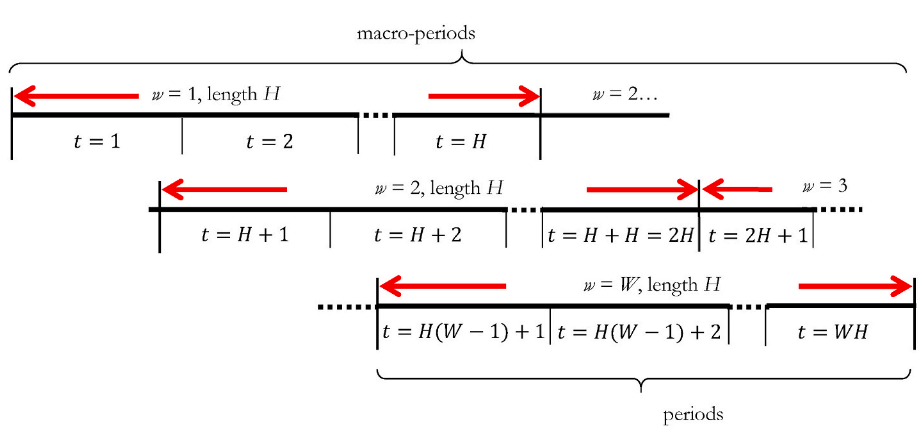

Fig. 2. Further illustration of macro-periods and periods.

j has a high congestion level (i.e., a long queue) or is not operational (i.e. is closed). The costs on the provider (Z_1) and demand (Z_2) sides are expressed as follows:

$$Z_1 = \sum_j \sum_t \left(K_j v_j + C_{jt} y_{jt} + \varepsilon_1 q_{jt} + \varepsilon_3 l_{jt}\right)$$

$$Z_2 = \sum_t \sum_j \left(\varepsilon_2 s_{jt} + \varepsilon_{4j} \sum_{k,k\neq j} r_{kjt} u_{kjt}\right)$$

Equations (2) represent the balance constraints. Constraints (3) ensure that each unit of demand (in the following, also referred to as *user*) is either served or leaves the system at the end of the time-period, while constraints (4) ensure that the amount of unserved demand is limited to *B*%; this expresses the required service level that the provider wants to achieve. Constraints (5) guarantee that the amount of demand served is within the capacity of the facility. Constraints (6) and (7) limit the movement of demand only to operational facilities. Constraints (8) and (9) ensure that the total operating periods for a given facility *j* are within an acceptable range (on a weekly and daily basis; with *H* denoting the standard length of each time-period within *T*). Constraints (10) restrict the reopening of a given facility *j*: once the facility is closed within a day, it will remain closed for the rest of the day. Conditions (11) ensure that no user is in a queue at the beginning and at the end of the day. Decision variables q_{jt}, l_{jt}, s_{jt} and r_{jkt} are non-negative (12), and y_{jt} is a binary variable (13).

The following section tests the model on a real-world case study; the model is employed in order to evaluate a potential reorganisation of the HWRC network in the Sheffield City Council area, an English local authority. All the calculations used to solve the model, including the sensitivity analyses, were conducted using CPLEX 12.6 on a Windows PC with 8.0 GB RAM and a 2.50 GHz processor.

4. A real-life case study: reorganising HWRC in sheffield, UK

Sheffield is an English city with a population of 556,000 spread between 230,000 households, within the South Yorkshire County. Sheffield City Council currently provides and manages five HWRCs. The Local Authority has experienced financial pressures, which have also led to contentious relationships with the contractor managing the entire waste management cycle; such tensions have resulted in service disruptions and labour disputes [52] which have damaged the reputation of the contractor and resulted in inconveniences for citizens [53]. 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 [54].

The Council has been constantly reviewing the performance of the HWRC network, with the aim of understanding demand patterns and considering alternative configurations. After possibly reducing operating hours and downsizing (or even closing) existing facilities, the remaining HWRCs would then be expected to provide a sufficient service to Sheffield's residents. Hence, the multi-period model introduced in Section 3 could provide suitable decision support tool for assisting the Council in the reorganisation of its HWRC operations.

4.1. Data collection and parameters setting

Currently, there are five operating HWRCs that are managed by Sheffield City Council. They are located in Beighton Road, Blackstock Road, Deepcar, Greaves Lane, and Longley Avenue. The location of these HWRCs is shown in Fig. 3. These five HWRCs are required to serve the 229,922 households that are located in 28 wards (that comprise a total of 206 districts). These facilities are operating between five to seven days a week, with 8-hour operational shifts per day.

From Fig. 3, it can be seen that Longley Avenue is located towards the centre of the Council's area of coverage, while the other four sites are located near to the Council's borders. In particular, Greaves Lane and Beighton Road are near to the edge of the Council's authority, and both are easily accessible by residents who live outside the Sheffield City Council area.

Each user in a given ward *i* will dispose of their recyclable materials at any preferred HWRC in Sheffield. Users are free to visit any of the five HWRCs, regardless of the area of Sheffield that they live in. Hence, it is important to reproduce the mechanism that guides users' preferences in their choice of HWRC.

Most HWRC facilities operate in environments characterised by uneven congestion patterns with a general lack of predictability in the arrival of the demand. However, the mean demand being served by each HWRC during a typical day and time of the week can be estimated based on historical data (provided by Sheffield City Council); as regards the spatial distribution of the demand, this can be estimated through an investigation of users' preference levels for facilities locations, recycling portfolio, and layout. Therefore, to capture the distributions of users at each HWRC, a spatial interaction model (originally formulated by Ref. [53] is adopted.

A spatial interaction model considers the attractiveness factor, the distance between each pair origin-destination, the parameters to be calibrated and the user generated by each origin. We adapted the spatial interaction model from Ref. [55] to allocate user at *i* to each HWRC. Hence, the allocation of users at each ward *i* per time *t* to each HWRC (i.e. facility *j*) d_{ijt}, is based on the spatial interaction model:

$$d_{ijt} = d_{it} \cdot \frac{Q_j \cdot \left(dist_{ij}\right)^{-n}}{\sum_j \left(Q_j \cdot \left(dist_{ij}\right)^{-n}\right)} \tag{14}$$

where d_{it} is the number of users in ward *i* during time period *t*, Q_j is the attractiveness of each HWRC, $dist_{ij}$ is the distance between user in ward *i* and facility *j*, and the value of *n* is chosen to minimise the difference between the actual and the estimated (survey-based) distribution of users at the HWRCs (see also [53]).

The values of each of the parameters needed to operationalise the model introduced in Section 3 were provided by Sheffield City Council, as follows.

- K_j is a general facility activation cost (for the whole time horizon), mainly related to administrative aspects. This confidential cost was provided by the Council.
- C_{jt} represents a combination of the staffing and operational costs for each period. This confidential value was provided by the Council.
- ε_1 is defined as the average cost of processing a user at a facility *j*. Note that it is assumed to be the same at each facility j as it is made up of the handling and recycling costs. In order to compute ε_1, a combination of the recycling cost (expressed in £/kg) and the amount of recyclable waste per user (kg/user) is employed. The components to calculate ε_1 were provided by the Council.
- The *holding* cost ε_2, is measured as an hourly opportunity cost. An opportunity cost is the profit gained or lost if another alternative is taken. For example, the cost of waiting for an hour in a queue could be set equal to 1 h of salary; this was assumed equal to the UK current minimum hourly salary (source: [56].
- ε_3 is defined as the cost faced by the council for a customer leaving the system, and not properly recycling their waste. In this case, it is assumed that they are illegally dumping this waste or fly-tipping it. There are two costs involved in solving fly-tipping; clearance costs[1]

[1] There were 1,002,000 incidents of fly-tipping reported in England in 2016/17, at a cost of £57.7M to clear the associated waste [21]. Thus, the clearance costs can be estimated as £57.52 per average incident.

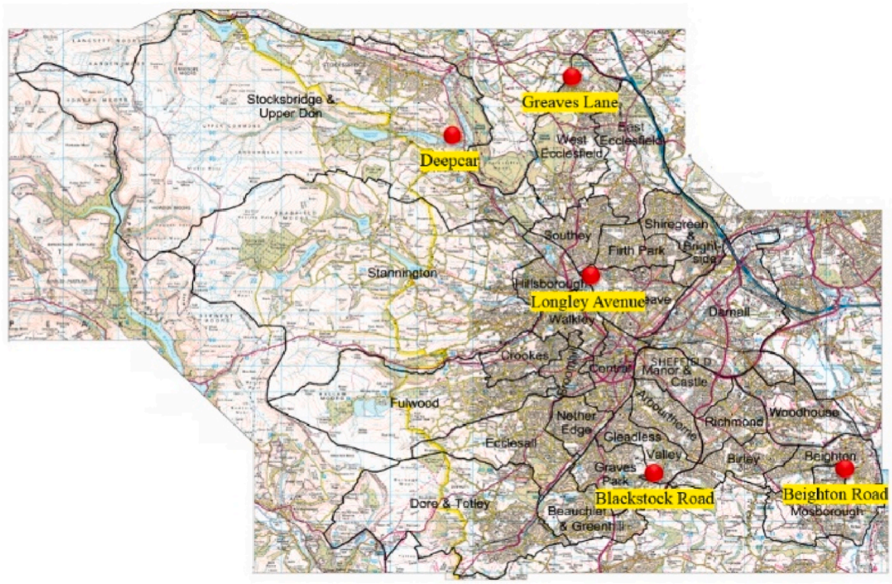

Fig. 3. Map of Sheffield showing HWRCs locations.

(estimated at £ 57.52 per incident) and enforcement costs[2] (estimated at £ 33.78 per action). Users also face the consequences of not recycling waste properly, by paying a fine.[3] Hence, from the provider's side, the ε_3 cost is assumed to be a combination of clearance and enforcement costs, minus the fine raised per each incident (£ 57.52 + £ 33.78 − £ 80.00); thus, the hypothesised ε_3 net cost faced by the local authority for each user leaving the system is £11.30.

- The ε_{4j} cost is assumed to be a combination of opportunity and transportation costs faced by a user in order to move to another facility. It is hypothesised that a transfer to another facility will require 15 min per user. Additionally, each user that moves to another facility j will be served within the same period.
  - o The opportunity cost is the loss suffered by the user if they move to another facility, due to the waste of time this involves. This cost is assumed to be £7.83 per hour or £1.96 per 15-min time frame.
  - o Meanwhile, the transportation cost is based on the current fuel price for an average car which is £1.94 for a 15-min time frame in an urban setting.

Hence, ε_{4j} is equal to £3.90 per movement.

- The parameter B, expressing the service level, is set equal to 0.05.
- The capacity level per time period of a HWRC (τ_{jt}) is based on the maximum amount of users visiting an HWRC per hour.
- u_{jkt} is the reachability of facility j from facility k at time t based on 15-min time frame; it expresses whether j can be reached from k within 15 min. The reachability may depend on the time t due to changing traffic conditions. However, for simplicity, we used a set of time independent values shown in Table 1.

Table 1 shows the value of 1 if the HWRCs reported on the columns can be visited by users departing from the HWRCs reported on the rows, 0 otherwise. The users of Beighton Road and Longley Avenue can move to Blackstock Road, and vice-versa. Meanwhile, Deepcar users will move to Greaves Lane, and vice-versa.

Table 1
The u_{jk} values.

HWRC		k				
		Beighton Rd	Blackstock Rd	Deepcar	Greaves Lane	Longley Avenue
j	Beighton Rd		1	0	0	0
	Blackstock Rd	1		0	0	1
	Deepcar	0	0		1	0
	Greaves Lane	0	0	1		0
	Longley Avenue	0	1	0	0	

- The minimum operation periods per day and per week for a given facility j (δ_{minj} and δ_{minjw}) are set at 50% of the maximum operation periods for both lower bounds; these are assumed equal to 28 h per week and 4 h per day, respectively. Also, it is assumed that each HWRC is able to operate from Monday to Sunday, from 10:00 a.m. until 6:00 p.m.; as such, the δ_j value, for all facilities, is equal to 56 h.

5. Results

The results are presented in two parts: (i) allocation of user i to each HWRC (facility j) and (ii) new operational times for these HWRCs.

5.1. Allocation of users to HWRC facilities

A short survey was conducted among a sample of Sheffield's residents to investigate the preferred criteria for choosing the recycling centres. Such a survey was utilised in order to calibrate the functioning of the spatial interaction model. Details of the survey, of the designed spatial interaction model and of its reliability are discussed in the following (for an extensive discussion, see also [53]).

The survey focussed on user satisfaction with their experience of the HWRC network; 504 respondents (from a University of Sheffield volunteers' list) took part in the survey. Among the survey's questions, two were specifically relevant to this study, which are related to preference rankings of HWRC facilities and factors determining their attractiveness.

The first question asked respondents who reside in any of the 28

[2] Enforcement costs reported in England in 2016/17 were equal to £16M for the almost 500,000 actions taken. Thus, the enforcement costs can be estimated as £33.78 per average action.

[3] Sheffield City Council set a minimum fly-tipping penalty of £80 per incident.

wards in Sheffield to rank their preferences of HWRC using a ranking of between 1 and 5, where "1" represented the most preferred centre, and "5" the least preferred. Such responses were then utilised to compute the quota of users originating from each ward for each HWRC. Then, the percentage of total respondents from a ward accessing a HWRC, based on each preference rank, was computed. This percentage can be interpreted as the probability that a user from a given ward will access one of the facilities. This resulted in the following overall distribution of users from the entire Sheffield City Council territory, as reported in Table 2: Blackstock Road (29.9%), followed by Longley Avenue (26.4%), Beighton Road (23.2%), Greaves Lane (11.1%) and lastly, Deepcar (9.4%).

The second question from the survey was employed to set the attractiveness parameter for the HWRC facilities in the spatial interaction model. This allowed computing the Q_j value for each HWRC, based factors related to the recycling portfolio and the organisation of the site, which were deemed as the crucial ones (besides distance) by users. After a calibration process aimed at minimising the deviation between the results provided by the model and the ones deriving from the survey, n was set equal to 1.59. Table 2 also provides the overall distribution of users (from all wards of Sheffield City Council) across the five HWRCs: Blackstock Road (28.7%), followed by Longley Avenue (25.9%), Beighton Road (22.6%), Greaves Lane (12.4%) and lastly, Deepcar (10.5%). The difference of the users' distributions between the survey and the spatial interaction model that was adopted from Zaharudin et al. (2021), is shown in the last column in Table 2.

From Table 2, it can be seen that the average absolute difference between the distributions produced by the survey and the model is 0.9%. Results show that, overall, the preference structure of the spatial interaction model reproduces in a very accurate way the users' distribution across the HWRCs. It can be seen that users choose HWRC facilities not just based on distance, but also due to a measure of attractiveness factor (based, in the model, on the number of waste containers and the recycling portfolio provided at each HWRC). Hence, in order to generate the number of users for the HWRC services from each ward within the facility network (x_{jt}), the values obtained from the spatial interaction model for the user allocations - see equation (14) - were implemented in the proposed mathematical programming framework illustrated in Section 3.

5.2. New operational times for HWRCs in Sheffield, UK

In order to solve the model and explore the solution space, the two components of the objective function (Z_1 and Z_2) were combined through a convex combination. Specifically, the provider's cost (Z_1) was assigned a weight equal to α_1; the weight of the supplier's cost (Z_2) weight was then set equal to $(1-\alpha_1)$. The model was solved for values of α_1 between 0.1 and 0.9; in the following tables and figures, results related to increments of 0.1 per step are reported. In terms of the considered facilities, y_1 refers to the opening of Beighton Road, y_2 to Blackstock Road, y_3 to Deepcar, y_4 to Greaves Lane and y_5 to Longley Avenue.

Table 2
The difference between the actual and predicted distributions at each HWRC.

HWRC	Percentage distribution of users - survey (A)	Percentage distribution of users - SIM[a] (B)	Absolute difference $= \mid A - B \mid$	Average absolute difference
Beighton Rd	23.1%	22.6%	0.5%	0.9%
Blackstock Rd	29.9%	28.7%	1.2%	
Deepcar	9.5%	10.5%	1.0%	
Greaves Lane	11.1%	12.4%	1.3%	
Longley Avenue	26.4%	25.9%	0.5%	

[a] Spatial interaction model.

Fig. 4 displays the variation of the costs faced by users and providers in order to operate the HWRC network based on changes to the α_1 parameter. It can be seen that, by increasing the α_1 parameter, more prominence will be given to the costs borne by the provider (Z_1); as such the model will propose solutions which shift the burden to the users' side (Z_2). Clearly, this will massively affect the network configuration and the flow of users within the system; details are shown in Figs. 5 and 6. In Figs. 5 and 6, the changes in q_{jt}, s_{jt}, l_{jt}, r_{jkt} and in the total number of operating periods, based on α_1 variations, are reported. Specifically, Fig. 5 highlights the effects of α_1 on provider's side dimensions, while Fig. 6 focuses on the user's side.

From Fig. 5, it can be seen that, as α_1 increases, the percentage of the total number of operating periods is reduced, due to the higher prominence given to provider's side costs that need to be minimised. Given the need to serve at least 95% of the total demand, just slight alterations can be observed in terms of q_{jt} and l_{jt}; however, it can be seen that, as more prominence is assigned to Z_1, the amount of users leaving the system is reduced, due to the need of minimising the harsh cost consequences for the provider. This might suggest, however, that such result is obtained by shifting more burden on the users, through an increase of demand circulation across existing facilities. This is further confirmed in Fig. 6.

Clearly, from Fig. 6, it can be observed that the amount of users moving to another facility increases drastically when $\alpha_1 \geq 0.3$ units and reaches approximately 50% at for $\alpha_1 = 0.9$ units (when the importance assigned to costs faced by the users is minimal). Also, the amount of users queuing at the end of time periods is not as large as one could expect, probably due to the relatively high queueing cost ε_2. Details of all the solutions obtained by implementing the model for different values of α_1 are presented in Table 3.

From Table 3, it can be seen that when α_1 is between 0.5 and 0.6, one HWRC is completely closed by the model. When $\alpha_1 \geq 0.7$, only three HWRCs are in operation. Looking at the α_1 values, the minimal percentage of operating periods across the whole HWRC network occurs when $\alpha_1 = 0.7$. Hence, if the intention of the planner is to obtain a schedule which minimises the opening of facilities, such a solution can be considered; this is associated with the detailed schedule shown in Table 4.

Table 4 indicates that Greaves Lane and Longley Avenue HWRCs are completely closed. However, due to the presence of only three operating HWRCs, a remarkably high value for r_{jkt} can be observed (see also Fig. 6). Table 4 also shows that only two HWRCs are in operation on Tuesdays and Wednesdays, which are Blackstock Road and Deepcar. Blackstock Road is completely open for the entire week, and for the entire periods. With three HWRCs, namely Beighton Road, Deepcar and Blackstock Road, about 97% of Sheffield's residents can be covered in terms of recycling. However, almost 50% of Sheffield's residents would be expected to be served at an alternative site, with an increased risk for these users to leave the system entirely. Details on users' movements are illustrated in Fig. 7.

Fig. 7 presents the movement of users after two HWRCs (i.e. Greaves

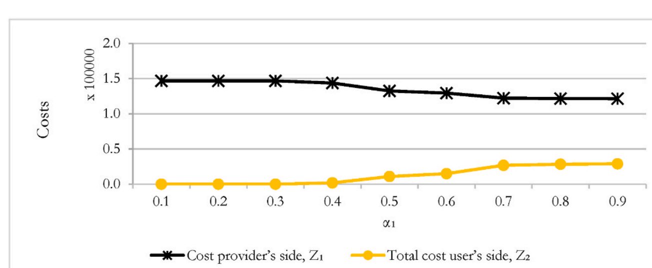

Fig. 4. Changes in objective function (total cost) values for Z_1 and Z_2 based on variation in α_1.

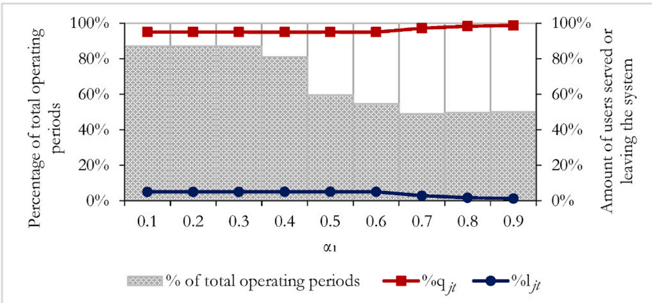

Fig. 5. The effect of variation in α_1 values on the percentage of total operating periods, the amount of users served, or q_{jt}, and the amount of users leaving the system, or l_{jt}.

Lane and Longley Avenue) were closed completely. When the Greaves Lane site was shut down completely, 92% of its users were expected to use the Deepcar site, while the remainder left the network. Meanwhile, 98% of Longley Avenue users were expected to move to Blackstock Road and 2% were expected not to recycle at all. Additionally, the remaining HWRCs were expected to have an overflow of users causing some users to leave the network (not recycling), to move to another HWRC, or to experience more intense queuing. For instance, some users of the Deepcar site left due to an increase of the demand transfer from Greaves Lane.

Conversely, it can be seen from Table 3, that if the objective is the minimisation of the overall total cost, the best solution is attained for $\alpha_1 = 0.5$; in this solution, only the Deepcar centre is completely closed, with the other facilities being operational for most of the week. Such a solution also involves a less radical demand transfer plan, as also highlighted in Fig. 6, and might be preferred by the planner.

6. Conclusions

Managing waste is a crucial challenge for modern societies. Within the UK government's ambitious targets, municipal HWRCs represent key facilities. However, local authority budgets are under severe strain due to reductions in central government funding. Therefore, local councils often need to perform reconfigurations of the recycling centres networks, by reducing the number of sites or their opening hours while still ensuring adequate service levels. In order to provide local authorities with decision support systems for performing reorganisational actions for HWRC networks, this paper has introduced a novel multi-period mathematical programming model. The model has been tested on a case study based on an English local authority, in order to demonstrate its applicability a real-world scenario. The flexibility of the model allows its use for determining revised schedules and configurations for HWRC

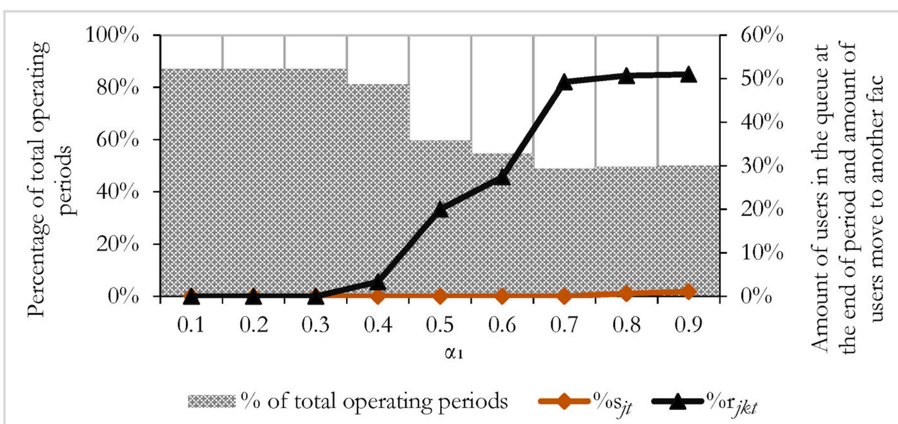

Fig. 6. The effect of variation in α_1 on the amount of users in the queue at the end of a period t (s_{jt}) and on the amount of users that move to another facility j (r_{jkt}).

Table 3
System performance.

α_1	$1 - \alpha_1$	Total cost (Z)	Cost on provider's side (Z_1)	Total cost on user's side (Z_2)	Opening periods per facility	Percentage of opening periods on total periods	Percentage of total users served	Percentage of users leaving the system	Amount of users in a queue at the end of a period	Amount of users transferred to another facility
0.1	0.9	146,747	146,747	0	[54, 54, 40, 43, 53]	87%	95%	5%	0%	0%
0.2	0.8	146,747	146,747	0	[54, 54, 40, 43, 53]	87%	95%	5%	0%	0%
0.3	0.7	146,747	146,747	0	[54, 54, 40, 43, 53]	87%	95%	5%	0%	0%
0.4	0.6	145,566	143,752	1814	[52, 54, 32, 41, 48]	81%	95%	5%	0%	3%
0.5	0.5	143,350	132,473	10,877	[41, 54, 0, 41, 31]	60%	95%	5%	0%	20%
0.6	0.4	144,272	129,354	14,918	[35, 47, 0, 43, 28]	55%	95%	5%	0%	27%
0.7	0.3	149,046	122,222	26,824	[33, 56, 48, 0, 0]	49%	97%	3%	0%	49%
0.8	0.2	149,990	121,689	28,301	[31, 56, 52, 0, 0]	50%	98%	2%	1%	51%
0.9	0.1	150,508	121,562	28,946	[31, 56, 53, 0, 0]	50%	99%	1%	1%	51%

Table 4
Weekly Schedule for HWRCs using $\alpha_1 = 0.7$.

Day	HWRC	Time							
		10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 - 15:00	15:00 - 16:00	16:00 - 17:00	17:00 - 18:00
Monday	Beighton Road								
	Blackstock Road								
	Deepcar								
	Greaves Lane								
	Longley Avenue								
Tuesday	Beighton Road								
	Blackstock Road								
	Deepcar								
	Greaves Lane								
	Longley Avenue								
Wednesday	Beighton Road								
	Blackstock Road								
	Deepcar								
	Greaves Lane								
	Longley Avenue								
Thursday	Beighton Road								
	Blackstock Road								
	Deepcar								
	Greaves Lane								
	Longley Avenue								
Friday	Beighton Road								
	Blackstock Road								
	Deepcar								
	Greaves Lane								
	Longley Avenue								
Saturday	Beighton Road								
	Blackstock Road								
	Deepcar								
	Greaves Lane								
	Longley Avenue								
Sunday	Beighton Road								
	Blackstock Road								
	Deepcar								
	Greaves Lane								
	Longley Avenue								

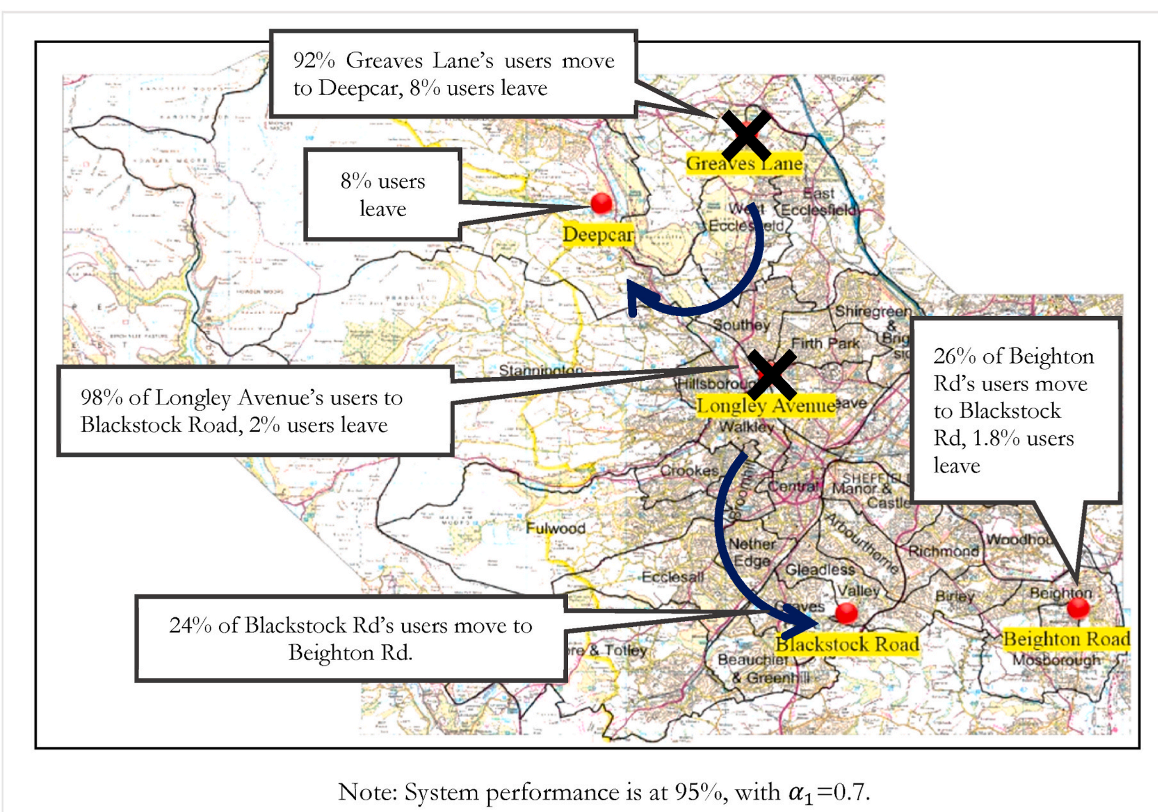

Fig. 7. HWRCs' user movement within the network.

networks; the model can effectively suggest reconfiguration actions for the whole network, such as the closure, downsizing, expansion and the rescheduling of opening hours of facilities.

Future research could be aimed at enhancing the model along several avenues. First of all, in addition to the use of a spatial interaction model for the distribution of spatial flows between wards and HWRCs based on mean arrivals at a facility during a period, demand for the service could be modelled through stochastic approaches. Furthermore, HWRC facilities could be modelled at a higher level of detail, explicitly considering modelling portfolios and internal layouts. Also, different demand reallocation mechanisms (for instance, based on individual preferences of users) could be tested. From a computational point of view, it would also be interesting to consider the behaviour of the model when solving problems with larger datasets, and exploring the need for heuristic algorithms.

Author statement

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We further confirm this study has been conducted with the ethical approval of the University of Sheffield.

We confirm that the manuscript has been read and approved by all named authors.

All authors have contributed equally to the study, in terms of Conceptualisation, Methodology, Data Curation and Writing.

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