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Weight-based pay-as-you-throw pricing model: Encouraging sorting in households through waste fees

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A R T I C L E I N F O

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A B S T R A C T

Municipal solid waste is associated with different systemic challenges, such as climate change, resource scarcity, and ocean plastic pollution. European countries are striving towards more circular material use and the European Commission has advocated the use of economic incentives to boost recycling. The pay-as-you-throw (PAYT) scheme is an economic instrument that applies the 'polluter pays' principle by charging for waste according to the actual amount of generated waste. Volume-based PAYT fees have shown to be potentially less effective in waste prevention and recycling than weight-based fees. This paper illustrates how waste management operators can price residual waste with weight-based fees that encourage recycling, are fair with respect to service levels, and cover the current income for municipal waste operators. The result, obtained by forming equations satisfying the above conditions, is a model with a linear, discrete price function, where the price of the residual waste generated by the citizen is a function of the service level. This model encourages efficient source separation through internal subsidies, wherein a citizen can decrease the price of household waste by 32% if they increase the sorting efficiency from a default of 40% to 80% efficiency. The application of the model was illustrated in a case example. The model developed in this study can be used to implement weight-based PAYT schemes locally, thereby supporting the formulation of waste management systems that facilitate waste reduction and recycling.

1. Introduction

Since the publication of the Intergovernmental Panel on Climate Change (2018) (IPCC) climate report, the debate around current environmental threats has been more active than ever before. Urgent actions are needed to tackle environmental challenges, such as climate change (Edenhofer et al., 2014), resource scarcity (European Commission, 2012), and ocean plastics (Ostle et al., 2019). Cities are the key operators for increasing the circularity of resource use because more than half of the world's population now lives in cities, and by the middle of the century, this share is expected to grow to two-thirds (United Nations, 2018).

Municipal solid waste (MSW) lies at the crossroads of these booming megatrends. MSW, often called plain municipal waste, is defined as waste generated by households, holiday accommodations, or other housing and similar waste generated due to administrative, service, and business operations (Ministry of Environment, 2011). In Europe, 4% of climate emissions are caused by MSW (European Commission, 2019a) and are mostly related to methane emissions from landfills. In developing countries, MSW is also linked to ocean plastic pollution. Regarding resource scarcity, MSW recycling has been included as an integral part of the European Union (EU) circular economy policy, which aims to radically increase resource efficiency and reduce pressure on natural resources (European Commission, 2019b).

Municipal waste constitutes approximately 10% of the total waste generated in Europe. However, the political emphasis on municipal waste is very high because of its complex character, distribution among many waste generators, and links to consumption patterns (Sahimaa, 2017). When improperly managed, MSW is detrimental to the environment, has direct negative consequences on the quality of urban life, and creates a considerable financial burden on municipalities (Bilitewski, 2008). Household waste is close to everyday life; it is a tool for educating citizens about concrete environmental actions as the correlation between mere environmental awareness and actual behavior can be rather weak (Diekmann & Preisendörfer, 1998; Gatersleben et al., 2002). Proper MSW management also aims to protect human health and

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isolate hazardous substances from material cycles. EU waste management policies include a range of complementary regulatory, economic, and informative instruments that aim to reduce environmental impacts (Morlok et al., 2017). The objective of reducing the environmental impact of MSW management is usually in line with the waste hierarchy process: first, produce less waste, reuse products, and finally, increase recycling (Elia et al., 2015). The revised Waste Framework Directive (European Parliament and Council, 2018) requires member states to reach 55% recycling rate by 2025, 60% by 2030, and finally 65% by 2035. These requirements are part of a wider EU circular economy policy.

In order to meet these requirements, the European Commission suggests economic incentives as a possible method to boost recycling (European Commission, 2011; Watkins et al., 2012). The pay-as-you-throw (PAYT) scheme is an economic instrument that applies the 'polluter pays' principle by charging the inhabitants according to the actual amount of waste they generate (Morlok et al., 2017). The principles of PAYT are based on three main factors (Bilitewski, 2008):

1. Identification of the waste producer
2. Calculation of the amount of waste generated
3. Unit pricing for individual charging in accordance with the services requested or provided.

When combined with well-developed infrastructure and good awareness levels, the performance of PAYT has frequently been linked to an increased collection of recyclables (Morlok et al., 2017). Several studies have reported that PAYT exhibits a significant waste reduction effect (Dahlén et al., 2007; De Jaeger and Eyckmans 2015; Folz and Giles, 2002; Noehammer and Byer, 1997; Reichenbach, 2008; Van Houtven and Morris, 1999). In addition, other benefits can be achieved by adopting the PAYT schemes. For example, PAYT can increase participation rates by providing positive feedback on sorting behavior through fair allocation of costs to users (Dahlén & Lagerkvist, 2010; Elia et al., 2015; Karagiannidis et al., 2008).

However, some negative effects concerning PAYT have also been reported (Berglund, 2005; Jenkins et al., 2003; Salmenperä et al., 2019; Thøgersen, 1994; Thøgersen, 2003). Economic incentives can undermine an individual's intrinsic morals and motivation and encourage waste tourism (i.e., waste moved to neighboring communities) or illegal dumping. In addition, increased amounts of contaminants in recyclables are a potential threat. Finally, additional costs from both investments and the operational side may appear (Dahlén & Lagerkvist, 2010).

In Finland, the focal point of this research, the prevailing method for waste pricing has been volume-based (collection interval and bin size). However, in different types of comparisons, the volume-based PAYT model has been found to potentially encourage less waste prevention and recycling than weight-based systems (Salmenperä et al., 2019). If a weight-based PAYT scheme is implemented, detailed information about waste generation can be applied to citizens. Meadows (1999) suggested that providing feedback can be a simple but powerful leverage point for people's behavior. For example, apartment-specific water meters have been proven to decrease water consumption by up to 40% in Finland (Ylä-Mononen, 2017). Regarding economic steering mechanisms, Finland's beverage bottle deposit system has resulted in very high return rates (PALPA, 2019). These examples indicate that weight-based PAYT could potentially produce promising results in Finland, especially when its effectiveness has already been demonstrated in many European countries (Interreg, 2019; Linderhof et al., 2001; Reichenbach, 2008; Rizzo & Secomandi, 2020)

Any PAYT scheme must be supported by a well-developed collection infrastructure, information for participants, and an appropriate transparent pricing policy (Bilitewski, 2008). When implementing PAYT, new fees must not make the operation unprofitable. Lack of data about pricing can seriously hinder waste management organizations when implementing weight-based PAYT schemes. Therefore, it is important to gain additional knowledge about unit pricing in weight-based PAYT systems. Only a handful of studies have focused on the explicit formulation of waste fees in weight-based PAYT systems. Even though weight-based pricing models were developed by Karagiannidis et al. (2008), the formulation of unit price in a weight-based PAYT model has not been addressed in detail. A comprehensive financial PAYT model for France was presented by Le Bozec (2008) whereas Batllevell and Hanf (2008) highlighted the legitimacy and acceptance of the pricing system.

None of the pricing models reported in previous research are suitable for PAYT implementation in regions with volume-based pricing of household residual waste, such as Finland. Therefore, the purpose of the research presented in this paper is to formulate a weight-based PAYT unit pricing model in the context of Finnish municipal waste management. However, the model or a modified version should be applicable to other countries and thus of interest to international scientific audiences. The specific research question addressed in this paper is: How can residual household waste in a weight-based PAYT system be priced so that the fees encourage waste prevention and recycling, are fair with respect to different service levels, and cover the current income levels of the waste management operator?

The remainder of this paper proceeds as follows. In Section 2, the current state of the Finnish MSW system and the different charging models used in the PAYT systems are explained. In Section 3, the necessary assumptions and key principles underpinning the model are presented. Section 4 formulates the derivation of the model, including a case example and a sensitivity analysis. In Section 5, the implications and potential limitations of the study are discussed. Finally, the key takeaways and suggestions for future research are presented in Section 6.

2. Background

2.1. Finnish waste management system

In 2018, 3 041 482 metric tons of MSW was generated in Finland, while the recycling rate was 42.3% (Statistics Finland, 2020). A total of 57.0% of MSW was incinerated, and only 0.7% was disposed of in landfills. Approximately 65% of Finnish MSW is generated in households (Salmenperä et al., 2019). One of Finland's main characteristics is a relatively scattered population, which creates a significant challenge for formulating an effective waste management system. Altogether only around 2 million people live in cities that have more than 100 000 inhabitants (Local Finland, 2019). The population density of the entire country is 18 pop./km^2.

Unlike many other European countries, the Finnish MSW management system is almost entirely based on source separation. Only two mechanical–biological treatment plants for household waste started to operate in Finland during the last few years (Fortum, 2019; Päijät-Häme Waste Management, 2017). Triggered by the organic waste landfill ban effective in 2016, newly built waste incineration plants have quickly replaced landfills in residual household waste treatment (Korhonen et al., 2018; Statistics Finland, 2020). These large investments in incineration instead of recycling are somewhat contradictory to EU recycling targets.

Municipalities are responsible for organizing household waste management. Waste fees normally consist of a fixed fee and variable collection fees. Collection fees are usually volume-based, meaning they are determined based on the bin volume and collection interval. Finnish waste legislation requires waste pricing that encourages recycling, but in reality, ordering additional waste bins often increases the total price of a household's waste management.

The coverage of door-to-door collection in different municipalities and housing types varies considerably, as municipalities have the freedom to determine local waste management regulations. Table 1 shows the waste management regulations in the capital of Finland, Helsinki, and three other cities.

Table 1
Population size, population density and the waste management regulations in four Finnish cities.

	Helsinki	Turku	Oulu	Jyväskylä
Inhabitants 31st December 2018	648,042	191,331	203,567	141,305
Population density (pop./km^2)	3034	780	69	212
Waste management regulations				
Residual waste	Always	Always	Always	Always
Biowaste	10 apartments	10 apartments	4 apartments	Always
Carton packages and cardboard	10 apartments	20 apartments	4 apartments	5 apartments
Glass packages	20 apartments	10 apartments	4 apartments	5 apartments
Small metal items	20 apartments	4 apartments	4 apartments	5 apartments
Plastic packages	Voluntary[1]	20 apartments	–	–
Paper	In accordance with the Waste Act[2]	In accordance with the Waste Act	In accordance with the Waste Act	Must be sorted separately

1. From 1st January 2021 onwards, collection is mandatory for buildings with 5 apartments or more.
2. According to Finnish Waste Act (646/2011), property holders are obliged to arrange a reception point for the collection of discarded paper products. This obligation does not, however, apply to detached houses or other corresponding properties, or properties located in a sparsely populated area.

The site collection network of the Finnish producer responsibility organization, RINKI, complements the door-to-door collection of municipalities. RINKI has the following number of collection points for household packaging waste: paperboard (1862), glass (1863), metal (1863), and plastic (624). For metals, other than packaging items can be delivered to collection points (RINKI, 2019). In addition, municipalities have their own bring site collection points that complement the collection network run by RINKI. In addition to the door-to-door and bring site collection network, other household waste fractions, such as garden waste and large items, can be delivered to civic amenity sites maintained by municipal waste management organizations.

Weight-based pricing is currently a common practice in large-scale operations, such as shopping centers and deep collection containers. In households with traditional waste bins, bin-specific weighing of waste has so far remained at the level of small-scale experiments.

2.2. Waste pricing models

Previous research on waste pricing models varies from holistic approaches to model formulations. One characteristic of these studies is that they are often designed for specific implementation requirements for a certain country. Bilitewski (2008) described the differences between traditional and modern charge models for waste fee systems, while Karagiannidis et al. (2008) used a full cost accounting model to price waste fee services for municipal solid waste. Both authors present the results of different PAYT scheme simulations. Financial models were also presented by Le Bozec (2008), whose model is for volume-based PAYT pricing, and household sorting is maximized under the condition of budget balance. A comprehensive and holistic framework was presented by Elia et al. (2015), whose study covered the design and management process for PAYT and included a unit pricing model containing equations on how to form the model with fixed and variable costs. There are few published papers on how to price household waste with a PAYT scheme that includes the service levels while considering the budget balance for the waste management company.

Waste fee systems can be roughly categorized into traditional and modern fee systems (Bilitewski, 2008). Traditional fee systems are based on tax financing, flat rates, or container-tag fee systems, and the fee is generally not determined by the amount of waste produced. Modern fee systems follow, to some extent, the rule of 'polluter pays' or pay-as-you-throw, also known as variable-rate pricing, unit pricing, or differentiated tariff system. Modern fee systems aim to create a fair and equal charging model (Bilitewski, 2008). Weight-based and PAYT systems were found to be price elastic (Bel & Gradus, 2016; Linderhof et al., 2001), implying that modern fee systems are relevant in order to meet the requirements of increased source separation and minimization of household waste.

There are two types of modern waste fee systems for municipal waste: one-component and multi-component pricing models (Fig. 1). The one-component pricing model relies on a single fee for the citizen, which can be a fully variable PAYT fee with no fixed amount. The multi-component pricing model is a combination of fixed and variable rates. The fixed-rate or basic fee covers some of the necessary expenses of waste management, while the variable rate is proportional to the weight or volume of some pre-determined waste quantities, usually non-recyclable waste.

Since the variable rate is proportional to the generated waste, the obvious choice is to charge by weight or volume. If the choice of variability is volume, waste is often simply charged by a bin or container. If the fee is determined by the number of bins or containers and their pickups, there are three waste charging policies that can be used. These can be categorized in terms of neutral, passive, or active policies, as described by Bilitewski (2008).

The neutral charging policy means that each collection unit, bin, or bag is the same price regardless of how many units a household has or produces. The passive policy means that the more collection bins the

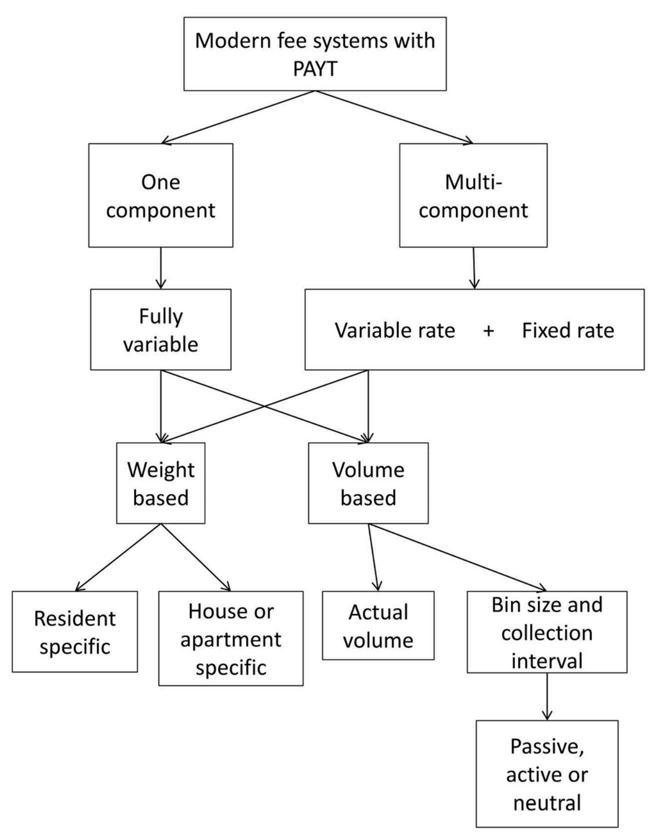

Fig. 1. Modern waste fee systems with PAYT based on Bilitewski (2008).

household has, the less they each cost; that is, the second unit is cheaper than the first and the third cheaper than the second. Active policy means that the more units the household has, the more they each cost; that is, the second costs more than the first and the third more than the second. The passive fee type implies that the more waste you produce, the less you pay for it per unit. The active fee type implies that the more you produce, the more you pay per unit. In a system where the unit fee is inversely proportional to the amount generated, it allows the citizens producing large amounts of waste to be subsidized by citizens producing considerably less waste (Bilitewski, 2008). In the largest cities in Finland, the fee type varies between neutral and passive, and the fee is often proportional to the number of bins and collection intervals.

3. Methods and prerequisites

In this section, the underlying definitions and assumptions of the pricing model are presented, along with the formulation of costs and revenue. The results of the model are presented in the following section (Chapter 4). The main components when defining the model perquisites are meeting the goals of internal subsidy (covering the costs of recyclable waste by residual waste fees), considering the service level, and considering the budget balance of the waste management company. These are presented in this section.

3.1. Assumptions and definitions

The model operates with input data from the waste management company. The required data are the approximate annual collection and transport costs with weight-based pricing. Input data is also required for the waste management company's area, such as information about residents, housing unit types, service levels, and waste generated per person. The average residual household waste composition is also required when using the model.

In the model, all costs and revenues were applied to the waste management company. The term price denotes the price that a citizen pays for waste management. By citizen, it is referred to the inhabitant who lives in the area managed by the waste management company and the citizen is, therefore, a customer of the local waste management company. A user is defined as a waste management company or person that operates the model to set the price.

3.2. Service level

This study considers a municipal waste management system, such as the one in Finland, where the waste management company is in charge of collecting, transporting, and possibly treating household waste. The number of possible material fractions that a citizen can separate from the residual waste and dispose of in door-to-door collection determines the service level (n). The service level can take integer values from 1, with $n = 1, 2, \dots, k$. Here, $n = 1$ means that the service level is the lowest, with door-to-door collection only for one waste fraction (normally residual waste), while $n = 2$ means that there is, in addition to residual waste, one recyclable material fraction and $n = 3$ means that there is residual waste and two recyclable material fractions at the door-to-door collection. The maximal service level is restricted to a specific amount of possible material fractions, denoted as k.

3.3. Subsidy

To strongly encourage source separation within the provided service level, the model was structured such that inhabitants can pay less for recyclable material fractions and more for residual waste, where the income from residual waste subsidizes the recyclable material fraction fees. In practice, this means using internal subsidies, where citizens cover each other's waste fees. The treatment cost of the waste from citizens who are efficient in their source separation is partly covered by citizens who are less efficient in their source separation. For the sake of clarity, it is assumed that there are no governmental or external subsidies.

In the model, the waste management company chooses a subsidy coefficient between 0 and 1. If the coefficient is 1, the citizen pays nothing for the produced recyclable waste fractions, and if it is 0, there is no internal subsidy, and every citizen pays for their own waste. The model incorporates two subsidy coefficients, s_o is the subsidy of operational costs and s_t is the subsidy of treatment costs.

3.4. The linear model

In general, citizens cannot choose freely between service levels but are often restricted to the pre-determined service level at their house. Therefore, pricing was constructed to be fair with respect to the service levels to ensure that citizens are not punished if they do not have the opportunity to dispose of recyclable waste. This was done by defining a linear, discrete price function at the service level. Let n be the service level and p the price per weight unit. Price is defined as a function (Eq. (1)),

$$p(n) = a(n-1) + b, \tag{1}$$

where a is the slope of the price and b is the price at level $n = 1$, that is, the price at service level 1. The user decides the lowest price, b.

There is no restriction that binds the fee to a linear model, and one can fit a number of functions to this model. A linear model was chosen to fit the prerequisite of the fairness of price; the higher the service level (n), the higher the residual waste fee p.

3.5. Formulation of costs and revenue for the waste management company

The different waste fractions are denoted by j, where j = residual waste, bio waste, carton, etc. The costs for the waste management company are the operational costs, that is, collection and transportation costs c_j^o for each material fraction j, summing up the operational costs to $\sum_j c_j^o$. Similarly, the treatment cost of each fraction is c_j^t and sums up to $\sum_j c_j^t$ (see Table 2).

The idea is to cover part of the recyclable material fraction costs with the residual waste fee from citizens. This part is determined by the subsidy coefficient. The revenue for the waste management company from waste fees related to transport, collection, and treatment is divided into two categories. The first revenue stream aims to cover operational costs. The second revenue stream is the income from a weight-based fee, determined by the weight of the waste and the service level at which it was generated (Fig. 2). If the subsidy coefficient for operational fees is less than 1, the fraction not covered by the residual waste fee can be decided freely by the waste management company. In this study, the

Table 2
Symbols used in equations.

Description	Symbol	Unit
Service level	n	–
Material fractions	j	–
Residual waste mass at service level n	m_n	1000 kg/year
Material-fraction-specific collection and transport cost	c_j^o	€/year
Total collection and transport costs	$\sum_j c_j^0$	€/year
Material-fraction-specific treatment cost	c_j^t	€/year
Total treatment costs	$\sum_j c_j^t$	€/year
Subsidy for collection and transport	s_o	Real number in the interval [0, 1]. No unit.
Subsidy for treatment	s_t	Real number in the interval [0, 1]. No unit.

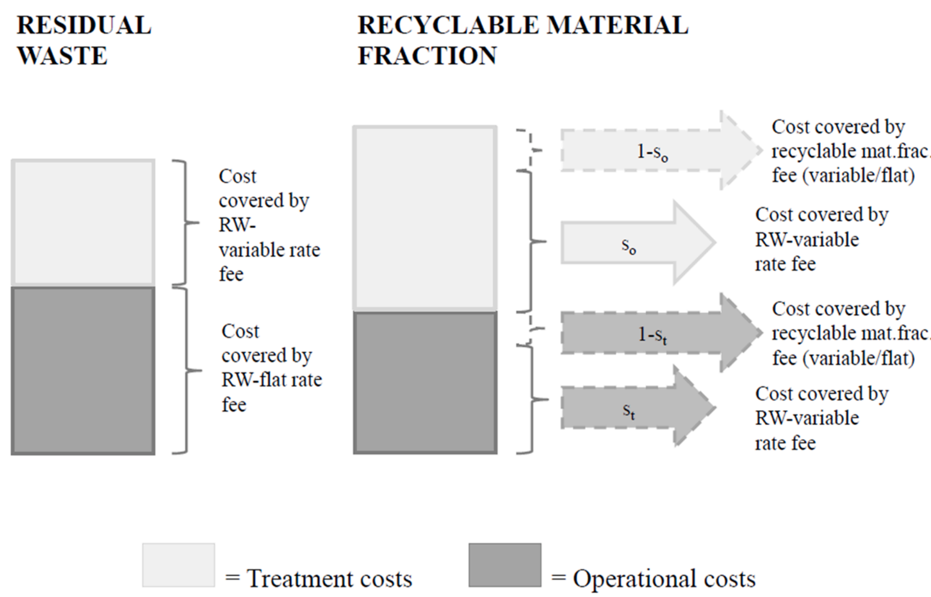

Fig. 2. Collection, transport and treatment costs for the waste management company are covered by the fees in the model. RW stands for residual waste.

formulation of the residual waste fee, which covers the residual waste costs and costs of the recyclable waste fractions at a level determined by the subsidy coefficient, has been carried out.

Revenues are formulated to cover both the operational and treatment costs. The residual waste price is denoted by p, as in Eq. (1), and the mass of residual waste by m_n at service level n. The revenue from the weight-priced residual waste is provided in Eq. (2),

$$R_{RW} = \sum_n m_n p(n), \tag{2}$$

where R stands for revenue and the subscript indicates the waste fraction.

When the unit-based price is assumed to be linear, as in Equation (1), the expression translates to Eq. (3):

$$R_{RW} = \sum_n m_n(a(n-1)+b) = a\sum_n m_n(n-1) + b\sum_n m_n. \tag{3}$$

The revenue from the recyclable material fraction fees, when $s_o < 1$ or $s_t < 1$, is denoted by R_{RMF} and should cover the costs of the non-subsidized part. This revenue can be collected by weight-based fees or flat-rate fees, and the choice lies with the waste management company. However, it should cover the treatment cost of the non-subsidized part, satisfying Eq. (4),

$$R_{RMF} = (1-s_0)\sum_j c_j^0 + (1-s_t)\sum_j c_j^t \tag{4}$$

where j denotes the recyclable material fractions.

4. Results

This section presents the pricing model based on the assumptions and formulations in the previous section. A practical example of the model is demonstrated in a case example, along with a sensitivity analysis.

4.1. The pricing model

In the pricing model, the constraint is that the total costs, from operation and treatment, are covered by the revenue from the waste fees of citizens. The weight-based residual waste fee should cover the costs associated with treating the residual waste, in addition to covering the treatment and operational costs for recyclable material fractions, determined by the subsidy coefficients s_o and s_t. This is expressed in Eq. (5),

$$R_{RW} = c_{RW}^t + s_o\sum_j c_j^o + s_t\sum_j c_j^t, \tag{5}$$

where R_{RW} denotes the revenue from the residual waste fees, c^t_{RW} is the treatment cost of treating residual waste, j denotes all recyclable material fractions, s_o is the subsidy coefficient for the operational costs, s_t is the subsidy coefficient for the treatment costs, and c denotes costs (see Table 2 for overview of symbols).

Now there are two equations for the revenue, Eq. (3) and Eq. (5), stemming from residual waste fees. Combining these results gives Eq. (6),

$$a\sum_n m_n(n-1) + b\sum_n m_n = c_{RW}^t + s_o\sum_j c_j^o + s_t\sum_j c_j^t. \tag{6}$$

To form a linear price, either a or b is set to a fixed number, and the equation is solved with respect to the other. Here, the choice was to set $b = b_0$, the price at the lowest service level, and solving for a. The reason for this is that the current volume-based fee in Finland can easily be translated into a weight-based flat fee; therefore, it is easy for the waste management company to set the weight-based fee at the lowest service level, whereas setting the slope a might be more difficult. Eq. (6) can be solved with respect to b as well.

Solving Eq. (6) for the slope a gives Eq. (7),

$$a = \frac{c_{RW}^t + s_o\sum_j c_j^o + s_t\sum_j c_j^t - b_o\sum_n m_n}{\sum_n m_n(n-1)}.. \tag{7}$$

By inserting this into Eq. (1), the expression for a linear weight-based price function is provided by Eq. (8),

$$p(n) = \frac{c_{RW}^t + s_o\sum_j c_j^o + s_t\sum_j c_j^t - b_o\sum_n m_n}{\sum_n m_n(n-1)}(n-1) + b_0. \tag{8}$$

4.2. Case example

To illustrate the residual waste price that the model yields, a demonstration of the input parameters and corresponding results are presented in this section. This section illustrates the use of the model and how a waste management operator or company can use it.

A set of input test data was chosen, illustrating a small part of a region where a pilot project for weight-based PAYT pricing could be performed. In this case, the weight-based fee b_0 for the first service level ($n = 1$) was set at 80 €/t. This was the fee for residual waste in the Finnish region of Pirkanmaa in 2018, transformed from a volume-based fee into a weight-based fee when the waste density is known. Using these input data, the residual waste function was computed. This resulted in a residual waste fee of 271 €/t at the highest (7th) service level, forming a linear price as a function of the service level.

To illustrate the price differences for consumers, an annual fee for a household was computed for different source separation efficiencies. The behavior of the citizen affects the annual fee, and with increased source separation, the waste fee decreases for a household (Fig. 3). In this example, increasing the source separation efficiency from 40% to 60% decreased the fee for citizens by 16%. Increasing the source separation efficiency further from 40% to 80% decreased the fee for residents by 32%, assuming a full internal subsidy with $s_o = s_t = 1$. Fig. 4 illustrates the distribution of fees. The treatment fee is large compared to the transport and collection fees. This is a result of the internal subsidy in this model, where the weight-based treatment fee mostly covers operational costs.

4.3. Sensitivity analysis

The weight-based price of the residual waste depends on the input values. Sensitivity analysis was conducted to illustrate this dependence. It was not meaningful to vary all input variables because many of them are related to the service level, which can be considered static. Therefore, when investigating how input affects the output, the subsidy coefficients and the lowest price were considered in the sensitivity analysis. These are variables in which the user of the model is free to decide.

The subsidy coefficient between 0 and 1 sets the weight-based price for residual waste. Eq. (8) illustrates that the relationship between the subsidy and price p is linear in nature. The linearity is illustrated in Fig. 4, where the input values are as in the case study, but the subsidy coefficient varied. The higher the subsidy coefficient, the steeper the slope of the function. With the maximal subsidy, the slope is the steepest, indicating that the difference between the price at the highest and the lowest service level is maximal.

Varying the lowest price b_0 with full subsidy coefficients, $s_o = s_t = 1$, is illustrated in Fig. 4. The analysis illustrates that the higher the lowest price, the less steep the slope is, which is consistent with the premise of keeping the income for the waste management company constant. The lines intersect at service level 5, which means that varying the lowest price while keeping all other input variables constant does not change the residual waste price at service level 5 in this example.

4.4. Interpretation of results

The weight-based residual waste pricing model in Section 4.1 forms a framework for PAYT pricing. The model is an equation that presents the residual waste price per weight unit at a given service level. The user has a recipe for setting residual waste prices when implementing a weight-based PAYT scheme with the required input data.

The residual waste price is linear with respect to the service level, with a price increment at each service level, implying a fair price. In the example, there were seven service levels, the general maximal number of bins with different waste fractions in Finland. Still, the number of service levels is not restricted to any upper limit and can be decided by the user. It should be noted that using only one level is not sensible when the idea is to encourage source separation and decrease waste production. In the example presented in this study, the monetary unit was the Euro and the weight unit metric tons, but the model can be used with any currency and unit of weight.

The slope of the residual waste price increases with increased subsidy coefficients. The user can set the steepness of the price function and thereby steer the price difference between citizens with different service levels. The model allows the user to decide the lowest weight-based price, which also adjusts the slope of the price function. Therefore, the user can control the prices, given that the input data are sensible. It should be noted that if the lowest price is set unreasonably high compared to the costs of waste transport and treatment, the model will not produce any sensible prices. The same applies to setting the slope to one, which does not produce any valuable information. Consequently, the use of the model requires a basic understanding of the mathematical functions and equations. The model was tested by a Pirkanmaa waste management company in Finland. However, they did not implement a weight-based PAYT scheme for household waste; therefore, there were no data to verify the model and its use in practice.

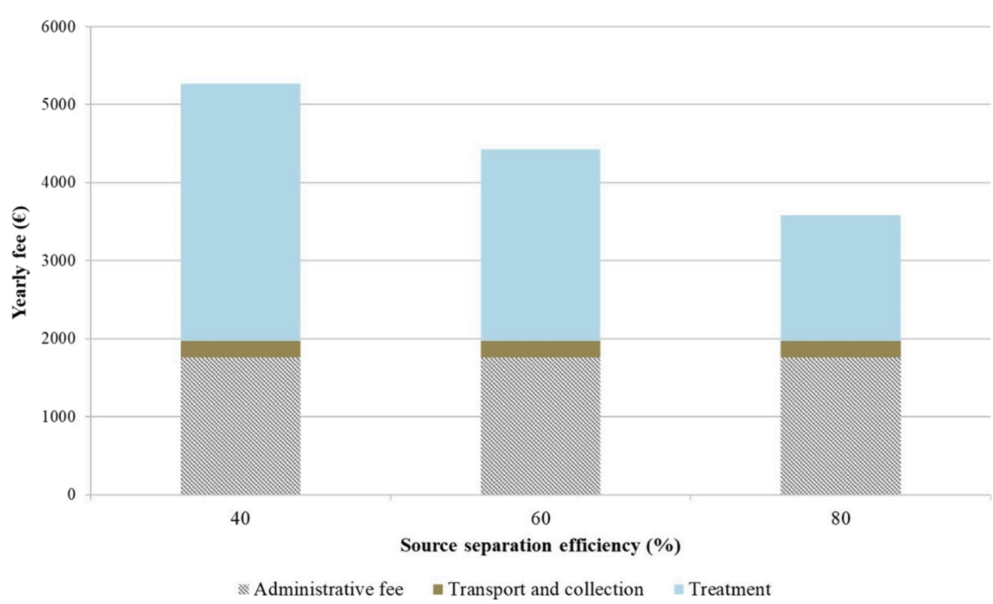

Fig. 3. Yearly fee for an apartment building with 75 residents and service level 7, with subsidy coefficient of 1 for operational and treatment costs. We assume that there is an administrative fee.

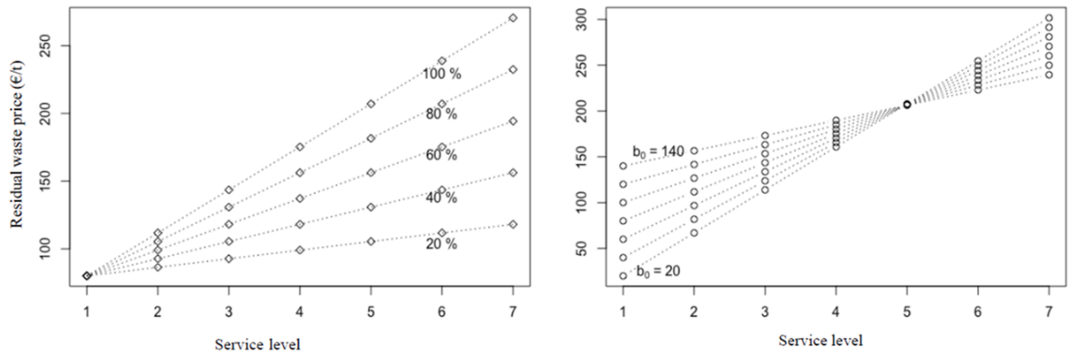

Fig. 4. Left: The residual waste price as a function of the service level, for different subsidy coefficients ranging from 20% to 100%. The percentage mark denotes the subsidy coefficient for treatment and collection and transport, eg. 80% meaning that $s_o = s_t = 0.8$. The remaining input values are kept constant. Right: The residual waste price as a function of the service level with different lowest price b_0, ranging from 20 €/t to 140 €/t. Here the subsidy coefficient is set to 1. The remaining input values are kept constant.

5. Discussion

5.1. Theoretical and practical implications

There is a growing interest in reducing the quantity of MSW and finding sustainable solutions for increased MSW recycling. Pricing waste can be one of the most important steering mechanisms used for this purpose (Bel & Gradus, 2016). The main contribution of this study is that the pricing model is an actionable tool for waste management companies in implementing weight-based waste pricing that encourages additional sorting by households. The model results in fair pricing of waste by considering the service level of different citizens and charging for residual waste accordingly. With the pricing model, actively sorting households can potentially decrease their waste management costs as source separation efficiency, along with how the waste management company sets the prices for recyclable waste fractions and connects the generated amount of waste directly with the size of the fee for each apartment building.

The weight-based pricing system enabled by the model can support the reduced residual waste and more circular material flows in cities. This is confirmed by the results of De Jaeger and Eyckmans (2015), who report a significant downward impact on the amount of residual MSW per capita after introducing weight-based waste pricing in Flanders. Several other recent studies have reported waste-reducing effectsor increased recycling because of weight-based waste pricing or other PAYT systems (Alves et al., 2020; Bel & Gradus, 2016; Morlok et al., 2017; Rizzo & Secomandi, 2020; van der Werf et al., 2020).

Meeting the recycling targets set by the EU is a topical issue in all member states. Reaching EU targets requires large-scale action (Sahimaa, 2017). Alves et al. (2020) found that PAYT systems offer a good incentive to increase sorted waste, thus supporting the EU recycling targets of 55% in 2025, 60% in 2030, and 65% in 2035. In general, economic steering mechanisms in a circular economy can be divided into taxes, incentives, and fees. Already a large variety of economic steering mechanisms are in use within the EU, but they could have a wider role in creating an operational environment that supports the circular economy. Economic steering mechanisms require other supportive policy instruments developed at the national or regional level, such as waste prevention plans, municipality-level recycling targets, and awareness-raising campaigns (Morlok et al., 2017; Salhofer et al., 2008). In the big picture, it can be evaluated that the EU recycling targets, general rise in environmental awareness, and other macro-level developments increase the demand for weight-based PAYT and other promising means to increase recycling in the future.

5.2. Limitations of the study

There are natural limitations to the applicability of this model and with PAYT systems in general. An internal subsidy is a subsidy that allows the price of recyclable waste fractions to be small or zero. This can be interpreted as an unfair model in which citizens who produce more residual waste pay for the collection, transport, and treatment of the waste produced by others. The choice of internal subsidies was made because the waste transportation and treatment expenses have to be covered by someone. In this model, the citizens who contribute the most to the residual waste stream pay the most. Even though an internal subsidy may be considered a negative aspect, it allows for a closed system without external funding. Batllevell and Hanf (2008) highlighted that the perception of the PAYT system's fairness affects acceptance and participation; therefore, waste management operators should be interested in clearly communicating the principles of pricing in order to ensure that the PAYT system is perceived as fair.

The model produces a price only for residual waste. Depending on the subsidy coefficient and individual decisions made by the user of the model, the recyclable fractions can have a price or be free of charge. The prices for recyclable materials are not computed in the model and must be set by the user. This choice was made because determining the price of recyclable fractions was beyond the scope of this study.

Predicting future costs related to waste management is not always possible. This could have consequences for the use of the model. Even if predictions could be made, there might be issues with their reliability. The price of the collection, transport, and treatment of waste can vary for a number of reasons, such as changes in gas prices. Consumer behavior also has an impact on the cost of waste management, but there are uncertainties when anticipating the impact of waste fees on consumer behavior (Le Bozec, 2008). The accuracy of the model relies on the currently known costs of the waste management company. An improvement in the predictions would be a dynamic model with dynamic pricing. The model could have consumer behavior as an input, along with other market indicators.

One of the assumptions for the pricing model was that the transport and treatment of waste is not free of charge but a cost to the waste management company. If the price of the treatment is zero or negative, the price calculation using this model can yield unfeasible results. This might be an issue if there are large investments in incineration of residual waste, especially regarding incineration plants with heat or power production. Investments can produce a lock-in scenario, in which the transition towards more sustainable technologies is slowed down due to long repayment periods (Corvellec et al., 2013). Even though the treatment is not free, since it relies on investments, the treatment can, practically and momentarily, be free of charge, or have a negative price due to income from energy production. In such cases, the pricing model is not applicable. The applicability of the model presented in this study also relies on an already established and modern infrastructure, which makes it less suitable for countries without developed waste management systems. In addition, some additional technical requirements of weight-based PAYT systems (Gnoni et al., 2013; Hong et al., 2014) must be in place to have the system in operation. These requirements relate to the technology for weighing, customer identification, and invoicing, often requiring substantial investments. Investment costs and increased administrative work (Bel & Gradus, 2016) can be a tangible obstacle for implementing weight-based PAYT. Other aspects also affect the viability of the PAYT schemes. For example, the question of whether and to what extent adopting a PAYT system actually increases illegal dumping in an area is not settled in the existing literature (Botetzagias et al., 2020). Heller and Vatn (2017) also suggested that normative motivations linked to doing the right thing for the sake of the environment and being a responsible person play key roles in explaining why people sort household waste, and only half of their sample was motivated to sort more household waste as a result of an economic incentive.

Despite being the top priority according to the waste hierarchy (European Parliament and Council, 2008), waste minimization can sometimes be forgotten when the recycling rate targets receive most of the attention. This is a limitation of this model. A low or zero price for recyclable material fractions, that is, a high subsidy coefficient, does not directly encourage waste minimization. In general, the waste reduction effect of weight-based PAYT systems is still contradictory because of the limited amount of research and depends strongly on the practical details of the waste management system (De Jaeger & Eyckmans, 2015). This underlines the need for further research on weight-based waste pricing and other economic incentives in different contexts.

6. Conclusions

This paper continues the tradition of relatively limited pay-as-you-throw (PAYT) research by tackling the pricing of waste as a potential hindrance to implementing weight-based PAYT systems. The model presented in this paper helps distribute waste fees fairly among citizens and can be adjusted to cover the collection of recyclables in residual waste fees fully or use lower subsidy rates.

There are two main conclusions of this study. First, more research and practical trials are needed to formulate a more holistic understanding of the impacts of weight-based PAYT schemes in different contexts. Pricing of waste is an important part of well-functioning weight-based PAYT systems, but there are also several other key factors: clear communication and perceived fairness of pricing, understanding geographical differences in waste management systems, and monitoring the functionality of the system. Moreover, implementing weighing and identification technologies in waste management systems is a multidimensional logistical and administrative challenge that needs to be addressed. When estimating the effect of the weight-based PAYT system, reliable waste composition and waste generation data are necessary to compare the output of different collection systems. The contextual differences in waste management in different countries make it difficult to evaluate the applicability of certain PAYT solutions. For example, the legislative framework may hinder the meaningful development of PAYT schemes in some places.

Second, wider implementation of weight-based PAYT could potentially be an important part of the policy mix supportive of recycling in different countries that aim to improve the national MSW recycling rate or waste reduction. The ambitious recycling targets of the EU have led to a situation where many EU member states supposedly need to implement several new policies to reach the targets.

In addition to economic incentives, regulatory and informative policy instruments are needed to promote environmentally-friendly behavior. It is important to recognize weight-based PAYT pricing as a part of a larger systemic change for more sustainable MSW management. In this reform, local waste management operators play a crucial role and must be supported with sufficient resources and capabilities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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