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Portable battery lifespans and new estimation method for battery collection rate based on a lifespan modeling approach

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ABSTRACT

Separate collection and recycling of used batteries is required in the EU member states and other countries, as a measure for environmentally sound management of batteries. Monitoring of collection rate of the separate battery stream is important for decision making, in particular for implementing interventions to improve the separate collection and evaluating their results. Limitations of the currently applied method for the estimation of battery collection rate are discussed and a new method, which improves the estimation, is suggested. The method utilizes a more accurate way of estimating the total battery waste generation. This estimation is based on batteries historical consumption estimated with material flow analysis method and distributions of batteries lifespan obtained from empirical data.

Empirical data from two decades of battery consumption and disposal in Sweden were analyzed and lifespan distributions have been found for eight different types of batteries by dating over 5000 disposed batteries. The lifespans stretched from 1 to 28 years, with a median lifespan of 3–8 years.

It is shown how the use of lifespan distributions in the suggested method could considerably improve the estimation of the collection rate. Consequently, the intervention potentials can be identified more accurately and the decision making for investments in the collection system can be improved. The observed lifespans are also useful for understanding batteries fate in households as well as trends in battery consumption and disposal.

1. Introduction

Due to their significant content of both valuable (Ag, Ni, Zn) and hazardous (Hg, Cd and Pb) metals, batteries are one of the priority products for protection of the environment and resource recycling. Proper management of used batteries is becoming increasingly important due to the exponential growth in the consumption of batteries which is driven by the use of portable electronic equipment (Guevara-García and Montiel-Corona, 2012; Kalmykova et al., 2015a,b,c; Patricio et al., 2015a). The current management approach in the EU member states, as well as in Japan and Australia and some other countries, is to separate the collection of batteries from other waste streams.

Majority of batteries used by households are portable batteries. Portable batteries are all sealed batteries and accumulators with weigh less than 3 kg that are not classified as automotive batteries, accumulators, industrial batteries or accumulators or batteries for electrical bicycles (Directive 2006/66/EC). The collection of portable batteries in Europe is regulated in Directive 2006/66/EC, which requires member states to achieve a collection rate of 45% by 2016. Sweden has defined a more ambitious collection target of 75% by 2016. According to statistics from the Swedish Environmental Protection Agency (EPA), 60.7% of the portable batteries sold in Sweden in 2015 were collected (Swedish EPA, 2016).

Large investments are being put into the infrastructure for separate collection of batteries as well as consumer education and collection campaigns. For example, in Sweden two ambitious nation-wide programs that included direct information and cultural interventions (music, TV, cinema, children's theater) have been implemented in 1987 and 1999. In 2012, a 10 million Euro information program was launched from the Swedish EPA battery fund for information purposes. Many of the decisions on the necessary improvements in the battery collection are based on the measured collection rate with respect to the defined collection target.

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Currently available method for the estimation of the batteries collection rate can be found in The Battery Directive (Directive 2006/66/EC). The Directive 2006/66/EC defines the collection rate as "... the percentage obtained by dividing the weight of waste portable batteries collected [...] in that calendar year by the average weight of portable batteries that producers sell [...] during that calendar year and the preceding two calendar years" (further referred to as "the Directive method"). However, this method of estimation can lead to implausible results, as in the case for NiCd batteries collection in Sweden, where collection rate has been estimated to be in the range of 300–1500% for the years 2009–2015. Therefore, it is important to re-examine the assumptions of the Directive method and the possible impacts of them on the accuracy of the collection rate estimation. It is also of importance to improve such estimations, if possible.

In this paper, we propose to use an approach similar to the methods used for the estimation of the Waste Electrical and Electronic Equipment (WEEE) generation: the Input-Output analysis method, as described in Wang et al., 2013 and to the lifespan modeling method as described in Oguchi et al., 2008 (Wang et al., 2013; Oguchi et al., 2008). In this study, the lifespan is set to the domestic service lifespan, defined as the period of time from initial manufacture until the point in time when a product is disposed of by the final owner (Murakami et al., 2010). According to Magalini et al. (2014), the Input-Output analysis and, in particular, the use of the sales or MFA time-series data together with lifespan distributions was considered as the most appropriate methodology to calculate WEEE waste generation for all the EU member states. The noncomplex calculation process, as well as the high potential of harmonization across the countries in Europe, are some of the advantages highlighted. The batteries collection rate could then be estimated by dividing the weight of batteries collected in a given year by the estimated total disposal in the same year, this estimation performed by applying the lifespan distributions.

Up to date, only one paper on waste batteries generation has been published. The waste battery flows for China were estimated using annual sales data as well as probable lifespan distributions of various batteries, obtained from relevant literature (Song et al., 2016). In that paper it is assumed that all primary (nonrechargeable) batteries in China are consumed within a year, and the average lifespan of secondary batteries vary from 3 to 6 years, depending on the chemical composition of the battery. On the other hand, actual lifespan distributions would give better precision in the results. Such study of batteries empirical lifespans has been conducted for Belgium, where the average lifespan of primary batteries (alkaline) was found to be 5 years (Desmet and Mertens, 2014).

The purpose of this study is to contribute to development of estimation methods for batteries collection rate. This is done by studying the lifespans of batteries in order to: 1) understand the lifespan of different primary batteries; and 2) develop a new estimation method for battery collection rate using lifespan data.

2. Theory

The collection rate is defined in this paper as the proportion of the batteries during a certain year that were disposed of through the separate collection system for batteries (further – "correct disposal"). Explicitly,

$$CR_t = \frac{C_t}{W_t} \tag{1}$$

with CR_t = collection rate in year t, C_t = amount of correctly disposed batteries in year t, W_t = total amount of disposed batteries in year t.

The amount of correctly disposed batteries each year can be obtained from public statistics. The total amount of disposed batteries, however, is unknown and needs to be estimated.

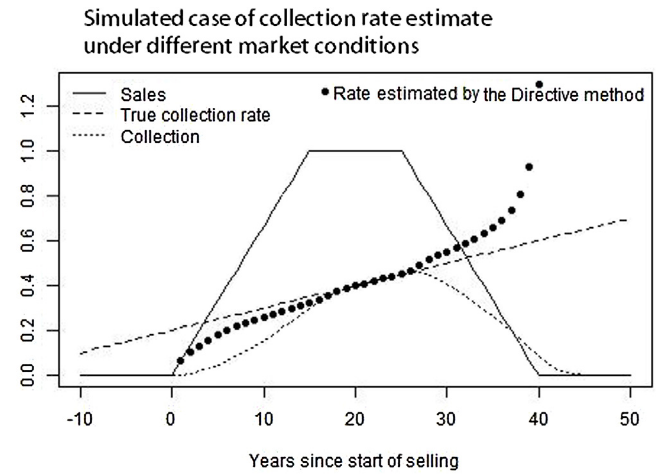

Fig. 1. Simulated case of the collection rate estimation by the Directive method.

The methodology, currently applied in the EU (the Directive method) uses the average of batteries sales during the last three years as an estimate of the total amount of disposed batteries in year t. Intuitively, such an approach is accurate only if sales are constant from one year to the next. Usually, this is not the case and a more sophisticated methodology that takes into account the change in sales over time might be needed.

The alternative method of estimating the total amount of disposed batteries that we propose in this paper can be briefly outlined as follows.

Let S(t) be the amount of batteries that are put on the market in year t. We hypothesize that these batteries will have a certain service lifespan i.e. time to their ultimate disposal, through separate collection or otherwise. This lifespan will not be deterministic, but, rather, follow a probability distribution with a cumulative density function that we denote as F(i). This would mean that, of all batteries sold year t, S(t)*(F(1) – F(0)) will be disposed of the same year, S(t)*(F(2) – F(1)) the year after and so on. This, in turn, would mean that the total amount of batteries that is disposed year t would be a mixture of batteries that were sold several years prior, weighted with the probability that the batteries will be disposed of during a particular year. Explicitly, Eq. (2):

$$W_t = \sum_{i=0}^{\infty} S(t-i) * (F(i+1) - F(i)) \tag{2}$$

with W_t = total amount of disposed batteries in year t, S_t = the amount of batteries that are put on the market in year t; F(i) = probability distribution.

Observe that we can view the methodology currently applied in the EU (the Directive method) as a special case of the approach suggested in this paper, with either sales S(t) assumed to be constant or lifespan distribution to be uniform. Such assumptions seem too strict, as there is evidence that the batteries lifespans can be different from 3 years and vary depending on the batteries type or chemical composition (Guevara-García and Montiel-Corona, 2012; Desmet and Mertens, 2014).

To illustrate the impact of violation of these assumptions, we might consider a simulated example of sales and disposal of batteries, where the sales first increase, then stay stable and then decrease while the battery lifespan follows a Weibull distribution (see Eq. (3)). In the literature, Weibull cumulative distribution function is often used to model lifespans of consumer products, in particular WEEE (Melo, 1999; Elshkaki et al., 2005; Polák and Drápalová, 2012). Consider Fig. 1. In this figure, the solid line indicates the sales, the dotted line – the correct disposal and the dashed line the true correct disposal rate (CR_t), which is assumed to increase due to the existing policies. In this scenario the resulting collection rate (denoted by dots) produced by the Directive method is underestimated in case of increasing sales and overestimated in case of decreasing sales.

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \quad (3)$$

with F(t) = cumulative distribution function, t = year, α (t) = shape parameter and β (t) = scale parameter

From Equation 2, two quantities have to be found: the quantity of batteries put on the market each year S(t) and the lifespan distribution F(i). In the following sections we describe how these can be obtained.

3. Method

This section is organized as follows: Sections 3.1 and 3.2 describe the new method for the battery collection rate estimation; Section 3.3 describes application of the developed method and Section 3.4 describes method for lifespan data collection.

3.1. Estimation of the quantity of batteries put on the market each year

The consumption of the product (in this case batteries) can be obtained from sales data, or estimated with material flow analysis (MFA) (Brunner and Rechberger 2004). In this paper, the quantity of batteries put on the market each year has been estimated with the MFA method, which has been described in detail elsewhere (Rosado et al., 2014; Patricio et al., 2015a). Description of data sources, data quality and the results confidence investigation can be found in (Patricio et al., 2015b). This MFA method systematically assesses the product flows by applying an internationally accepted nomenclature (the Combined Nomenclature classification, CN) to trace Imports, Industrial Production and Exports of material and goods. In the CN classification, each product type is assigned an 8-digit classification code. The Imports and Exports data is retrieved from original international trade statistics at a product level, available at a country level. There is no information on the data accuracy for these data at the product level. The product consumption is accounted using the MFA indicator Domestic Material Consumption, also known as "apparent consumption", in the year t: $DMC_t = Imports_t + Industrial\ Production_t - Exports_t$. The annual balances are estimated in metric tons and units (number) for different types of batteries. An example of how the DMC was accounted for cylindrical alkaline batteries (CN 85061011) in 2013 can be found in Eq. (4).

$$DMC_{CN85061011} = \mathrm{IMP}_{CN85061011} + \mathrm{IP}_{CN85061011} - \mathrm{exp}_{CN85061011}; (4)$$

$$DMC_{CN85061011} = 124,347,257 + 0 - 49,881,650 = 74,465,607\,units$$

One of the main advantages of using MFA is that this method not only considers the batteries that are put in the market, but also removes the batteries that were exported to other countries for various reasons, as for instance product discontinuation. Additionally, the data for each product by CN code is publicly available at country level in Eurostat both in tons and number of units for different years. In fact, CN code nomenclature was identified as the best classification methodology for classifying EEE equipment with similar attributes (Magalini et al., 2014).

3.2. Lifespan distribution F(i)

In this study the batteries lifespan distribution F(i) is estimated using empirical data. Sampling of used batteries in Sweden is possible from the battery collection containers provided at recycling sites by the company responsible for battery collection – Elkretsen (2016). In these containers, batteries are disposed of directly by individuals and small businesses. Batteries collected from other collection points are also added. These include residence-adjacent collection boxes; boxes placed in shops; and boxes for towns, municipalities and regions. According to Elkretsen almost the entire flow of used and separately collected batteries ends up in these containers, and this flow is used to estimate the nation-wide collection rate (Elkretsen, 2016). See Section 3.2 Lifespan data collection for details on sampling of batteries.

Given the data obtained in such manner, there are several possible ways of estimating F(i). For instance, we can assume that F(i) belongs to a certain family of parametric distributions, such as Weibull or Gamma, and use the data to estimate its parameters (see e.g. Elshkaki et al., 2005; Polák and Drápalová, 2012). We can also estimate F(i + 1) − F(i) (as used in Eq. (2)) directly by dividing the number of sampled batteries of each age with the total amount of sampled batteries (see Supplementary table for the empirical distributions obtained in this way). Both approaches (mainly using Weibull as the parametric family) gave similar results. Only the results obtained from the latter, non-parametric, approach will be presented here. This choice is motivated by the fact that the lifespans seen in our data, although very similar to Weibull, do not quite seem to follow this distribution, displaying a larger year-to-year variability than the distribution allows.

Using the lifespan distribution function, we define an indicator, P80, to describe the flatness of the lifespan curve. The P80 indicator is the number of years until 80% of all batteries put on the market in a given year are discarded by the households.

3.3. Application of the method for estimation of battery collection rate

The developed method is tested for estimation of the collection rate of the portable primary batteries consumed in Sweden during 1996–2015. This study considers alkaline and manganese oxide batteries, the most representative portable primary in Sweden, representing in total approximately 83% of the total number of primary batteries sold in 2013 (Patricio et al., 2015a,b). In Step 1, DMC (t) is found (as described in Section 3.1) as a measure of quantity of batteries put on the market each year. In Step 2, the W(t), total amount of disposed batteries in year t is forecasted according to Eq. (2). Finally, in Step 3, the collection rate (CRt), for each year is calculated by dividing the amount of collected batteries (public statistics in this case) (Ct) by the total amount of disposed batteries W(t) in year t, as shown in Eq. (1).

3.4. Lifespan data collection

Batteries from 10 containers at different recycling centers, based in municipalities of different size and geography, were collected in 2014 (Fågelmyra Borlänge, Falun, Gothenburg Alelyckan, Månsemyr Orust, Tjörn Heås, Karlstad Våxnäs, Skovde Risängen, Åmål/Säffle Östby, and Örebro Mellringe). The inside dimensions of the containers were length x width x height = 110 × 70 × 60 cm and they were sampled when full. One bucket sample was collected from each container, each with a volume of approximately 10 liters, which contained approximately 500 batteries.

The following data was registered for portable batteries: brand/marketing name; size, chemistry, rechargeable (if applicable); any printed dates (production date, PD or expiration date, ED); any other markings. The labels are found in various locations on the batteries. Most are available on the casing, but in some instances the label is found on the cathode (manganese batteries) or the plastic ring around the cathode. The total sample from all the studied

Table 1
Battery distribution by size in three subsamples.

Size	Size Distribution, all battery types		
	Mean, %	Standard deviation, %	Confidence interval, ±%
AA	56.0	5.50	13.8
AAA	31.3	4.70	11.7
R14	4.67	2.08	5.2
R20	4.33	1.15	2.9
F22	2.67	0.58	1.4

containers included 5100 portable batteries, from which 21% of the batteries were marked with PD as well as ED. No PD or ED label could be found on 14% of the batteries. For batteries with a single date label, this was interpreted as the ED, and the PD had to be estimated. The estimation was done using the subsample of batteries that had both PD and ED. This subsample showed that all the batteries produced in 2012 or earlier had a difference of 5 years between PD and ED, and for the batteries produced in 2013 or after, 69% had 5 years of difference, 2% had 6 years, 22% had 10 years and 6% had 11 years of difference. Therefore, for batteries without PD produced in 2012 or before, it was assumed that PD was 5 years before the ED, and for the ones produced in 2013 or after the shares found for the subsample were assumed. In this study, the lifespan is set to the domestic service lifespan, defined as the period of time from initial manufacture until the point in time when a product is disposed of by the final owner (Murakami et al., 2010). On the other hand, it is assumed that batteries are sold the same year that they are produced.

To evaluate the sampling procedure, and in particular in order to determine how representative a one-bucket sample of batteries is for the sampled containers, three grab samples were taken with 10 L buckets from one of the containers (Tjörn Heås) and number of batteries and the distribution of different battery types by size and chemistry were studied.

The results presented in this paper mainly consider primary batteries (non-rechargeable). All secondary (portable rechargeable, tool, computer, mobile phone etc.) batteries were excluded from the lifespan study, regardless of size. Similarly, button cells were left out because of their small numbers and low weight compared to other batteries.

4. Results

The results in this section are organized following the two aims of this paper: to study the lifespan of the batteries (section 4.1) and to apply these lifespans for collection rate estimation (section 4.2).

4.1. Lifespans of batteries

The combined sample from all the studied containers contained 5100 portable batteries. It included approximately 200 re-chargeable portable batteries, batteries from portable computers (10), mobile phones (48), hearing aids (14), tools (22) etc. with a total weight of 22 kg, and approximately 4 kg of lead batteries (≥1 kg each). The distribution by size and chemical composition of the more common (≥0.1% of the total) 4900 batteries, with a total weight of 130.1 kg, is presented in Table 2.

4.1.1. Representativeness of samples

The size distribution (based on number of batteries of a certain size) was similar for the three samples taken from the same container (Table 1) for the abundant AA and AAA sizes, while there was variation in shares for the more uncommon batteries, such as R14, R20 and F22. Also, the chemistry of the AA and AAA batteries was found to be similar among the three subsamples. In particular, 88 ± 8.0% of the AA batteries were alkaline and 6.7 ± 2.9% were NiMh. For the AAA batteries, 89 ± 5.7% were alkaline and 4.7 ± 6.3% were NiMh. On the other hand, shares of the AA and AAA batteries of other chemistry (MnO, Zinc-carbon) and the chemistry of the R14, R20 were considerably different in the three subsamples because these batteries were rare in the samples.

4.1.2. The composition of collected batteries

The predominant battery were AA and AAA alkaline batteries, representing in total 72.2% by number and 51.8% of the weight of all the collected batteries (Table 2). Considering total number of batteries collected, 82.9% were alkaline batteries, 10.4% were Manganese batteries, 4.1% NiWh batteries and 2.3% lithium batteries. NiCd batteries are not shown, but constitute 0.12% in number and 0.10% in weight.

As expected, AA and AAA batteries' sizes (of all chemistries) are the most common batteries collected (53.7% and 29.8% of the total number respectively) and their share (83.5% combined) is very similar to 86.4% of the collected AA and AAA batteries in Mexico for 2007 and 2008 (Guevara-García and Montiel-Corona, 2012). The main difference is the share of AAA and AA batteries, with a higher percentage of AAA in Sweden (29.8%) when compared with the results obtained for Mexico (10.1%). R20 batteries, also known as D batteries, represented 4.5% in number but 21.4% of the total weight. R14 batteries, or C type batteries, totaled 5.4% in number and 12.7% of the total weight. Even though in number type R20 and R14 are not a large share of the collected batteries, they represent a significant share of the total weight (34.1% of the total weight, against 9.9% of the total number).

Table 2
Battery distribution (%) in the total sample, by number (#) and weight (Kg).

Size	Alkaline		MnO		Lithium		NiMh	
	#, %	Kg, %	#, %	Kg, %	#, %	Kg, %	#, %	Kg, %
AA	46.5	40.8	4.0	2.7	0.43	0.24	2.8	2.6
AAA	25.7	11.0	2.8	0.89			1.3	0.58
F22	3.0	5.1	0.57	0.82	0.06	0.08		
LR1	0.08	0.03						
R12	0.06	0.36					Unknown chemistry	
R14	4.1	10.4	1.3	2.3			#, %	Kg, %
R20	2.8	14.4	1.7	7.0			0.02	0.08
CR2032					1.5	0.23		
CR123					0.08	0.05		
CR2					0.10	0.04		
CR2025					0.06	0.01	0.08	0.007
CR2430,2450					0.02	0.005	0.06	0.012
LR44							0.45	0.038
Cr15-16							0.12	0.007

Table 3
Areas of use for common batteries.

Size	Power	Areas of Use
 AA	1.5 V, 1800–2600mAh	Small rod lights with LED light, hence the name Penlight (light pen), wall clock, alarm clock, remote controls, measuring instruments, calculators, toys, such as radio controlled cars including the radio
 AAA	1.5 V, 250–1200 mAh	flashlights (LED), remote controls, calculator, alarm clock, thermometer, measuring devices, video cameras, older still cameras, toys, such as radio controlled cars including the radio, MP3 players, walkmans
  R12	4.5 V	Flat flashlights with high current output
 R14	1.5 V, 4000, 8000 mAh	Torches, portable radio and stereos
 R20	1.5 V, 1800–2600 mAh	applications with high power output such as flash lights, portable radio receivers, portable cassette and CD player, electric motors, Geiger counter, megaphones
 R25	6 V	Hand lanterns, road closure lamps, some toys and hobby devices with high power output, i.e. glow plug engines
 F22	9 V	Smoke alarms, memory battery for the alarm clock and desktop phones, measuring instruments

4.1.3. Key properties of lifespans

The lifespans of batteries were found to be up to 20 years or more, with median lifespans of 3–8 years (Table 4 and Fig. 2). The variations may reflect both differences in type of application, but also patterns of household handling of batteries both during and after their use, see Table 3. For example, 9-V batteries (F22) are often used in devices requiring low effect for a long time, e.g. smoke alarms and fixed telephones. However, because R12 batteries are rarely used in modern appliances, the collected R12 batteries must have been stored in households for a long period of time, which is confirmed by their lifespans of 14–20 years (8 batteries were dated, not shown). Also MnO R14 batteries were rare (19) with a median lifespan of 12 years and the P80 of 23 years.

In general, the batteries used in less common appliances, such as the R12, R14 and R20, have flatter lifespan distributions with a P80 of 9–11 years. Observed lifespans indicate that a large number of batteries, both new and exhausted, may be stored without use for extended periods, perhaps forgotten as they are located in rarely used or broken devices. Cylindrical batteries, by far the most consumed primary batteries in Sweden, have a median lifespan of 3 years and a P80 value of 6 years for alkaline batteries and a median lifespan of 7 years and a P80 value of 10 years for MnO batteries (Table 5). These batteries are mostly used in everyday electronics equipment such as remote controls, wall clock alarm clock, toys, etc. (see Table 3, AA and AAA size batteries).

Detailed lifespans for portable batteries are rare in the literature. For Belgium the average lifespan of alkaline batteries was found to be 5 years, and P80 of 8 years (Desmet and Mertens, 2014), results similar to the obtained for Sweden (average lifespan = 3 years, P80 = 6 years).

4.2. Estimated collection rate

Below, we will demonstrate how the lifespan distributions, obtained in the section 3.1, could be used to estimate the collection rate. We will mostly concentrate on the total amount of batteries for this demonstration. Later we will also discuss a special case.

When considering the total amount of collected batteries, the following battery types were included: Cylindrical Alkaline (which includes AA, AAA, R14, and R20 batteries); Square Alkaline; Cylindrical MnO (AA and AAA batteries) and Square MnO. For each of these battery types the total amount of disposed batteries Wt was calculated separately using the corresponding lifespan distribution. It should be noted that lifespan data has been aggregated to find lifespans for Cylindrical Alkaline (using data for n = 3413 units of AA, AAA, R14, and R20) and Cylindrical MnO (using aggregated lifespan for n = 181 units of AA and AAA).The resulting quantities were added to represent the total batteries flow.

4.2.1. Step 1: historical batteries consumption

Batteries consumption as DMC in Sweden for 1996–2015 has been accounted following the MFA method described in section 3.1 and reported elsewhere (Patricio et al., 2015a). See Fig. 3 for the time series of consumption (in bars). The negative consumption values for square batteries in 1997 and 2008 indicate that export (from the stock) has been higher than the import.

Table 4
Lifespan distributions.

Battery type	#	Lifespan median	P80	Scale Parameter (β)	Shape Parameter (α)
AA, Alkaline	2043	3	6	5,49458	1,46907
AAA, Alkaline	1062	3	6	5,34746	1,58267
R20, Alkaline	123	6	10	8,32852	1,7032
R14, Alkaline	185	3	9	6,69253	1,16693
AA, MnO	104	8	11	10,0581	1,49865
AAA, MnO	77	5	9	9,57542	1,54661
R20, MnO	38	6.5	9	10,3278[a]	2,41743[a]
Alkaline Square, F22	143	5	9	8,11387	1,96886
Aggregated Alkaline cylindrical	3413	3	6	5,61787	1,46384
Aggregated MnO cylindrical	181	7	10	9,32619	1,61681

[a] Be aware of worse fit due to low number of samples.

Table 5
Battery Collection rate 2009–2013 in Sweden.

Year	Consumption, MFA, tons	Sold (statistics)	Total disposed	Collected (statistics)	Collected/Total disposed (new method)	Directive method[a]	Swedish EPA[b]
2009	3227	3517	3773	1069	28%	30%	30%
2010	3223	3976	3686	1642	45%	44%	41%
2011	3306	3361	3557	2177	61%	60%	65%
2012	4032	3372	3521	2465	70%	69%	73%
2013	3325	3443	3560	2425	68%	71%	70%
2014	3896	3434	3572	2135	60%	62%	62%
2015	4245	3497	3632	2477	68%	72%	71%

[a] Obtained from the division of the weight of waste portable batteries collected in a certain year, and the average put on the market during that year and the preceding two years.
[b] Obtained from the division of the weight of waste portable batteries collected in a certain year by the amount put on the market during that year.

Table 6
NiCd batteries consumption and collection rate.

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
MFA, tons	180	67	6	48	94	19	53	65	219	41
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
MFA, tons	25	57	27	14	10	6	17	23	11	11
Sales statistics, tons (Swedish EPA, 2016)				20	24	19	16	15	11	11
Collected statistics, tons (Swedish EPA, 2016)				53	130	164	179	196	174	181
Collection rate by the Directive method				263%	587%	775%	907%	1158%	1231%	1432%
Collection rate by the new method				7%	21%	30%	37%	47%	47%	56%

4.2.2. Step 2: combining batteries consumption with lifespans

An example of how the W(t) for the year 2015 is calculated for cylindrical alkaline batteries can be found in Eq (6). Please refer to the Supplementary Table for values of the F(i + 1) − F(i) increments.

$$W_t = \sum_{i=0}^{\infty} S(t-i) * (F(i+1) - F(i)) \quad (6)$$

$$W_{2015} = \sum_{i=0}^{19} (S(2015-i) * (F(i+1) - F(i))) = 3940 * 0.08 + 3525 * 0.19 + 2962 * 0.18 + 3695 * 0.12 + 2933 * 0.10 + 3071 * 0.07 + 3170 * 0.06 + 3509 * 0.05 + 4340 * 0.02 + 3313 * 0.02 + 3526 * 0.02 + 3756 * 0.01 + 3899 * 0.02 + 2863 * 0.01 + 2143 * 0.01 + 1591 * 0.004 + 1395 * 0.004 + 1972 * 0.004 + 1843 * 0.01 + 1950 * 0.002 = 3310 \text{ ton.}$$

4.2.3. Step 3: estimating the collection rate

The collection rate for each year is found by dividing the amount of collected batteries with the total amount of disposed batteries shown in Eq. (2).

National statistics (available from 2009) for the collected batteries have been compared with the total amount of disposed batteries obtained in Step 3, see Table 5. In the same table, collection rate calculated with the Directive method is also provided for comparison as well as the Swedish EPA calculation, where year-to-year sales and collection are used. The differences between the Directive method and the new method vary from 1% to a maximum of 3%.

4.2.4. A special case

As we could see earlier, the collection rates are very similar for the three methods. This is not unexpected as the sales for the dominant group of batteries, cylindrical alkaline batteries, have been relatively stable over the past decade. However, as discussed previously, in case of increasing/decreasing sales this might not be true. As an illustration, let us examine the NiCd batteries.

Consider Table 6, where the sales, the consumption of these batteries (calculated by the MFA method) as well as the collection rate estimated by the Directive method and the official collection rate from the Swedish EPA are displayed (Swedish EPA, 2016). Note greater than 100% collection rates estimated by the Directive and the Swedish EPA methods, which are clearly implausible. It is apparent that this behavior is the result of much larger historical sales than are observed today in combination with long battery lifespans.

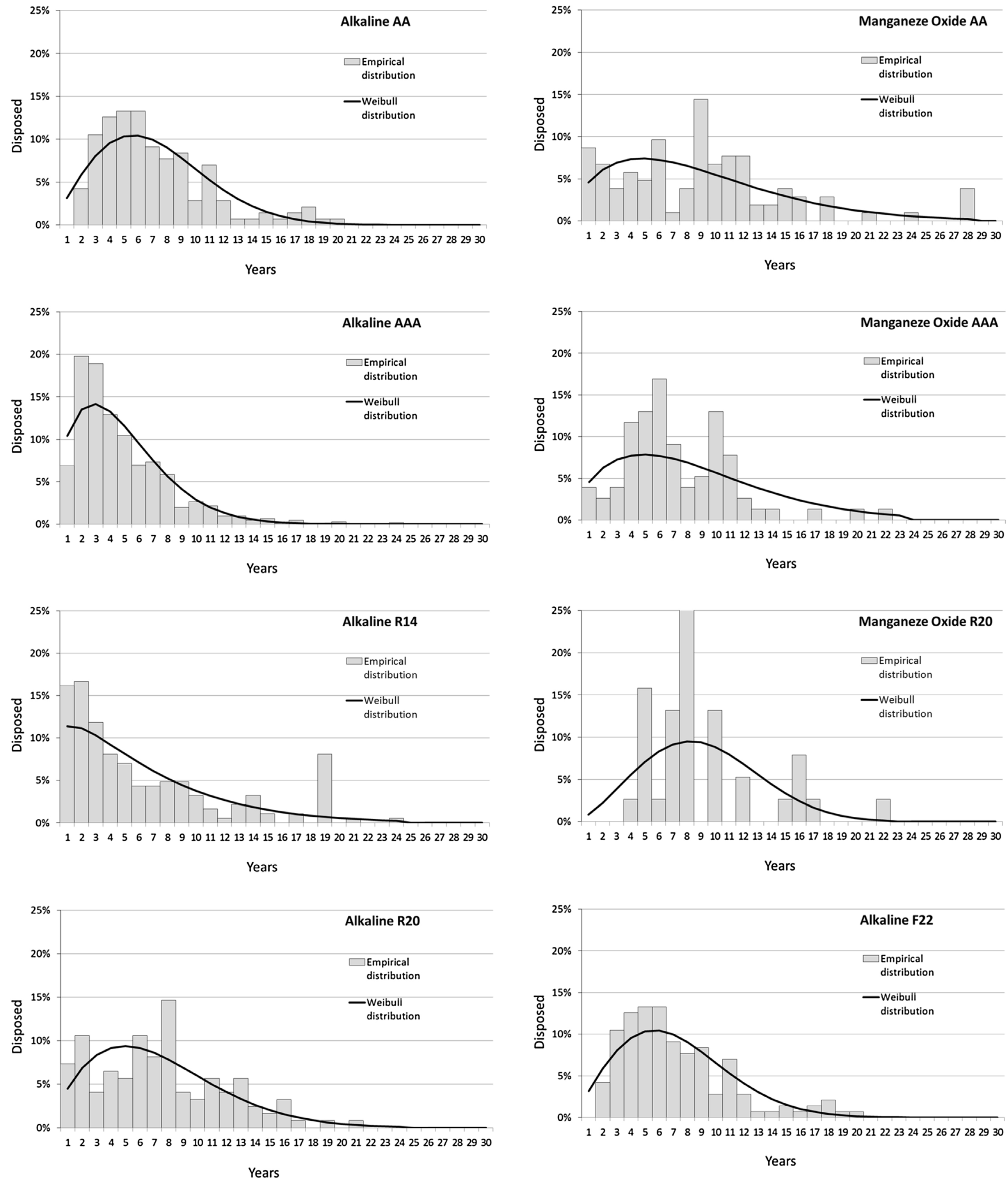

Fig. 2. Empirical lifespan distributions and Weibull distribution fit.

Unfortunately, no lifespan distribution could be estimated for the NiCd batteries collected in this study, because they were too few and most of them were not marked with any date. Thus, to illustrate how such data might have arisen, we will simply assume a lifespan distribution with a heavy right tail, namely Gamma (5, 0.5). This distribution allows for lifespans as long as 30 years. As there is no data available before year 1996, the batteries sales before year 1996 has been estimated by fitting a parametric distribution to the MFA data for 1996–2015 and extrapolating it to earlier years. The curve fitting (by least squares method) leads to the expression sales = $\exp(-0.15^{*}(\text{years-1996})) \times 150$. Combining the Gamma distribution with the fitted sales and dividing by the actual collection gives collection rates that are far more realistic than the ones supplied by the Directive method: 0.07, 0.21, 0.30, 0.37, 0.47, 0.47, 0.56 for year 2009 up to 2015.

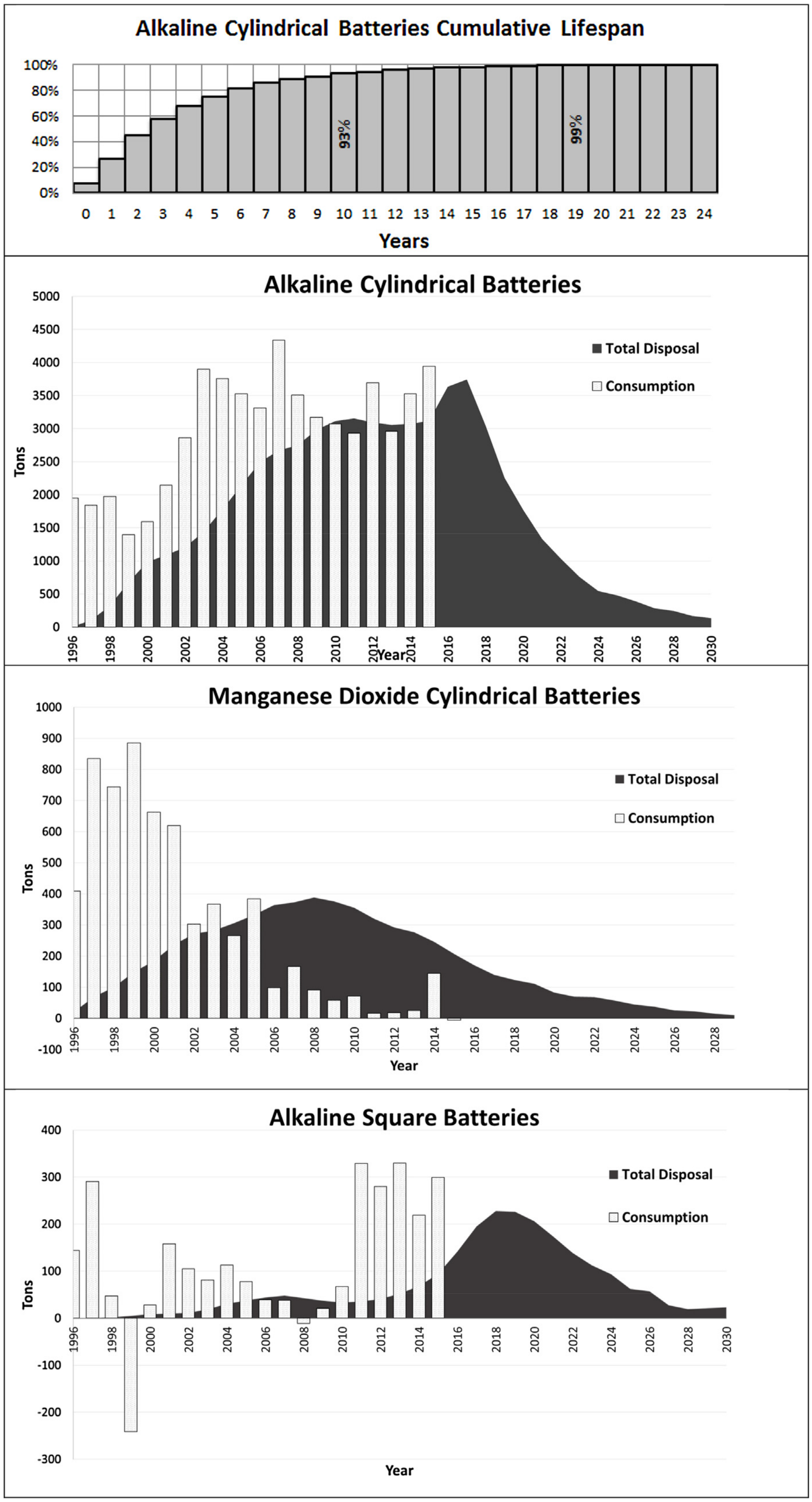

Fig. 3. Historical battery consumption and expected disposal curves.

5. Discussion

5.1. Sampling procedure

Our study of representativeness of a single bucket sample showed that the one-bucket sampling method is only representative of the distribution of batteries in the certain container (i.e. of a certain location) for the alkaline batteries of sizes AA and AAA. Yet, these battery types make up about 72% of the total flow (see Table 2). This means that when a location is considered, one-bucket sampling and dating of the AA and AAA batteries may be sufficient to investigate whether the battery collection has changed. This sampling method does not, however, allow the study of other sizes and types of batteries. We consider the combined sample from the 10 sampled locations in Sweden, 13 buckets of batteries in total (about 5100 batteries) to be representative of the batteries included in the national battery flow even for the more rare batteries. This is because these batteries are sufficiently common in the combined sample (13 buckets), in contrast to the one-bucket subsamples. However, we have no means of checking this assumption because combined sampling has been performed only once.

5.2. Observed lifespans

As can be seen in Fig. 2 the obtained empirical lifespan distributions appear to resemble the Weibull distributions. The estimated parameters of these distributions are displayed in Table 5. However, as mentioned previously, the distributions are not a perfect fit (as can be detected, for example, by performing a goodness of fit test). A brief examination of the discrepancies between the actual and the expected lifetime seems to indicate that this is caused by additional year-to-year variability. Thus, if a parametric description of the lifespan is desirable, a more complex modeling approach that takes the possibility of such additional variation into account might be of use.

Results of this study allow examining whether the lifespan of batteries is at most 3 years, which is one of the assumptions that would make the Directive method for estimating the collection rate accurate. This assumption cannot be applied for Sweden, as the batteries lifespans varied between 1 and 28 years, with a median lifespan of 3–8 years and the P80 values between 6 and 11 years. Only the half (median lifespan 3 years) of cylindrical batteries, the most consumed primary batteries in Sweden, is disposed within 3 years and an additional 30% are disposed within the next 3 years. Also, a longer average lifespan of 5 years for alkaline batteries was found in Belgium (Desmet and Mertens, 2014). Under these conditions, applying the Directive method would result in an underestimated collection rate if the sales are increasing and an overestimated collection rate if the sales are decreasing.

5.3. Collection rate estimation

It should be noted that sufficiently long time series of consumption are necessary in order to produce good estimates of the total amount of disposed batteries in Step 3 of this method. This is because lifespans of batteries may be up to 20 years, with P80s of up to 10 years. If no such data is available, an attempt at extrapolation similar to the one used in the special case above can be made. However, it can be observed that such extrapolation becomes more and more imprecise the farther from the available data it is employed. Note also that for the most common battery type, alkaline batteries, 93% are disposed of within 10 years (Table 4 and Fig. 2). Therefore, if no longer time series of batteries consumption are available, 10 years of consumption may be sufficient to provide a reasonably good estimate.

The projection of future batteries consumption is not included in this study. Instead, it is suggested that the method should be implemented every year, when the international trade data is available. To give the best possible precision, the total amount of disposed batteries needs to be updated annually with the disposal figures for batteries consumed during the previous year, in particular to account for batteries with lifespans of up to two years, which represent up to 30% of the batteries.

It should be noted, that neither MFA nor sales data accounts for the batteries preinstalled in the electric and electronic devices. These batteries are therefore not accounted in consumption but influence the disposal figures. On the other hand, part of batteries are disposed installed in WEEE. This flow is accounted in the correctly disposed batteries. During the period 2013–2015, 17% of the collected batteries were collected as WEEE, however, only a minor part (about 3,7% by weight) are primary batteries while the rest are built-in-batteries (Elkretsen, 2016).

5.4. Implications

Implementing the suggested method on a national and European level could improve accuracy of the collection rate estimate, which in turn could lead to more informed decision making regarding battery collection strategy compared to the currently used methods. This is because the decisions on the necessary improvements in battery collection are based on the difference between the estimated collection rate and the collection target. Even when the estimated collection rate is close to the target, a difference in few percent may still result in tens of millions euro unnecessarily spent on investments in case of underestimated collection rate. From other side, overestimated rate would result in insufficient investments in collection system. As explained earlier, it is especially advisable to use the described method in situations where battery sales are varying each year, whereas currently used methods will produce larger error and in some cases will produce implausible estimates (such as collection rate greater than 100%) rendering decision making difficult.

The proportions of different battery types (Table 2) can be used to estimate mass flow of a certain type of battery based on the weight of the container. However, the non-portable batteries must be removed before the analysis takes place. By sampling the changes in the distribution of batteries by type, changes in patterns of battery use and consumer behavior can be inferred.

The proposed method is valid and useful for implementation in other countries than Sweden. It can directly be replicated in the EU countries. First of all, regarding the MFA data collection, same statistical protocols are used in the EU. For other countries, similar statistical trade data exists. The same legislation and collection rate estimation is applied throughout EU. As has been shown on the example of comparison of the batteries lifespans in Belgium and Sweden, they are within the same range and possibly can be used in other countries as a first approximation.

6. Conclusions

In this study a new method for estimation of collection rate of batteries disposed through the separate collections system has been presented. The method takes into account lifespan distributions of batteries in order to project total batteries waste generation. The collection rate is estimated as the ratio of the collected batteries to the expected battery waste generation in a particular year.

There are three main improvements in the presented method in comparison to the currently used methods, the Batteries Directive method and the one used by the Swedish EPA. First, the presented method is insensitive to variations in batteries sales and produces equally good estimates in conditions of the constant, increasing or decreasing sales. This feature of the method addresses the vulnerability of the Batteries Directive method to the changing sales that has been illustrated in this paper. Second, an alternative way for estimating the amount of batteries put on the market is suggested, based on the MFA. Using MFA enables estimation of historical batteries consumption, which is necessary to account for possibly important contribution of batteries sold many years ago. In particular, as shown in example of Sweden, batteries lifespans vary between 1 and 28 years, with a median lifespan of 3–8 years and P80 values of 6–11 years. In such a way, only a half or less of batteries are disposed within the 3 years of purchase, while another 30% within the following 3–11 years. Finally, the presented method allows estimation of waste generation and collection rates for different types of batteries separately, whereas the current methods only provide estimate for aggregated group of batteries. This is important because different batteries exhibit different usage patterns, and therefore lifespans are considerably different.

This paper contributes in theoretical terms by identifying the limitations of the currently available method for estimation of batteries collection rate, prescribed by the Batteries Directive to be used in the EU member states. It also contributes in methodological terms in three ways: by estimating historical batteries consumption through MFA; by adopting lifespan modeling approach to battery waste generation; and by analyzing empirical lifespan distributions with regard to Weibull distribution. In practical terms, the determined lifespan distributions illustrate patterns of lifetime and disposal for different types of batteries. Analysis of these patterns can be useful for designing interventions in the battery collection systems, with respect to households' behavior and collection infrastructure. In addition, the obtained results for Sweden can be used for estimating collection rate in the coming years.

There has been a number of methodological limitations in this study. First, neither MFA nor sales data accounts for the batteries preinstalled in the devices. In addition, part of the batteries sample could not be dated. For another part of the sample, the production date had to be inferred.

Future research should include up to date analysis of the batteries lifespans. In particular, such studies should be conducted after the information and collection campaigns or after the interventions in the battery collection systems, in order to evaluate their effects. The lifespan distributions should also be updated so that they are in line with future patterns of batteries usage and disposal due to the changes in the electronic devices and batteries properties and types.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2017.01.006.

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