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Selectively closing recycling centers in Bavaria: Reforming waste-management policy to reduce disparity

Malena Schmidt[1] | **Bismark Singh**[2]

[1]Faculty of Electrical Engineering, Mathematics & Computer Science, Delft University of Technology, Delft, Netherlands
[2]School of Mathematical Sciences, University of Southampton, Southampton, UK

Correspondence
Bismark Singh, School of Mathematical Sciences, University of Southampton, Southampton, SO17 1BJ, UK.
Email: B.Singh@southampton.ac.uk

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University of Southampton, UK and the Bayerisches Staatsministerium für Wissenschaft und Kunst, Germany.

Abstract

Recycling centers sort and process collected waste in the interest of the environment, but also lead to damaging climate effects via released emissions and pollutants in their operation. Consequently, governments are closing such centers to fulfill climate and carbon neutrality goals. However, such closures risk populations being forced to travel further to facilities that collect waste, and can cause an unfair burden on the remaining open centers, thereby reducing participation in recycling. Using a facility location optimization model and mobility survey data within the state of Bavaria in Germany, we show how selective closures of these centers can still lead to high levels of recycling access. Our analysis ensures that even when 20% of facilities are closed smartly, the median travel distance by residents to their assigned recycling center increases by only 450 m. Additionally, we find Bavaria suffers from disparity in recycling patterns in rural and urban regions, both in terms of motivation to recycle and the locations of the facilities. We promote a policy that favors retention of recycling centers in rural regions by reserving 75% of open facilities to be in rural areas, while selectively closing facilities in urban regions, to remove these regional differences. Success of recycling campaigns depends on public perception of closures of such facilities and also on their ease of access. As policymakers gradually implement further closures, such data-driven strategies can assist in being more transparent to the public thereby increasing the willingness to participate in such recycling programs.

KEYWORDS

facility location optimization, policy reforms, recycling centers, rural-urban disparity, sustainability, waste management

1 | INTRODUCTION

In a span of only 35 years, between 1985 and 2020, Germany nearly halved the amount of residual waste produced per inhabitant [9]. The German Federal Environment Agency (*Umwelt Bundesamt*) credits a significant portion of this achievement to the mechanisms of collecting residual and recyclable wastes which are conducted differently [9]. In 2020, the 70% recycling rate of Germany is the highest in the European Union (EU) [23], and also among the highest worldwide [8]. This success is due to the 1991 German Packaging Ordinance (*Verpackungsverordnung*) through which manufacturers and distributors of goods are responsible for ensuring packaging is either returned or recycled to extents depending on the material used [8]. This regulation was updated into a national German law in July 2021, in response to the European Parliament and Council's Directive 94 (EU 94/62/EG), and is now known as the German Packaging Act (*VerpackG*) [19]. The facility responsible for the collection of recyclable waste that cannot be disposed off directly in households—due to concerns of large sizes or safety—is the "recycling center" (*Wertstoffhof*). Examples of waste collected at such recycling centers are electronic devices, chemicals, bulky items and furniture [39]. Residents are often required to travel to these recycling centers to hand-over such waste, where it is then sorted, recycled, and finally disposed. Although such systems are common in several other European countries—such as, the *déchetterie* in France, the *parc á conteneurs* in Belgium, and the Household Waste Recycling Centres in the United Kingdom—our work is specifically motivated by the current context in Germany.

The organization Environmental Action Germany (*Deutsche Umwelthilfe*) acknowledges the important role played by these recycling centers in ensuring a circular economy and protecting the environment and natural resources [26]. Recycling centers also play a vital role in following the European Commission's Waste Framework Directive 2008/98/EC, by recycling items before their eventual disposal to landfills [24]. However, recycling centers—despite their benefit to the circular and green economy—are themselves sources of pollution, for example, via increased levels of melamine in and around e-waste recycling centers [37], increased risks of spontaneous fires [33], air pollution via volatile organic compounds [21], and methane emissions from the facilities [57]. Further, recycling centers are a nuisance to the public due to the resultant traffic and foul smells around them. Consequently, there is increasing debate over the value of such recycling centers compared to other direct mechanisms such as landfilling waste and incineration, see, for example, [2]. With this background, the German state of Bavaria is steadily closing recycling centers in the last two decades—between 2003 and 2020 the number of recycling centers has dropped from 1763 to 1573 [5]. The Bavarian State Ministry of the Environment and Consumer Protection (*Bayerisches Staatsministerium für Umwelt und Verbraucherschutz*) further attributes such closures to redundancies resulting from changing modes of waste collection, for example, some residential areas are moving towards systems of waste collection rather than residents having to travel to the recycling centers [5]. For an examination of the relationships between recycling facility closures based on both the the amount of toxins released and their economic performance, see [35].

Due to the services provided by the recycling facilities their closures might seem contrary to the desired climate policy goals. However, if such closures are conducted smartly—such that similar levels of access (and, hence, magnitude of recycled waste) are achieved—then significant benefits are possible. These benefits are realized both in terms of the upfront environmental emissions released by the operation and setup of these facilities as well as in the reduction of the nuisance-nature of these facilities on the communities hosting them. For example, Malaysia transformed its waste management policy to include safe closures of landfill sites under its 2005 National Strategic Plan for Solid Waste Management [40]. Sensible closure of facilities is even more important as Germany plans to achieve climate neutrality (reflected via greenhouse gas neutrality) in 2045—revising its plan from 2050 by the Federal Climate Change Act (*Bundes-Klimaschutzgesetz*) in 2021 [12]. Waste management is specifically mentioned in this act, where a reduction in CO_2 emissions in 2030 to a level half of that in 2020 is required [11], app. 2. On the other hand, poor political choices of such closures can demotivate residents to travel larger distances, leading to lower amounts of recycled waste [58]. Without comfortable access to recycling access, there is a risk of greater amount of waste accumulated in the nature via dumping, see, for example, [49]. An additional complication arises if the open facilities face a disproportionate burden of visitors thereby increasing perceptions of recycling centers as a source of distress by their neighboring host communities, further accelerating their image as an undesirable facility [41].

Bavaria is Germany's largest state by area and also contains the largest number of recycling centers [36]. In 2019, households in Bavaria produced nearly 4.3 million tonnes of recyclable waste; wood and electronic devices—both of which must be brought to a facility—amounted to 7.8% and 2.6% of this amount, respectively [4]. However, the population density of Bavaria is several times less than other German constituent states, for example, North Rhine-Westphalia or Berlin. The landscape of Bavaria is rural, with extensive forest cover and mountains. Such "open-spaces" influences both the public policy of locating recycling centers as well as the attitudes of the population for visiting them [18]. Acknowledging that closures of recycling centers are necessary, a natural question facing policymakers is: how do we make informed choices of such closures while ensuring both high degrees of access for the residents and fair burdens on the open facilities?

Our work seeks to answer this highly relevant and topical question. There is extensive literature devoted to the many theoretical (see, e.g., [50]) and applied (see, e.g., [32]) aspects of this problem studied by both policymakers and operations researchers under the tags of the so-called "undesirable" or "obnoxious" facility location problems; for an early survey of such problems, see [22]. For example, Tuzkaya et al. [53] study the problem of locating solid waste collection facilities in Istanbul (Turkey); however, they do so without formulating a mathematical optimization model. In contrast to [53], the work by Yu et al. [30] considers the problem of relocating postal service centers in Narvik (Norway) via two optimization models. Minimizing the costs of setup and operation of solid waste management facilities is another aspect that has been studied [52]. Our work does not seek to extend this already rich body of literature, but instead to influence waste-management policy by utilizing a recently proposed quadratic mathematical optimization by Schmitt and Singh [44]. Our analysis is based on the state of Bavaria, although the insights we derive have value in other geographies, especially in Europe, as well. Acknowledging the disparity in recycling patterns of the rural and urban populations in Bavaria, we provide data-driven guidance to policymakers to specifically inform future closures in both rural and urban areas. With this background, the following are the main contributions of this work.

(i) Firstly, we utilize a systematic mathematical scheme to provide data-informed choices on which environmentally problematic recycling centers to close. Despite the closures, we ensure that all populations are within sufficient reach of open recycling centers thereby not significantly reducing recycling participation while the open centers are not overburdened either. Our analysis ensures that even when 20% of facilities are closed smartly, the median travel distance by residents to their assigned recycling center increases by only 450 m.

(ii) Secondly, we provide quantitative evidence that highlights already existing disparities in both the recycling participation and motivation in the rural and urban regions of Bavaria. Despite this, we demonstrate that equal levels of accessibility for both rural and urban populations facilities can still be achieved—by preventing closures of facilities in rural regions. For instance, ensuring about three quarters of the open facilities are selectively located in rural regions alone can help increase the efficiency of waste management programs by nearly eliminating differences in access to recycling across the two regions.

(iii) Thirdly, despite large extents of closures, our analysis shows that violations of equitable use of the remaining open centers do not occur. This ensures no facility is used unfairly more than another facility. Variability in usage of the recycling centers remains low even when 75% of the facilities are favorably reserved for rural areas.

The structure of the rest of this article is as follows. In Section 2, we briefly summarize the mathematical models we use. In Section 3.1, we demonstrate the need of a systematic way to inform closures rather than ad hoc methods. In Section 3.2, we highlight the disparity in rural and urban recycling participation due to the current positioning of the recycling centers. In Section 3.3, we provide quantitative policy guidance on reducing this disparity. We provide a concluding discussion in Section 4.

2 | METHODS

We adopt and employ the discrete quadratic optimization model originally proposed in [44] that we summarize below:

$$\min_{x,y,u} \quad \sum_{j\in J} C_j\left(1-u_j\right)^2 \tag{1a}$$

subject to

$$\sum_{j\in J} y_j \leq B \tag{1b}$$

$$u_j = \frac{\sum_{i\in I} W_{ij}x_{ij}}{C_j} \qquad \forall j \in J \tag{1c}$$

$$\sum_{j\in J} x_{ij} = 1 \qquad \forall i \in I \tag{1d}$$

$$x_{ij} \leq y_j \qquad \forall i \in I, j \in J \tag{1e}$$

$$y_j \in [0,1] \qquad \forall j \in J \tag{1f}$$

$$x_{ij} \in \{0,1\} \qquad \forall i \in I, j \in J \tag{1g}$$

$$u_j \in [0,1] \qquad \forall j \in J. \tag{1h}$$

Unlike traditional facility location models (see, e.g., [16]), model (1a–h) seeks to simultaneously ensure a low variance in the usage, u_j, of the facilities, $j \in J$, and a high accessibility of users, $i \in I$, to the facilities. All residents from a ZIP code i with a population U_i are assigned to their closest open recycling center j if the capacity, C_j, of that center permits; that is, to a single ZIP code. The parameter W_{ij} is the product of the two parameters, U_i and P_{ij}. If there are multiple recycling centers in a single ZIP code, we treat this as a single facility located at the centroid of all these centers with a capacity equal to their sum. The model is then run with a given number of open ZIP codes containing recycling centers (henceforth, recycling centers), B, as input to determine the subset of centers to keep open, y_j, and the corresponding assignments of residents, x_{ij}. The binary nature of the x variables is ensured due to the totally unimodular structure of constraints (1d)–(1g). For further structural properties of model (1a–h), see [44].

Residents have lower motivation levels to travel to facilities they do not prefer. For example, households might prefer recycling centers that are on route to daily commuting trips, those that are known to be less congested, or those that are open on weekends. Since the optimization model allocates all residents to a single ZIP code that might not be their preferred choice, a discounting factor can be employed to reduce the number of residents that actually travel to a recycling center that is not preferable. This is acknowledged based on distance via a decaying exponential-styled gravity model fit to a survey commissioned by the German Federal Ministry of Transport and Digital Infrastructure and carried out by the Institute for Applied Social Sciences [20]. Separate functions account for recycling motivation in the rural and urban regions with sharper declines in motivation for distances below 5 km:

$$\hat{P}_{urban}(d) = \begin{cases} \exp(-0.255d^{0.867}) & \text{if } d < 5\text{km} \\ 4.639\exp(-1.499d^{0.329}) & \text{if } d \geq 5\text{km} \end{cases} \tag{2a}$$

$$\hat{P}_{rural}(d) = \begin{cases} \exp(-0.250d^{0.820}) & \text{if } d < 5\text{km} \\ 1.611\exp(-0.689d^{0.437}) & \text{if } d \geq 5\text{km}. \end{cases} \tag{2b}$$

The recycling motivation rate is then captured as follows. For each user ZIP code i and facility in ZIP code j, the factor P_{ij} determines the the proportion of users in i that are willing to use recycling center j if they are assigned to it. Such behavioral models have previously been employed in the context of the distribution of pandemic influenza antiviral drugs [46]. There are other existing models for motivation and behavior as well. Belen et al. [6] develop a mathematical model for the spread of rumors while the interaction of motivation and performance is measured in [42]. Such subjective social behavior is not captured within our model, although previous studies have acknowledged that recycling behavior is influenced by social norms [31] as well as publicity campaigns [25].

One metric to assess participation in a recycling campaign is the overall access to recycling centers. We calculate this by the ratio of the number of people going to recycling facilities and the total population; that is, $100 \times \frac{\sum_{i\in I} W_{i,j_i}}{\sum_{i\in I} U_i}$, where j_i is the facility i is assigned to. In Section 3, we provide computational experiments for a variety of campaigns that are parameterized by the number of recycling centers that are closed.

3 | RESULTS AND ANALYSIS

3.1 | Policies to guide closures of recycling centers

In the absence of smart schemes to guide choices of closures, a policymaker can resort to intuitive or improvised ways to determine closures that can significantly diminish the recycling capability of the state. We consider a budget of recycling centers, as a fraction of the total number of currently available recycling centers, that a policymaker seeks to close in an effort to reduce nuisances from operations. With this budget, we compute the access for the entire population to the remaining open centers. Figure 1 plots this trade-off that we discuss below.

Accessibility for recycling naturally drops when more facilities are closed. However, as Figure 1 demonstrates, even when a large number of centers are closed, the models we adopt ensure that recycling access is not significantly affected. Consider the green policy that closes facilities optimally. Specifically, with all centers open, 62.20% of the population is within reach of recycling. Even when 976 facilities are optimally selected and closed (i.e., 70% of the total existing facilities in Bavaria), the drop in recycling access for residents is only 9.59% points. In practice, closing such a large number of facilities is impractical, and a policymaker is more interested in the area given by the left of this curve. For example, if conducted optimally, a 10% drop in upfront emissions by closing facilities leads to a reduced recycling access of only 0.48%. Hence, our analysis demonstrates the importance of employing mathematical models in determining the proper choice of these facilities that do not dampen recycling motivation.

For example, if these facilities are chosen arbitrarily—as given by the black policy in Figure 1—residents are impaired with much larger drops in access. Here, we randomly select the facilities to close but nonetheless optimally assign the populations to the corresponding open facilities. These results are still optimistic as the assignment of populations to open facilities is made in

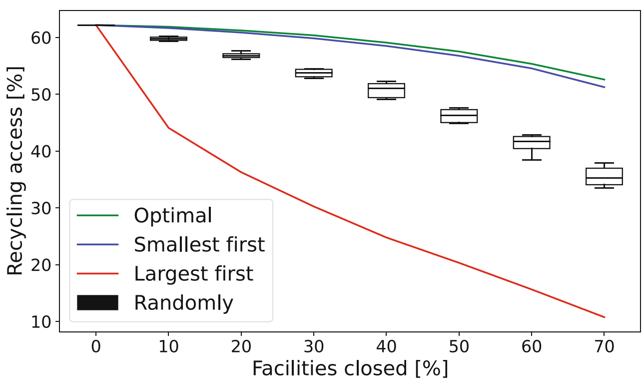


FIGURE 1 Impact of various policies that close a selection of recycling centers on the accessibility of the remaining open centers to residents. In the green, blue, red, and black policies the recycling centers are closed optimally, from the smallest facilities to the largest, from the largest to the smallest, and arbitrarily. For details, see Section 3.1.

the best possible manner; in practice, implementing such a choice would lead to even more reduced access. We further repeat this experiment ten times to reduce bias in these random selections. The box plots in Figure 1 present the 10th and 90th percentiles plus the median of the recycling access. Recycling access already drops by more than 8% points when only 30% of facilities are closed. This drop translates into an increase in the median travel distance of residents from 2.0 to 3.2 km. This seemingly small increase of 1.2 km can be a significant barrier for recycling motivation, see, for example, [28]. Closing more facilities leads to populations being forced to travel even further, resulting in a drop in motivation of recycling. This is further accelerated as seen from Equation (2a,b). The impact of increased travel distances on the motivation to recycle has been observed in multiple studies. Sidique et al. [45] conclude from data collected from eight recycling drop-off facilities, where individuals voluntarily travel to recycle, that residents are likely to use such sites more frequently if their travel distances were shorter. Similarly, a study compiled on recycling habits in Glasgow by Belton et al. [7] noted that the predominant reason for people not recycling was that there was no recycling bank (i.e., a multi-purpose recycling site for recovery of glass, newspapers, aluminum, etc.) close to their home. In a more general setting, Manaugh and El-Geneidy [38] have explored travel distances one is willing to conduct as opposed to those one is happy to conduct.

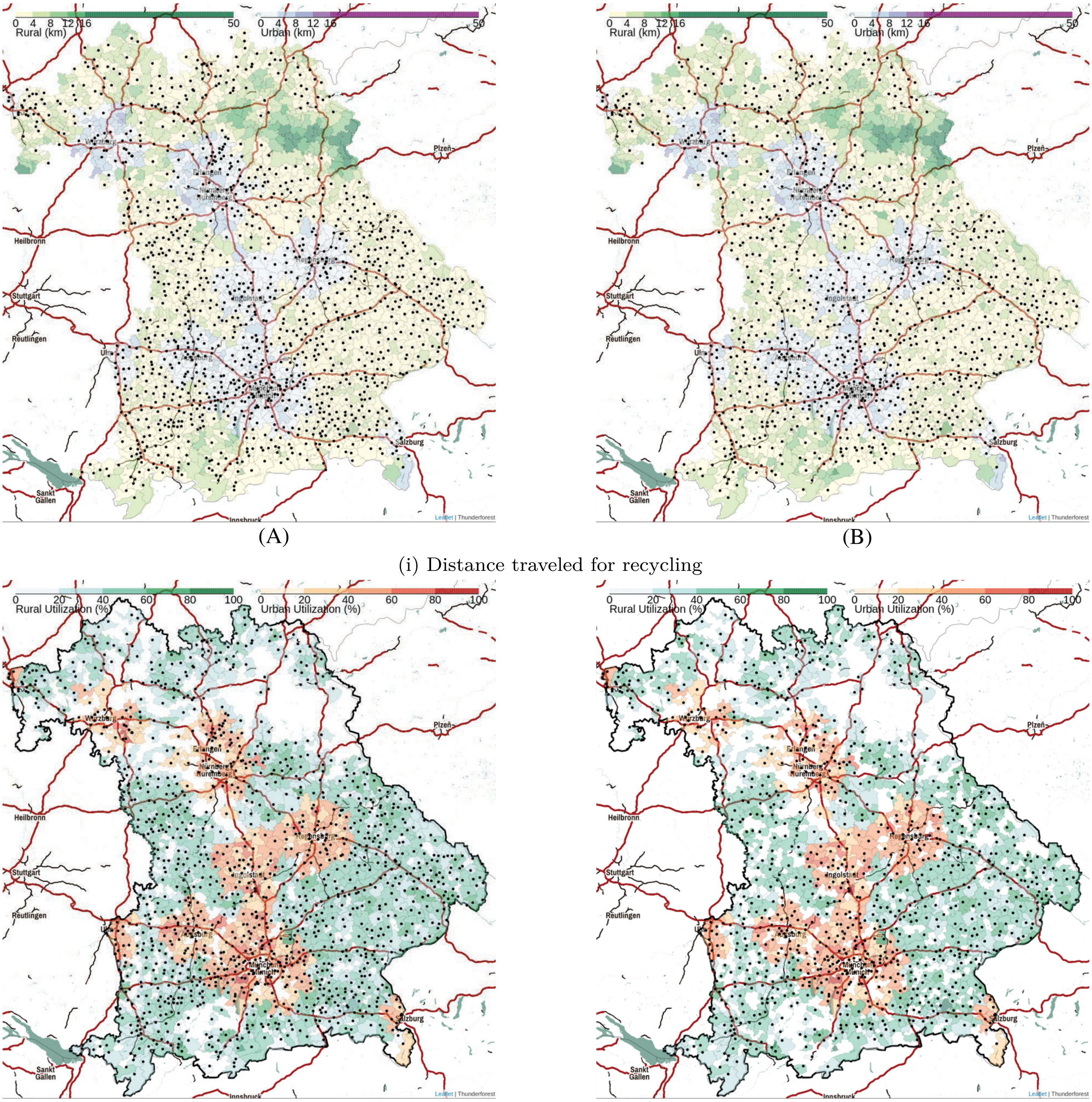
We further compare our results with two additional policies that a planner might choose. First, we consider the policy that closes the facilities with the largest capacity first; that is, those that can accommodate the most number of individuals. For a precise definition of the capacity of a facility as it relates to the catchment population, see [44]. The red curve in Figure 1 presents this policy. Here, the drop in access is significant—demonstrating that large facilities are crucial to achieving good levels of recycling. Closing 15 of the largest facilities in Bavaria diminishes access by more than 4% points from the optimal choice, while for increasing number of closures this marginal drop increases even further. If the 50 largest facilities in Bavaria are closed, some residents are forced to travel a lot further to recycle: the 90th percentile of the travel distance is 8.3 km as opposed to 6.1 km where the choice of these 50 facilities is made optimally. In contrast, a natural policy is to instead close the smallest recycling centers. We do so in the blue curve of Figure 1, and the drop in access from the optimal choice is remarkably small. These results provide data-backed validation to a simple but powerful recycling policy: in the choice of determining which recycling centers to close to cut-down on environmental emissions, we should prefer the closure of smaller facilities as that does not compromise the population's recycling access. The benefits of recycling centers are fully realized only with the support and participation of the population. Highlighting policy choices of closures, that are backed by data, can assist policymakers in ensuring transparency to the public.

The analysis so far masks the burden placed on population communities that live near the recycling centers. As we mention in Section 1, these host communities are naturally averse to disproportionate levels of recycling in their neighborhood. We perceive a communities burden as acceptable when other communities have similar levels of burden as well. Ensuring the same level of utilization—given by the ratio of number of people accessing the facility to the maximum that can possibly access—throughout the state is one way to handle this disparity. However, such a metric risks assigning populations to facilities that are far from their residence endangering the desire or motivation to recycle. To compare this disparity, we consider the variability of the utilization of the open facilities for both these policies. The standard deviation of the utilization of open facilities is consistently lower for selections made optimally as opposed to the simple policy of closing the small facilities, for example, the standard deviations are 0.115 (0.118) and 0.123 (0.126) for 20% (40%) closures of the optimal and small facilities, respectively. With this background, the acceptability of a simple policy of closing the small facilities is lesser than one may initially believe and a comprehensive scheme that balances both these goals is necessary if low variance in utilization is a goal. In the proceeding sections of this work, we analyze the optimal selection in further detail.

3.2 Imbalances in rural and urban recycling participation

A significant portion of the Bavarian landscape is classified as rural by the German Federal Ministry for Digital and Transport (*Bundesministerium für Digitales und Verkehr*) [10]. Although 1408 of the 2060 ZIP codes in Bavaria are rural, they include only half of Bavaria's population. The black dots in Figure 2A present all of the 1394 ZIP codes in Bavaria that contain a recycling center; 971 of these are rural and 423 are urban. The north-east of Bavaria, near the towns Neustadt am Kulm, Erbendorf and Bärnau, includes a large area with no recycling centers[1]. Despite this skewed topography, the distribution of recycling centers in Bavaria is fairly balanced: 69.0% and 64.9% of rural and urban ZIP codes, respectively, contain at least one recycling facility. A strong preference also exists in terms of the residence of populations and their most preferred facility for recycling: 98.8% (98.2%) of populations residing in rural (urban) ZIP codes prefer recycling centers in rural (urban) regions. However, in spite of this seemingly disjoint landscape of the two regions, the additional responsibility and burden imposed

[1]After our data collection, a new recycling center was opened in Parkstein. To the best of our knowledge, this facility has a limited range of acceptability of recycling materials [47]. In addition, the regions around these towns operate a collection system and have containers for specific waste like garden waste set up, instead of operating recycling stations [44].



(A) (B)

(i) Distance traveled for recycling

(C) (D)

(ii) Utilization of recycling facilities

FIGURE 2 Recycling patterns within Bavaria. Panel (i) displays the travel distances to the closest open recycling center in kilometers, and Panel (ii) shows their utilization. The utilization is the percentage of the total capacity of a center that is filled by the visiting populations. The black dots represent the open facilities on all maps. Rural and urban areas are shaded on two different scales to highlight their differences. The maps in the first column include all the recycling facilities in Bavaria, while those in the second column have 20% of the facilities optimally chosen and closed. For details, see Section 3.2, and also the first and third rows of Table 1. (A) All facilities open. (B) 20% facilities closed. (C) All facilities open. (D) 20% facilities closed.

when even a few facilities are closed falls disproportionately on the rural regions. Next, we quantify this burden and explain the reasons that contribute to this disparity.

First, as we mention above, opening larger facilities accommodates more people leading to larger degrees of recycling access. The urban regions of Bavaria host the largest facilities: 9/10, 21/25, and 36/50 of the largest facilities are located in urban regions. Further, the average accommodation capacity of a facility in an urban area is nearly double that of a facility in a rural area. Next, behavior patterns of populations in rural regions of Bavaria indicate that they are slightly more motivated to travel the same distance for recycling as compared to their urban counterparts [44]. Such trends have been reported before in different contexts. For example, Jewett et al. [34] report that driving times to mammography facilities in urban regions of Wisconsin were lower than those in rural regions. Similarly, Vitale et al. [54] report that in Nova Scotia, Canada, children in rural areas

TABLE 1 Disparity in recycling participation of rural and urban populations in Bavaria parameterized by the number of available recycling centers.

Facilities closed (%)	Disparity in access (% points)	Disparity in travel distance (km)		
		10th	median	90th
0	−1.2	0.1	0.2	1.8
10	−1.7	0.1	0.4	2.3
20	−2.3	0.0	0.6	2.6
30	−3.3	0.0	1.1	2.6
40	−4.5	0.1	1.7	3.1
50	−6.4	0.2	2.5	3.2
60	−7.5	0.4	2.9	2.9
70	−8.9	0.7	3.1	3.4

Note: The first column denotes the percentage of facilities that are closed by a policymaker from the total number of currently existing facilities. Access denotes the percentage of population within reach of a recycling center, while the travel distances denote the percentiles of the distance of users to their assigned facility. Disparity is measured as the difference between rural and urban. Negative values in the second column indicate that rural regions have lower access, reflected in more travel distances in the 10th/50th/90th percentiles of the travel distances in the third column. For details, see Section 3.2.

have significantly longer travel distances to school, resulting in 40% of urban children being able to walk or cycle to school while this is only 5% in rural regions. We observe similar patterns of disparity within Bavaria—even when all the centers are open, the distances traveled by the rural populations for recycling are higher than those by the urban populations. The 10/50/90 percentiles for the distances traveled by rural and urban populations are 0.7, 2.1, 6.6, and 0.6, 1.9, 4.8 km, respectively.

As we report in Table 1, closing facilities increases this imbalance even further, leading to disparities in access to recycling. This is further reflected in a consistent increase in the difference between urban and rural travel distances in the median and 90th percentile; closing 30% of the facilities leads to median rural populations traveling an excess of a kilometer above their urban counterparts for recycling. As rural users are already more motivated to travel farther for recycling than urban users, larger travel distances are expected to some extent. However, as reflected by the disparity in the access, increased travel distances are not attributable to motivation alone; that is, the selective positioning of the recycling facilities in rural and urban regions drives such choices.

We analyze this further. Figure 2 compares the effect of optimally selecting and closing 279 recycling centers in Bavaria; that is, 20% of all the existing centers. In determining these facilities, we make no preference to a rural and urban region and optimize to achieve a balanced portfolio of high access and fair utilization throughout the state. In Figure 2, the travel distances denote how far the given population travels within or out of its ZIP code, while the utilization is from the perspective of the facilities in the ZIP code. Figure 2A,B demonstrate redundancies in the existing positions of several recycling locations: even with this large magnitude of closures, travel distances are only minimally increased. Slight increases in travel distances are most noticeable on the borders of Bavaria, for example, south-west and south-east of Munich and west of Salzburg. From Figure 2C,D, we observe that with such optimal closures the utilization does not change significantly either. The greater white areas in Figure 2D show the optimal selection of the 279 facilities to close. We notice that our policy targets facilities with low utilization to close, for example, centers in regions to the north of Augsburg and west of Ingolstadt are closed (marked in white in Figure 2D) as they already had lower utilization (marked in light shades in Figure 2C). We include analogous maps for different budgets of closures in the appendix in Figures A.1 and B.2.

3.3 | Reducing disparities in recycling participation

Our analysis so far demonstrates that rural populations must travel farther no matter how many recycling centers are available. We also observed that most urban residents prefer an urban center, while rural residents prefer a rural center. Next, we investigate how inherently rooted such disparities are within the topography of the recycling centers in Bavaria. This allows us to re-examine any disparity or bias that is artificially induced as a result of a policy of selective closures of recycling centers. To this end, we now include a factor that provides a quota of centers that are always reserved for rural regions. We then employ the following optimization model:

$$\min_{x,y,u} \quad \sum_{j\in J} C_j \left(1 - u_j\right)^2 \tag{3a}$$

subject to

$$\sum_{j\in J_r \subseteq J} y_j \geq \lceil B\overline{r} \rceil \tag{3b}$$

$$\sum_{j\in J} y_j \le B \tag{3c}$$

$$u_j = \frac{\sum_{i\in I} W_{ij} x_{ij}}{C_j} \qquad \forall j \in J \tag{3d}$$

$$\sum_{j\in J} x_{ij} = 1 \qquad \forall i \in I \tag{3e}$$

$$x_{ij} \le y_j \qquad \forall i \in I, j \in J \tag{3f}$$

$$y_j \in [0,1] \qquad \forall j \in J \tag{3g}$$

$$x_{ij} \in \{0,1\} \qquad \forall i \in I, j \in J \tag{3h}$$

$$u_j \in [0,1] \qquad \forall j \in J. \tag{3i}$$

In model (3a–i), $J_r \subseteq J$ is the subset of facilities that are available in rural regions, $\overline{r}$ denotes the "rural-reserve" or the fraction of available centers that are reserved for the rural regions, and $\lceil \cdot \rceil$ denotes the smallest integer greater or equal to its argument. Thus, if 30% of the total facilities are closed (i.e., $B = 0.7|J|$) and $\overline{r} = 60\%$, then at least 42% of the open facilities need to be in rural regions (i.e., at least 60% from the 70% open facilities are in rural regions). The remaining constraints of model (3a–i) are exactly the same as model (1a–h). For computational tractability of model (3a–i), one could preprocess and remove the y_{ij} variables corresponding to small enough values of W_{ij}. These assignments could then be determined following the optimization, see, for example, [46]. This applies to model (1a–h) as well. We do not do so in our implementation as both models are tractable for the problem sizes we consider.

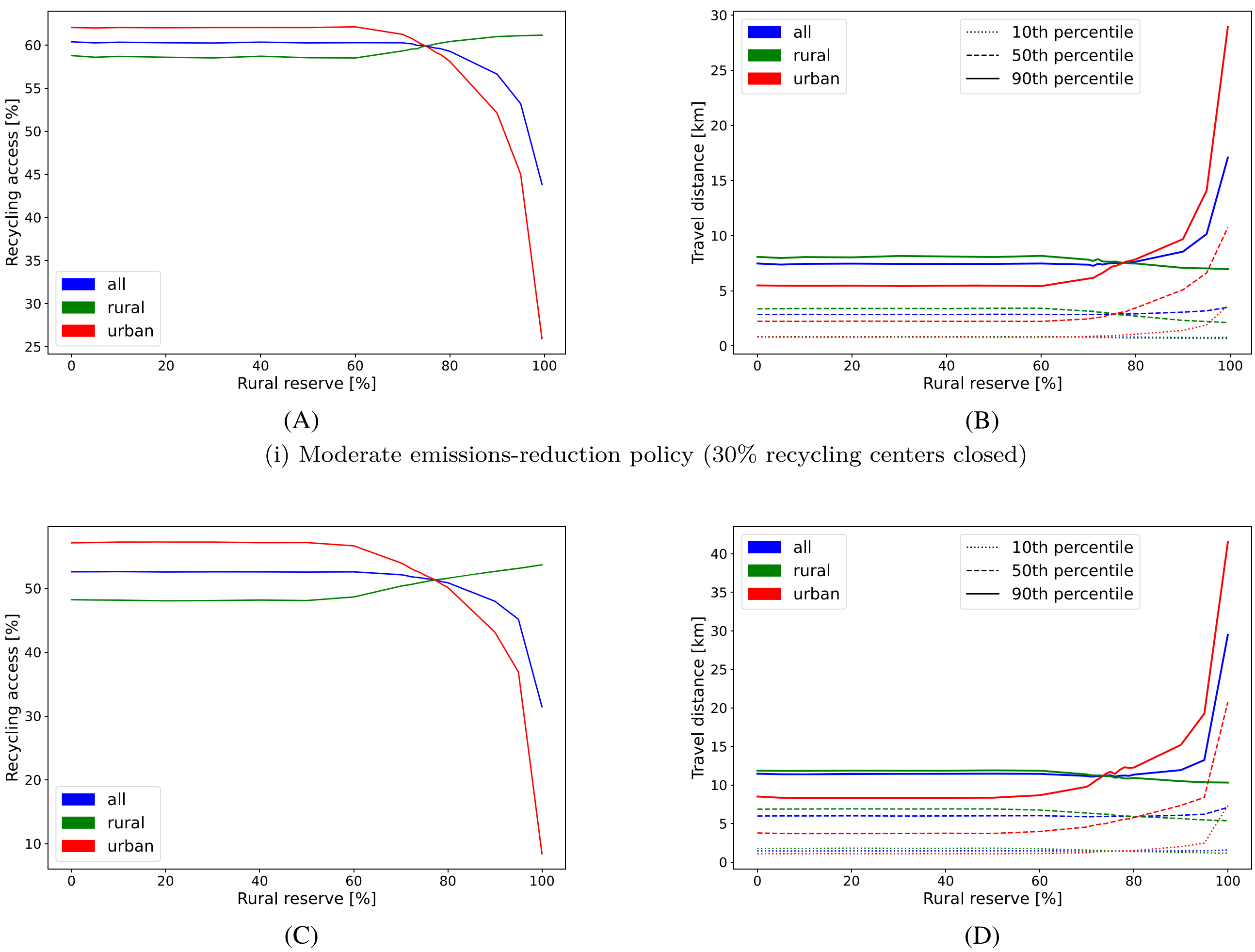
We now consider two situations: (i) a moderate emissions-reduction policy where 30% of all centers are closed (results in Figure 3 (i)), and (ii) an extreme emissions-reduction policy where 70% of all centers are closed (results in Figure 3 (ii)). For both situations we vary $\overline{r}$ between 0 (i.e., no facilities in rural regions are assured) and 100% (i.e., all the facilities, up to the maximum available, are assuredly in rural regions alone). When closing 30% of facilities, we run out of rural facilities at $\overline{r} \approx 99.5\%$ as there are no more rural facilities available, so we ran it for 99.5% instead of for 100%. Without a reservation, an optimal solution selects nearly two-thirds of the facilities in rural regions. Thus, the curves in Figure 3 (i) are relatively flat until $\overline{r} = 60\%$ (we run the analysis in increments of 10% of $\overline{r}$). However, even when all the rural facilities are open (i.e., $\overline{r} = 99.5\%$), access for recycling in rural regions increases only to 61.2% from the optimal value of 58.8%. The price to pay for this reservation is high—with only five urban facilities open, access for recycling in urban regions drops from 62.0% (no reservation) to 26.0% (99.5% reservation), increasing median travel distances in urban regions from 2.2 to 10.8 km. Analyzing this massive drop in access for urban residents further, we find that almost half of the urban facilities in the $\overline{r} = 95\%$ solution are in or around the Bavarian capital of Munich; closing these centers would severely deprive the urban populations of any recycling access.

Reserving about three quarters (75%) of the open facilities for the rural regions ensures the same level of recycling access for urban and rural regions, thereby removing disparity. We vary $\overline{r}$ in 1% increments between the 70% and 80% regimes to precisely compute this threshold. To achieve this balance, the urban residents pay a small price with respect to the scenario of no reservation in terms of slightly larger travel distances for recycling: the 10/50/90 percentiles of travel distances increase by 110 m, 600 m, 1.7 km, respectively. This suggests there are likely fewer urban residents with a recycling center in their vicinity in this new solution. Travel distances over all users are however almost the same in solutions for $\overline{r} = 75\%$ and $\overline{r} = 0$, with an increase of less than 30 m for the 50/90 percentiles and a decrease of 15 m for the 10th percentile. Overall recycling access is also not significantly impacted, dropping from 60.4% to 59.9%. Utilization, too, is not significantly impacted with this reservation. With $\overline{r} = 75\%$, facilities in urban regions have higher utilization while those in rural regions have lower utilization as compared to the scenario of no reservation. This is expected since more facilities are available in rural regions. However, the variability of utilization slightly increases: the standard deviation of rural and urban utilization with no reservation is 0.115 and 0.122, respectively, while in the 75% reservation case this increases to 0.120 and 0.126, respectively.

The above results provide strong quantitative evidence that to ensure the same recycling participation in rural and urban regions, a policymaker must reserve 75% of the open recycling centers for rural regions alone. Although consequently overall access (travel distance) is slightly decreased (increased), the detrimental impact to urban populations is only marginal. Reserving three-quarters of the facilities in rural regions alone might seem a difficult policy decision, however it is not so if put properly in context: in an optimal solution of the moderate policy with no reservation, nearly 66% of the facilities are indeed chosen in rural regions alone. Thus, a policymaker seeking to ensure balance between the two regions only needs an additional 9% points reservation of facilities for rural areas. Additionally, as of now, almost 70% of recycling centers are rural. Hence, only a slightly higher proportion of recycling centers need to be in rural areas than is currently the case in order to ensure no disparity between rural and urban areas. This further underlines why the optimization model without rural-reservation leads to larger disparity: the proportion of rural facilities is decreased instead of increased from the current situation, further widening the gap between rural and urban.

The results for the extreme emissions-reduction policy follow the above trends, however the extent of disparities is larger, see, also the last row of Table 1. Figure 3 (ii) presents these results. A rural-reserve of 77% now ensures the same levels of recycling access for the two regions. However, the price paid to seek this balance is higher than with the moderate policy. Urban access drops by 5.7% points to increase rural access by 3.1% points. This ensures both populations now have a 51% access as opposed to 48% and 57% in rural and urban regions without a reservation. The 90th percentile of distances traveled by urban populations for recycling increases significantly compared to the solution with no reservation, forcing some urban populations to travel even longer than rural populations. Since the motivation to travel large distances to recycle for urban populations is already lower than rural populations, such a policy is not recommended for sustainability goals of recycling. Indeed, median utilization levels of both the rural and urban facilities are now higher (with similar levels of variability) providing further evidence against implementation of reservations in an extreme policy.

We conclude this section with a summary of the above analysis. Although disparities in recycling patterns of rural and urban regions of Bavaria are rooted in the existing positions of the facilities, their effect can be positively dampened with selective strategic decisions. For moderate or light emissions-reduction policies where a few facilities are closed to achieve sustainability goals, our analysis suggests implementing a rural-reserve is worth the additional policy effort. Such efforts can nearly eliminate differences at a relatively small cost. However, for extreme policies that require closing a substantial number of recycling centers, implementing reservations is not recommended. Then, such an additional policy is more harmful to the cause of sustainability than the gain it seeks to make.



(A) (B)

(i) Moderate emissions-reduction policy (30% recycling centers closed)

(C) (D)

(ii) Extreme emissions-reduction policy (70% recycling centers closed)

FIGURE 3 Impact of reserving a fraction of open facilities solely in rural regions (rural-reserve, $\overline{r}$) on overall recycling patterns in Bavaria. Panel (i) presents results for a moderate policy where 30% of all recycling stations are optimally closed, while Panel (ii) includes an extreme policy where 70% are closed. For both panels, the rural-reserve on the x-axis denotes the minimum percentage of centers that are guaranteed to be open in rural regions alone. Recycling access denotes the percentage of population within reach of a recycling station, while the travel distances denote the percentiles of the distance of residents to their assigned facility. For details, see Section 3.3 and also the first, fourth, and last rows of Table 1. (A) Recycling access. (B) Distance traveled. (C) Recycling access. (D) Distance traveled.

4 | LIMITATIONS AND CONCLUSIONS

Our work addresses the challenging question of how to conduct closures of undesirable facilities, such as recycling centers, which are important for the environment but damaging in their operation. Although our hypothesis was specifically motivated by the topical concerns faced by waste-management policymakers in Bavaria, it naturally extends to other jurisdictions. Financial concerns are another driver of such closures. For example, the UK has seen closures of several recycling centers (or, so-called Household Waste Recycling Centres) in recent years [56]. Similarly the state of California has observed this pattern since 2016 [1]. In Brazil, several such facilities have been closed for safety reasons with an attempt to improve recycling methods, but the sites still continue to operate informally [59]. A lack of the required competencies in human resources for operating recycling centers could also be a concern; such concerns have been raised in the context of logistics, see, for example, [29].

To derive the insights offered by this work, we employed several simplifying assumptions that we state below. For limitations on the mathematical formulation we employ, see [44]. We assume the entire population of a ZIP code lives at its centroid. For residents living close to a facility, this is not an oversimplifying assumption. However, for ZIP codes where the centroid is away from the facility, residents could prefer recycling centers in neighboring ZIP codes. In our data, 38 of the 1394 ZIP codes have a facility that prefers centers in another ZIP code. An example is the ZIP code 63 741, a rural ZIP code at the edge of Aschaffenburg, that includes a recycling center within its southern edge. The distance from its centroid to a facility just west of the ZIP code is lesser than to the facility within its own ZIP code; thus, our model assigns the entire population to the neighboring ZIP code. This suggests that some residents might travel shorter or longer distances to recycle than those we anticipate from our model. Employing a granularity finer than the ZIP code is one way to improve this analysis.

Motivation to recycle is correlated with the publicity or promotions done by regional policymakers [25]. In our model, the parameter P_{ij} seeks to capture this motivation of residents in ZIP code i that travel to j. As a policymaker closes facilities in efforts to reduce environmental emissions, our employed model predicts that sustainability goals are counteracted by the drop in public motivation to travel farther for recycling. Without an effective awareness campaign, this motivation would drop even farther than that predicted by our results. On the other hand, by communicating why these closures are being made—based on data-driven models such as our work—plus ensuring closures are done smartly keeping public accessibility in interest, the inclination of populations to recycle can in fact be increased. Such causes have been especially highlighted within the German context [48]. Then, our stated results are conservative, and would be even better in practice.

Estimating the precise capacities of recycling centers is another challenging task. Since the capacities of a recycling center are one of the main criteria to determine the closures, different values would drive a different set of centers to close, see, also, [15], section 4.4.2. We treat two facilities in the same ZIP code as a single aggregated facility. Such facilities are, on average, 3.45 and 4.96 km away from each other in urban and rural regions; however, such variations do not alter the policy guidance on closing recycling centers that we provide. Further, if our employed travel distances differ from those in reality, by the same amounts then the optimal set of closures remains the same as that presented above. Finally, our work favors opening larger facilities than smaller ones on two grounds. First, large facilities can accommodate more residents leading to increased levels of recycling access. Second, larger facilities are better equipped at controlling air pollutants [14]. Smaller facilities often employ uncontrolled combustion and cooling systems that cause greater environmental harm than larger facilities [14, 55]. For instance, a study from Taiwan estimated that 11 medium-sized incinerators emitted pollutants per-unit 50 times those emitted by 21 large-sized incinerators [13].

We summarize and conclude our analysis. Recycling centers are a necessity that contribute both for and against climate change goals. Our analysis demonstrates it is crucial to have a data-driven policy to selectively close these recycling centers. Naive policies of closures lead to decreased public access that harm the cause of recycling waste. As recycling centers were

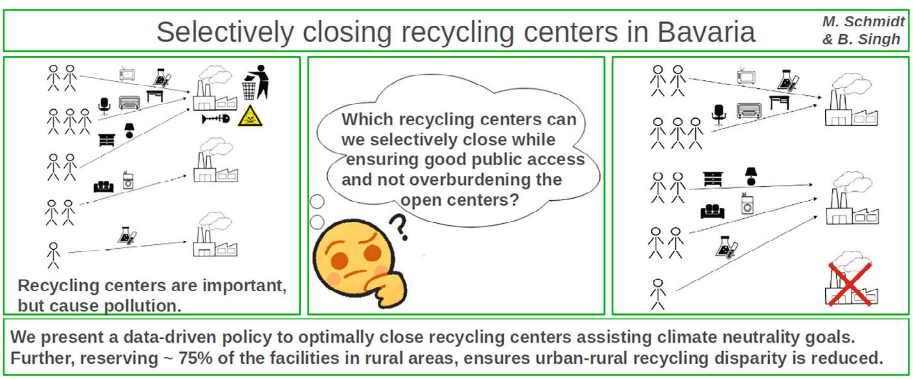


FIGURE 4 An illustrative summary of this work.

developed and constructed at various locations over the past several decades in Bavaria, a disparity between rural and urban populations was induced. As governments decide on closures of the recycling centers, this disparity increases further. Although, it is expected from a political and practical standpoint that recycling centers would close a few at a time rather than hundreds together, such differences lead to biases in recycling patterns in the state, reducing the cause of recycling. We show that a policy that favors retaining centers in rural regions, and optimally closing urban centers, can soften this disparity in access. Such policies that are favorable to marginalized groups, such as the rural populations or lower-income populations, have found advocates worldwide. In Chile, Araya-Córdova et al. [3] recommend resource allocation policies for recycling that favor rural communities in allocating resources. Motivated by the response to the 2009 H1N1 pandemic, Singh et al. [46] recommend antiviral distribution policies that specifically target smaller ZIP codes and underinsured populations. In our analysis we find that the effect of such a favorable policy is most visible when a few recycling centers require closures. Our results acquire greater value if policymakers roll forward such strategical decisions periodically.

Figure 4 provides a visual summary of this work. An online appendix accompanies this work. All our codes and data are publicly available at https://github.com/schmitt-hub/preferential_access_and_fairness_in_waste_management.

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All computations for this work are performed on the DelftBlue [17] system with 1 core on an Intel XEON E5-6248R 24C 3.0GHz processor. All maps for this work are generated with the Folium library [27], using Thunderforest [51] and OpenStreetMap contributors [43]. We thank Christian Schmitt for his inputs. Parts of this work were supported by the Interdisciplinary Research Pump Priming Fund of the University of Southampton and the Bavarian State Ministry for Science and Art (*Bayerisches Staatsministerium für Wissenschaft und Kunst*) under the project "Greedy algorithms for fair allocations and efficient assignments within facility location optimization problems". The funding source had no involvement in study design, collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in GitHub at https://github.com/schmitt-hub/preferential_access_and_fairness_in_waste_management.

ORCID

Bismark Singh https://orcid.org/0000-0002-6943-657X

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SUPPORTING INFORMATION

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