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ORIGINAL ARTICLE

Effect of informal recycling on waste collection and transportation: the case of Chiclayo city in Peru

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Abstract This paper analyses the evolution of national solid waste policy in Peru and the increasing relevance of informal recycling. Despite this rise in relevance, source separation and incorporation of informal recyclers within municipal plans is still slow, and collection of mixed waste is being considered. Waste collection and transportation costs represent the main share in municipal budgets and this research calculates cost reductions as a result of informal recycling and waste picking. The city of Chiclayo in Peru is presented as a case study. The paper finds that so far, waste picking has resulted in a reduction of two collection rounds but not a reduction in the number of vehicles collecting waste. Looking to the future, recovery of the remaining materials will not have an effect on collection rounds and number of vehicles. The research concludes that synergy between municipal systems and informal recycling can be maximized if new operational conditions are implemented. It introduces the concepts of "critical work shift," which is the time of the day when the system requires maximum quantity of resources (i.e. vehicle-hours), and "sensitivity to variations in waste amounts," and proposes strategies to promote recycling based on these new operational concepts.

Keywords Collection and transportation · Waste picking · Recycling · Landfilling

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Introduction

A review of successive documents on solid waste policy issued by Peruvian national authorities shows an increasing relevance of informal recycling and the need to include informal recyclers within municipal plans. Until 2003, Peru did not have an articulated national policy on solid waste and municipal plans were oriented mainly to increase collection capacity through acquisition of collection vehicles, while all Peruvian cities except the capital, Lima city, relied on open dumping as final disposal.

In 2004, Peru's National Environmental Council (CONAM) issued the Guidelines for Formulation of Integrated Solid Waste Management Plans [1], which was a reference for many municipalities to formulate their integrated plans or *PIGARS* (in Spanish: *Plan Integral de Gestión Ambiental de Residuos Sólidos*). *PIGARS* were formulated as a need to formulate coherent plans for investments in waste collection and transportation, material recovery and landfilling. However, the role of informal recycling was not clear in many of these plans, particularly for middle-size cites (more than 50,000 inhabitants), which considered collection of mixed waste together with centralized material recovery facilities next to the new landfills. The Guidelines for Projects in Solid Waste Management [2] released in 2008 by the Ministry of Economy and Finance (MEF) was a clear example of this emphasis on centralized separation facilities. Nevertheless, thanks to these integrated plans, all the municipalities started to systematically think ahead about the location and construction of sanitary landfills and micro-landfills, urged as well by the foreseen collapse of their open dumps.

Since 2009, informal recycling and its potential effects have received central attention in national policy documents. In this year, the newly created Ministry of the

Environment (MINAM) issued the National Report on Solid Waste Management [3] where there is a detailed presentation of relevant experiences on source separation and recycling conducted by municipal governments with participation of informal recyclers. The document emphasizes the need of source separation and recycling as way to raise environmental awareness among residents, maximize material recovery and recycling, and improve working conditions of informal waste pickers.

A new report presented by MINAM [4] in 2010 revealed that recycling and composting programs conducted by municipal governments or private operators in Peru totalize 41.5 t/day for organic waste (food waste) and 74.4 t/day for recyclables (paper, glass, plastics and metals), representing 0.27 and 0.48 % of national waste generation, respectively. In addition, the report introduces the amounts of informal recycling. In Peru, there are about 100,869 waste pickers, 50 % of which are in the Lima area. Waste picking and informal recycling totalize 403 t/day for organic waste and 2,017 t/day for recyclables, representing 2.6 and 12.9 % of national waste generation, respectively. Recyclable materials are picked along the streets just before waste is collected, from collection vehicles, and from open dumps. Materials enter into specialized logistic chains and are utilized by the increasing local industry of recyclables while much of them are exported.

Research questions

Considering the current situation of solid waste policy formulation and implementation in Peruvian cities, this paper raises the following questions: (1) to what extent does informal recycling represent savings in collection, transportation and landfilling for municipal governments?; (2) from economic, social and environmental perspectives, what is more sustainable for Peruvian cities: source separation and separate collection, or collection of mixed waste and centralized material recovery facilities?; and (3) what kind of operational improvements can be made in current collection and transportation systems to maximize the effects of source separation with participation of informal recyclers?

Savings in waste collection and transportation

Literature about the effects of recycling on waste collection and transportation comes mainly from developed countries, where the content of recyclables is higher. Lavee [5] cites Staudt to explain that the high cost of recycling in some German cities arose from their failure to reduce the number of garbage removal rounds. According to the study, collection rounds could be cut in half, thereby saving almost half the cost of the municipal-collection segment. Ackerman [6] adds that communities can benefit from less frequent garbage collection. Additionally, Lavee [5] remarks that municipalities can take advantage of the less volume required for garbage containers due to waste separation. He points that collection costs in Israel are determined by volume, and the average volume-to-weight ratio of recyclable waste is twice the average volume-to-weight ratio of general waste.

Savings in landfilling

Increasing the amount of materials recycled results in a reduction in the amount of land needed for landfilling. The report on Collection of Municipal Solid Waste 2011 by UN-Habitat (Coad) [7], which is dedicated to developing countries, explains that segregation at source for the purpose of recycling is pointless unless wastes are kept separated when they are collected. Furthermore, the document reaffirms that compaction of mixed waste degrades the quality of recycled materials that may later be removed by sorting.

Likewise, MINAM [3] indicates that cities that have already constructed their sanitary landfills, like Lima, Cajamarca and Huaraz, have opted for the implementation of source separation and separate collection with formalized recyclers. This option reflects the fact that, as cities implement controlled landfills, savings from landfilling become as relevant to their budgets as are current savings from collection and transportation.

Incomes from recycling

The current situation in Peru, and international experiences such as in Brazil [8] and other countries, show that it is very unlikely that recycling can generate additional income for municipal administrations. It is generally informal recyclers, or their associations, and the subsequent actors in the recycling chain that carry the costs and capture the added incomes from recovered materials. Coad [7] concludes that cities that have effective informal sector recycling should look for ways to improve its output rather than trying to replace informal recycling with municipal systems.

Methodology

Objective

This study aims to estimate changes in round trips, number of vehicles and costs of collection and transportation of municipal solid waste that result from changes in levels of informal recycling. The year 2010 is taken as reference and the following relation is applied to calculate amounts of waste (in t/day):

$$\begin{aligned}&\text{Municipal collection and transportation}^{2010}\\&\quad = +\text{Waste generation}^{2010} - \text{Informal recycling}^{2010}\\&\quad - \text{Uncollected waste}^{2010}\end{aligned}$$

Model development

Previous works such as Tchobanoglous (presented by Michel and Villeneuve [9]) and Wilson and Baetz [10] propose systems of equations to calculate round trip time, number of round trips per day and number of vehicles. However, these equations consider that vehicles work continuously throughout the day without work shifts. This paper introduces work shifts, which reflects the case of cities in Peru.

Figure 1 presents a diagram of vehicle operations, where B is travel distance until the vehicle is full and D' is distance to landfill. The model considers that waste is uniformly distributed along the streets (curbside collection) and that there are not transfer stations.

$$C_{Tot} = C_{Coll} + C_{Trans} + C_{Treat} + C_{Landf} \tag{1}$$

$$C_{Coll} + C_{Trans} = CC\&T = K + P + CO\&M \tag{2}$$

Time per round trip is calculated with the following equation:

$$\begin{aligned}\text{Time.1r} &= \frac{B}{v} + t_u + \frac{A+C+D+F}{v'} + t_L\\ &= \frac{B}{v} + t_u + \frac{2D'}{v'} + t_L\end{aligned} \tag{3.1}$$

$$B_z = \frac{L_z}{W_z} W_c \tag{3.2}$$

where C_{Tot} is the total cost of waste management (US$/day); C_{Coll} the collection costs (US$/day); C_{Trans} the transportation costs (US$/day); C_{Treat} the treatment costs (US$/day); C_{Landf} the landfilling costs (US$/day); $CC\&T$ the integrated collection and transportation costs (US$/day); K the capital cost of collection vehicles (US$/day); P the personnel cost of collection vehicles (US$/day); $CO\&M$ the operation and maintenance costs of collection vehicles (US$/day); Time.1r the time spent in one round trip (h); B the collection distance until vehicle is full (km); D' the distance to landfill (km); A, C, D, F the distances from Fig. 1 (km); v the average speed in collection route (km/h); v' the average speed in the way to landfill (km/h); t_U the time spent to load up the vehicle (h); t_L the time spent in landfill operations (h); Wz the amount of waste in collection zone z (t/day); Lz the total length in collection zone z (km); Wc is the vehicle's capacity (t).

Likewise, the required number of round trips per work shift Ns and total round trips N, as well as the maximum number of round trips per work shift $N_{zs.max}$ are presented as follows:

$$N_{zs} = \frac{W_{zs}}{W_c} \tag{4.1}$$

$$N = \sum_{s=1}^{3}\sum_{z=1}^{Z} N_{zs} \tag{4.2}$$

$$N_{zs.\max} = \frac{T_s}{\text{Time.1r}} \tag{5}$$

Notice that $N_{zs.max}$ is limited by T_s, the effective time that a vehicle spends in collection and transportation routes. The number of vehicles in each work shift N_{V_s} is calculated by dividing the required number of round trips by the maximum number of round trips and adding all collection zones:

$$N_{V_s} = \sum_{z=1}^{Z} \frac{N_{V_s}}{N_{zs.\max}} = \sum_{z=1}^{Z} \frac{N_{zs} \times \text{Time.1r}}{T_s} \tag{6.1}$$

$$N_V = \operatorname*{Max}_{s=1}^{3}(N_{V_s}) \tag{6.2}$$

We define "critical work shift" as the time of the day (morning, afternoon, night) where the number of required vehicles N_{Vs} is maximum. "Critical work shift" contains the maximum demand to the collection and transportation system in terms of vehicle-hours ($\Sigma N_{zs} \times$ Time.1r) and determines the size of the fleet N_V. Collection and transportation costs are then calculated with the following equation:

$$\begin{aligned}CC\&T = N_V \times K + \sum_{s=1}^{3} N_{V_s} \times P + N \times\\ (B + 2D')\frac{p(1+\alpha)}{\eta}\end{aligned} \tag{7}$$

where N_{zs} is the required round trips in collection zone z, shift s; N the number of round trips (trips per day); N_{V_s} the

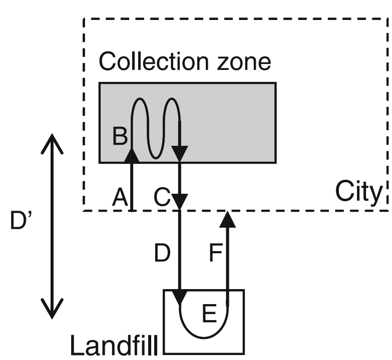

Fig. 1 Diagram of movements for waste collection and transportation. One round trip consists of traveling between collection zones and landfills. There are not transfer stations in our case study

number of vehicles required in s; N_V the size of the fleet; T_s the effective operation time per vehicle per shift (h); η the vehicle's fuel efficiency (km/gallon); p the fuel price (US$/gallon); α is the vehicle's maintenance costs as a percentage of fuel costs.

Description of variables

Data provided by municipality of Chiclayo

Information about collected waste W_z, collection routes, vehicle's characteristics (volume, compaction factor, capacity W_c), round trips per vehicle per work shift N_{zs} and number of vehicles per work shift N_{V_s} is provided by municipality of Chiclayo.

However, the waste amount that arrives to dumpsite in each vehicle is not measured and municipal officers consider that vehicles are full ($W_z = W_c$). This waste amount is estimated using the following formula:

$$W_c = \text{volume} \times \text{compaction factor} \times \text{density of waste}$$

$$W_c = 12\,\text{m}^3 \times 2.0 \times 0.25\,\text{kg/m}^3 = 6\,\text{t/vehicle}$$

Data obtained from digitized maps

Length of streets L_z and distance to disposal site D' in every collection zone is taken from digitized maps. Travel distance until vehicle is full B is estimated considering that waste is uniformly distributed along L_z, with Eq. (3.2).

Data obtained from national guidelines and available studies

Variables such as average speed in collection route v, average speed in transportation route v', time to load up the vehicle t_u, time spent in landfill t_L, as well as effective operation time per work shift T_s are taken from national guidelines for solid waste projects [2] and other available studies in Peruvian cities [11], which represents our best approximation.

Costs per vehicle (capital K, personnel P, fuel p, η, and maintenance α) are also taken from national guidelines. Capital cost K corresponds to investment in collection vehicles amortized with discount rate of 11 % [2].

Table 1 Costs of solid waste management in Latin American cities (in US$/t)

Item	IADB (1998)[a]	IADB (2009)[b]	CEPIS (2002)[c]	MEF (2008)[d]
Collection and transportation	15–40	35–85	25–40	~25
Disposal in sanitary landfill	7–12	8–19	4–10	~15
Total collection, transportation and disposal (without street cleaning)	24–70	38–85		~40
Recycling and composting treatment	Composting			Integrated
	20	10–40		~11

[a] Acurio and Rossin [12]

[b] Terraza [13]

[c] Paraguassu and Rojas [11]

[d] Long term costs calculated by the authors from MEF [2]

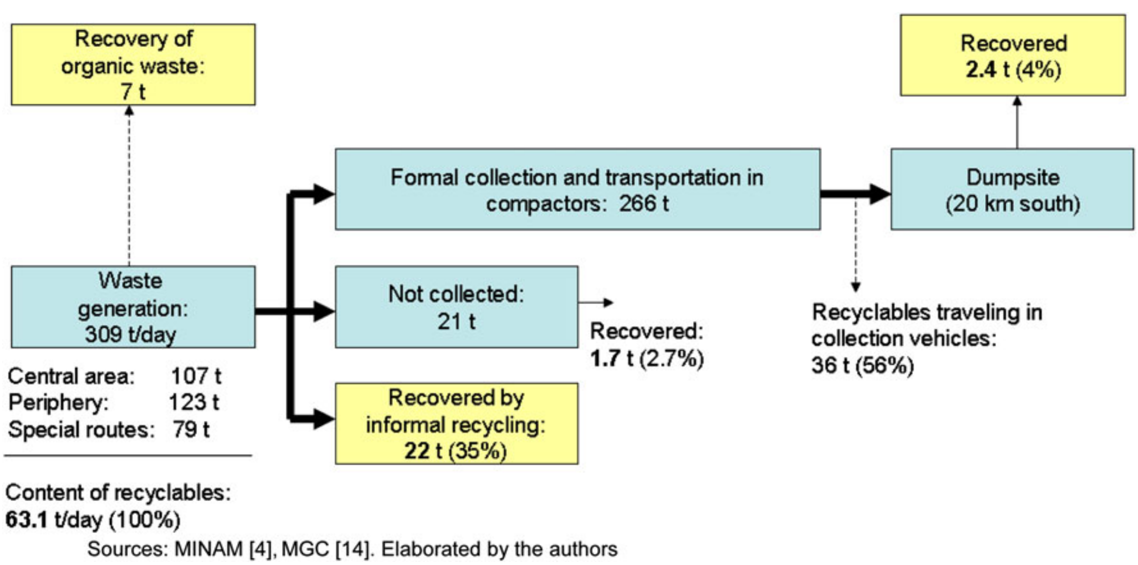

Fig. 2 Waste flow diagram of Chiclayo district. Thirty-five percent of recyclables (paper, glass, plastics, and metals) are recovered along the streets and 4 % is gathered in the dumpsite, representing roughly 40 % of total content of recyclables collected (63.1 t/day). Further recycling could be done if residents separated waste at source

Table 2 Collection zones in Chiclayo district

Collection zone[a]	Collected waste (t/day)[a] X	Sum of streets length (km)[b] Y	Distance to disposal site[b] (km)	Waste spatial density (t/km) X/Y
Center				
Z-1	24.0	26	22	0.92
Z-2	18.0	30	22	0.60
Z-3	6.0	13	24	0.47
Z-4	12.0	24	25	0.50
Z-5	12.0	12	24	1.04
Z-6	18.0	21	21	0.85
Z-7	6.0	12	21	0.48
Periphery				
Z-8	26.8	42	23	0.64
Z-9	12.0	21	27	0.57
Z-10	6.0	24	25	0.25
Z-11	6.0	14	24	0.43
Z-12	18.0	41	23	0.44
Z-13	6.0	19	23	0.32
Z-14	8.8	16	21	0.53
Z-15	6.0	12	22	0.50
Z-16	6.0	23	24	0.27
Z-17	6.0	21	25	0.29
Special Routes Center-West (1,2,3,4)	38.81	33	24	1.17
Special Routes Center-East (5,6,7)	29.24	23	24	1.28
Total waste collection	265.7		Collection efficiency	86.3 %

Configuration of collection zones and collected waste is provided by municipality of Chiclayo. Sum of street length and distance to disposal site is taken from digitalized maps

[a] Municipality of Chiclayo (MGC [14])

[b] Digitalized maps

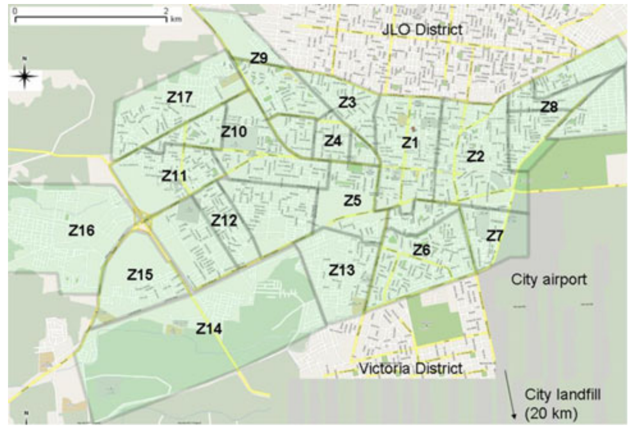

Fig. 3 Map of collection zones in Chiclayo district. This map corresponds to the current configuration made by the municipality of Chiclayo

Validation of the model

Assumptions and estimations are validated with the following steps:

1. Time spent in one round trip Time.1r (Eq. 3.1) cannot exceed effective operation time per vehicle per work shift T_s. Accordingly, T_s cannot exceed the duration of one work shift, which is 7 h in our study case.
2. Estimations made by the model equal municipal data in the following variables: (1) round trips per vehicle per work shift N_{zs} (Eqs. 4.1 and 4.2), (2) number of vehicles per work shift N_{V_S} (Eq. 6.1), and (3) size of the fleet N_V (Eq. 6.2) which is 17 vehicles.
3. An additional verification consists of comparing our cost calculations with estimations made in Latin American cities by Acurio and Rossin [12], Terraza [13] and Paraguassu and Rojas [11], which are based on mixed waste (Table 1).

Application of the model: the case of Chiclayo city in Peru

Chiclayo city has a population of about 600,000 and is comprised of three districts: Chiclayo, JLO and Victoria, each with their own collection and transportation management, but sharing the same disposal site. Chiclayo district is the largest and will be evaluated in this study. Its waste generation has a composition of 51 % organic or food waste, 18 % recyclables (paper, glass, plastics and metals) and 27 % non-recoverable (such as dust and hazardous waste). Although there are not source-separation programs, about 40 % of the recyclable content is separated and taken by waste pickers, as shown in Fig. 2 [4, 14, 15].

Collection is organized among 17 collection zones in downtown and residential areas, and along seven special routes corresponding to city markets, street cleaning, commercial centers and hospitals (Table 2; Fig. 3).

Determinants of the size of the fleet

This section identifies the critical work shift and the factors determining the number of vehicles N_V for our case study. Under current operational conditions, 16 compactors of 13 m^3 (*C1…C5*, *C16…C26*), and 3 trucks of 10 m^3 (*T1*, *T2*

Table 3 Parameters of waste collection and transportation

Parameter	Unit	Compactor	Truck	Parameter	Unit	Compactor	Truck
Waste density (volumetric)	kg/m^3	0.25		Daily cost (investment)	US$/day	107.3	56.4
Capacity (volume)	m^3	12.0	10.0	Daily cost of personnel	US$/day	51.3	51.3
Compaction factor		2.0	1.2	Average collection speed	km/h	10.0	10.0
Capacity (weight)	t	6.0	2.8	Average transportation speed	km/h	25.0	25.0
Investment	US$/vehicle	123,600	65,000	Fuel efficiency	km/gal	12.0	15.0
Replacement period	years	5	5	Maintenance costs (% of fuel costs)	%	18 %	20 %
Personnel (crew)	People	4	4	Fuel price	US$/gal	4.2	
Effective operation time per shift	h	4.2	4.2	Time spent at landfill	h	0.25	
Time to load up the vehicle	h	0.6	0.3				

Values of parameters were taken from guidelines for solid waste projects and available studies on Peruvian cities

Source: MEF [2], Paraguassu and Rojas [11], MGC [14]

and *T26*) travel every day from collection zones to a disposal site located about 20 km south. Vehicles are scheduled in three work shifts: morning, afternoon and night. Table 3 contains detailed information of vehicles' parameters and operation.[1] Vehicles' schedule in each work shift, as reported by municipality of Chiclayo, is presented in Table 4. The authors did not find major seasonal variations in waste generation and collection.

Table 4 presents collection service demand in terms of required vehicle-hours. It is observed that the maximum service demand of 72 vehicle-hours corresponds to the afternoon shift when collection is done in periphery zones and times per round trip are longer. Number of vehicles is obtained by applying Eqs. (6.1) and (6.2) where effective operational time per vehicle per shift T_s is 4.2 h. As a result we have N_V of 17 vehicles.

A way to reduce N_V is to transfer demand to other shifts such as the night shift where current requirement of vehicle-hours is the minimum. Alternatively, idle vehicles during the night shift can be used to collect garbage from accumulation points, support neighboring municipalities or cooperate with the association of recyclers in transportation of recovered materials.

Effect of informal recycling on waste collection and transportation

To evaluate the impact of informal recycling, we consider that recyclables are picked in all the collection zones proportionally to waste generation. As shown in Fig. 2, about 35 % of recyclable content is already taken from along the streets, and 56 % is transported in collection vehicles. Figure 4 shows total collection and transportation costs (Eq. 7), number of round trips, and number of vehicles as a result of reduction of waste due to recovery at source.

We appreciate that:

1. After recovering 35 % of recyclables or about 22 t per day, waste picking accounts for a reduction of two formal collection round trips (in collection zones Z-1 and Z-12) but not a significant reduction of the number of vehicles, which may fluctuate between 17 and 18.
2. Number of vehicles is always defined by collection in periphery areas, during the afternoon shift.
3. In addition, no additional reduction of round trips and no significant change in number of vehicles are expected if further source separation and recycling is promoted in residential areas under the current operational conditions.
4. From the point of view of open dumping, 22 t per day represents a savings of about 1 ha of land per year (density of waste 0.7 t/m^3 and 1 m deep open dumping).

Identifying new operational conditions

Our observations in Chiclayo and other cities indicate that waste picking is mainly concentrated in central and commercial areas where the content of recyclables is higher. For this reason, it is expected that reductions in the number of round trips occur in these areas rather than in periphery areas with lesser recyclable content per km.

To obtain reductions in both round trips and the number of vehicles, central and commercial areas will have to determine the critical work shift. In other words, some periphery areas should be transferred to morning and night shifts.

[1] Time spent to load up the vehicle t_u is estimated on the basis of a crew of four people and a 6-t compactor. We consider a value of 0.6 h in residential zones and 1.2 h in special routes. In residential areas t_u is lower because vehicles keep a slow speed and do not stop during waste collection.

Table 4 Vehicles' schedule

Collection zone	Work shift (vehicle scheduling)[a]			Round trips[a] X			Time of one round trip (h)[b] Y	Vehicle-hours (service requirement) $X.Y$		
	Morning	Afternoon	Night	Morning	Afternoon	Night		Morning	Afternoon	Night
Center										
Z-1	*C24*		*C2,C22,C24*	1		3	3.3	3.3		9.9
Z-2	*C21*		*C3,C5*	1		2	3.6	3.6		7.2
Z-3		*C4*			1		4.0		4.0	
Z-4		*C17,C21*			2		4.0		8.0	
Z-5	*C25*		*C26*	1		1	3.3	3.3		3.3
Z-6	*C23*		*C23,C25*	1		2	3.2	3.2		6.5
Z-7	*C1*			1			3.8	3.8		
Periphery										
Z-8	*C19,C17*	*C1,C20, T2*		2	3		3.7	7.3	11.0	
Z-9		*C22,C16*			2		4.1		8.1	
Z-10		*C25*			1		4.2		4.2	
Z-11		*C24*			1		4.1		4.1	
Z-12		*C19,C18,C26*			3		4.0		12.1	
Z-13		*C23*			1		4.2		4.2	
Z-14		*C5, T3*			2		3.6		7.2	
Z-15		*C2*			1		3.8		3.8	
Z-16	*C2*			1			4.2	4.2		
Z-17		*C3*			1		4.2		4.2	
Special Routes Center-West (1,2,3,4)	*C22, C20, T26, C18, C3*		*C4, C21*	5		2	3.8	18.8		7.5
Special Routes Center-East (5,6,7)	*C26, C5, T2, T3*		*C19, T2, T3*	3		3	3.7	11.1		11.1
Back up units	*C16, C4*		*C17*							
Not scheduled		*T26*	*C1,C16,C18,C20 T26*							
Total	19	19	19	16	18	13		59	71	45

Waste generation in each collection zone is transformed into a service demand in terms of vehicle-hours in each work shift. The largest demand occurs in the afternoon work shift

[a] Municipality of Chiclayo [14]

[b] Time of one round trip Time.1r is calculated with Eq. (3.1)

In general, the critical work shift should be defined by collection zones having a higher potential for waste reduction through waste prevention, recycling, composting, pig feeding or other measures. In this way, campaigns to raise residents' awareness can also be focused in critical collection zones, and the efficiency of invested resources and efforts can be increased.

Identifying marginal savings

Utilizing Eqs. (1)–(7), we calculate the unitary cost of waste collection and transportation in Chiclayo district (CC&T/W): 18.5 US\$/t. However, introduction of the "critical work shift" concept makes clear that every ton of recycling does not necessarily save the full per-ton cost of collection and transportation, such in the case of landfilling.

1. We simulate a reduction of 6 t during the morning shift. The result is a reduction of one round trip with a total savings of 76.7 US\$/day (12.8 US\$/t), representing savings in fuel consumption (25 US\$/day) and personnel (51 US\$/day).
2. On the other hand, after a reduction of 6 t during the afternoon shift, the result is a decrease of one round trip and one vehicle, with a total savings of 184.5 US\$/

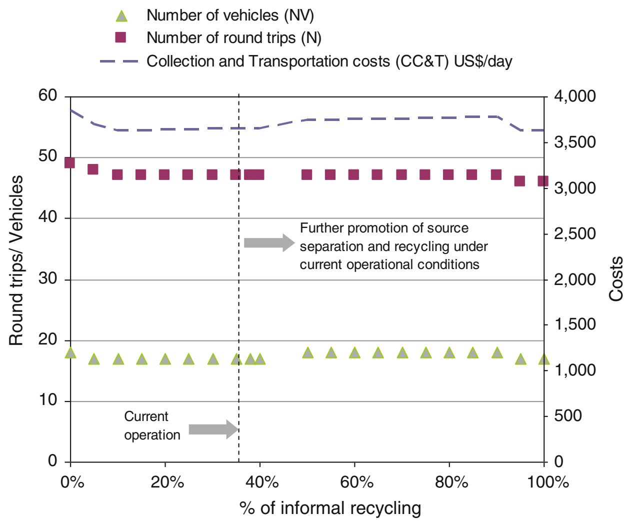

Fig. 4 Effect of informal recycling on waste collection and transportation. Recycling rate is calculated as the percentage of total content of recyclables (63.1 t/day). If today's recycling rate is increased, e.g. through residents' separation at source, no reduction of municipal collection vehicles N_V is expected. New operational conditions are needed to allow cost savings

day (30.8 US$/t): 107 US$/day correspond to vehicle amortization, 51 US$/day to personnel (crew), and 26 US$/day for savings in fuel consumption.

Discussion

Model behavior at high rates of waste reduction

Current levels of informal recycling represent 8 % of waste generation. Estimations made by the model for different levels of waste reduction in collection zones of urban periphery are shown in Fig. 5.

Collection zones Z-10, Z-16 and Z-17 have the lowest amount of waste per km (waste spatial density) and their travel distance until vehicle is full *B* must be large; however, some parts of these zones cannot be reached because time per one round trip Time.1r cannot exceed T_s (Fig. 5d). For this reason, vehicles of 6 t assigned to these zones do not return completely full (Fig. 5b) and some waste remains uncollected (Fig. 5e).

As rate of waste reduction advances, the following events are predicted:

1. Amount of waste per kilometer decreases and travel distance until vehicle is full *B* must increase.
2. If it is possible to merge areas (saving vehicles), as in the case of collection zone Z-8 (Fig. 5a), travel distance *B* increases (Fig. 5c) and time in one round trip Time.1r increases as well (Fig. 5d).
3. Reduction of vehicles is constrained by the imperative that Time1.r cannot be longer than T_s.
4. If waste reduction continues with the same number of vehicles, collected waste per vehicles decreases (Fig. 5b) as *B* and Time.1r remain unchanged.
5. When waste reduction exceeds 36 % almost all vehicles are collecting less than 4 t and operating during all the available time (Time1.r = T_s).
6. Beyond this level, all vehicles should be changed to a lower capacity (for instance 2.8 t) but the number of vehicles will not be reduced.

Waste reduction of 36 % can be reached by combining recycling, composting and other forms of material recovery. To keep high collection efficiency (avoid uncollected waste) with a low number of vehicles, the system would need some of the following ways of restructuring:

1. Increase of T_s: for instance, reducing preparation time of vehicles, locating a garage near periphery areas, or extending duration of a work shift (double work-shift).
2. Systemic reduction of time spent in collection: for instance, shortening collection trajectory with implementation of collection points or small transfer stations with some form of primary collection in periphery areas.
3. Reduction of collection frequency to increase amount of waste per kilometer.
4. Systemic reduction of Time.1r: for instance, with implementation of transfer stations.

Sensitivity to variations of waste amounts

In the last section we have seen that sensitivity of size of the fleet (N_{V_s} and N_V) to variations of waste amounts is defined by two operational constraints: (1) the need to fill up the vehicles, and (2) the need to make complete round trips within the effective time of a work shift T_s.

Regarding the need to fill up the vehicles, the following changes are possible as recycling rate increases:
Two zones reducing waste by 50 % can be merged into one zone, saving 1 vehicle,
Three zones reducing waste by 33 % can be merged into two zones, saving 1 vehicle,
Four zones reducing waste by 25 % can be merged into three zones, saving 1 vehicle,
Five zones reducing waste by 20 % can be merged into four zones, saving 1 vehicle,
Six zones reducing waste by 17 % can be merged into five zones, saving 1 vehicle, etc.

From these numbers, savings of vehicles when recycling increases are more likely when there is large number of zones, which is the case of medium-size or large cities.

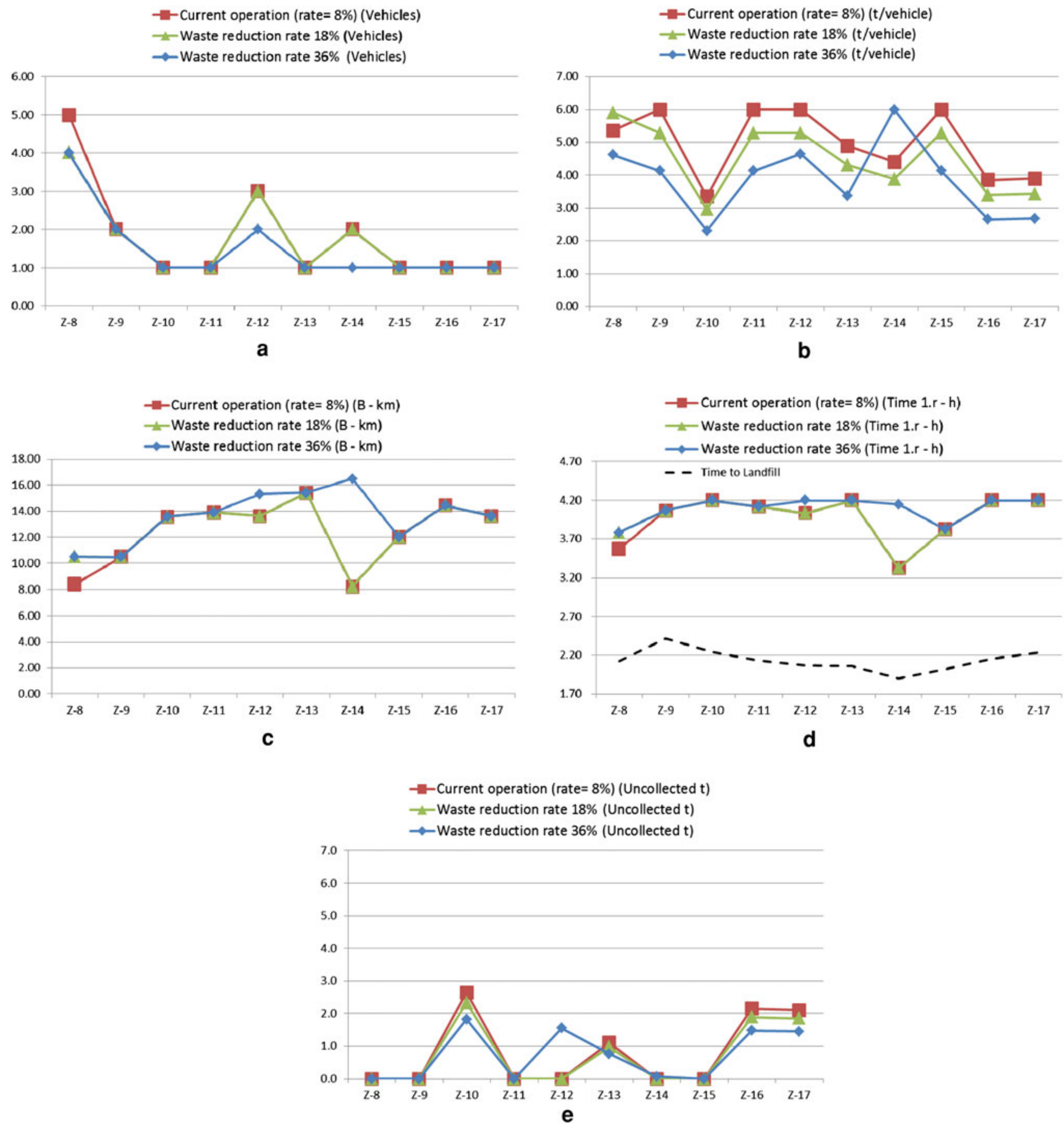

Fig. 5 Model behavior under waste reduction in collection zones of urban periphery. Waste reduction rates are calculated as percentages of waste generation. Waste reduction is possible through recycling, composting or other measures. Effects are seen on the number of vehicles (**a**), metric tons collected per vehicle (**b**), distance until vehicle is full (**c**), time spent in one round trip (**d**), and uncollected waste (**e**). Beyond 36 %, most vehicles carry less than 4 t (**b**) and operate for a time limit of 4.2 h (**d**). Reconfiguration of the municipal system is needed to avoid excess of vehicles' capacity and keep the number of vehicles low

Conversely, as waste amounts increase due to higher population densities and economic expansion, the time until a vehicle is full can be reduced but time spent in transportation to a landfill located at 20 km or more remains unchanged and prevents more than one round trip per vehicle. Future research should consider interrelations between parameters such as size and number of vehicles, number and duration of work shifts, and distance to landfill or transfer stations when waste amounts increase.

Effect of changes in density of waste

All calculations made in this study consider that density of waste (t/m^3) remains constant as recycling rates advance. However, as low-density recyclables are recovered at source, the weight of remaining waste is reduced but the volume of this waste is reduced faster.

Therefore, considering that vehicles actually carry and compact volume rather than weight, vehicles will reach excess of capacity faster than predicted in previous section. Consequently, major reconfiguration of the system will be needed before reaching levels of 36 % of waste reduction.

Conclusions and recommendations

1. This paper calculates the impacts of informal recycling on collection and transportation costs, which are currently the biggest share within municipal budgets. As cities implement their controlled landfills, savings in landfilling will be equally relevant.
2. A model that estimates key variables such as round trips and number of vehicles for different levels of waste amounts is developed. This model offers a framework to (1) identify key variables, their interrelations and their constraints, (2) support construction of databases, and (3) guide more specific studies of times and motions. For instance, daily records of waste carried to landfill in each vehicle are necessary. Likewise, records of time spent in collection and time spent in transportation will support future decisions regarding configuration of collection zones and possible location of transfer stations.
3. From the point of view of total savings, source separation and separate collection appears more cost-efficient than collection of mixed waste and centralized recovery facilities next to the landfills, since amounts of material recovery can be maximized and informal recycling systems cost municipal administrations almost nothing.
4. Nevertheless, willingness to include informal recyclers in municipal waste management will depend on the ability of the former to appreciably contribute to cost reductions; for instance, reductions in the number of municipal vehicles.
5. Synergy between municipal and informal recycling can be maximized under new operational conditions. This paper introduces the concept of "critical work shift," which is the time of the day when the system requires maximum quantity of resources (i.e. vehicle-hours), and states that if cooperation and waste reduction measures are maximized during this time, the number of vehicles and total costs can be minimized.
6. The concept of "sensitivity to variations in waste amounts" is also introduced and offers a useful approach to designing key parameters such as vehicles' capacity, distance to landfill and transfer stations, and the number of work shifts for both mixed waste and recycling systems. We expect to identify new conditions for joint operation of these two systems in our future research.

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