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A comparative case study of the efficiency of collection systems for paper and biodegradable municipal solid waste

O. Chotovinský* and V. Altmann

Department of Machinery Utilisation, Faculty of Engineering, Czech University of Life Sciences in Prague, Kamycká 129, CZ165 21 Prague 6 – Suchdol, Czech Republic
*Correspondence: chotovinsky@tf.czu.cz

Abstract. The need to increase municipal solid waste recycling rates has led to the study and analysis of recycling schemes from the perspective of the technical issues that may be involved. This paper compares two waste collection systems, which are operating in the Vysočina region of the Czech Republic: a municipal solid waste collection system for paper (including cardboard) and a biodegradable municipal solid waste collection system. Both collection systems were introduced at different times to cover one selected urban area. The emphasis has been placed on an evaluation of the development of individual, separate collections between 2014 and 2016. Analysis of the technological operation and performance of the collections are observed and evaluated by measuring a range of waste collection system indicators. Efficiency levels, especially when it comes to separate collections of both types of municipal solid waste, are compared to their relative representation in the remaining bulk of municipal solid waste. The changes in representation of these types of waste against those in the rest of the municipal solid waste shows which collection systems are more successful from the perspective of the implementation of the directive which covers landfill usage. The results also describe why systems could be more successful within the view of well-chosen or inappropriately-selected technological parameters for materials separation. The possibly statistically significant impact of paper waste production in terms of the relative amount of paper waste across the rest of the municipal solid waste has also been shown.

Key words: municipal solid waste, rest municipal solid waste, biodegradable municipal solid waste, biodegradable municipal solid waste collection, paper and cardboard waste collection, material compositions.

INTRODUCTION

In the Czech Republic, the mean production per capita of municipal solid waste (MSW) is about 339 kg per year and, typically, 50% of the total mass is bio-waste, eg. food waste, and paper (PCMSW) and biodegradable municipal solid waste from parks and gardens (BMSW). PCMSW and BMSW which is produced within a municipal area is a quantitatively highly important category of waste, and the way in which it is treated can both positively and negatively influence environmental components. PCMSW and BMSW contributes to the accumulation of the anthropogenic greenhouse effect and planetary climate change. The greenhouse gases which are produced during the process of bio-waste decay at landfill sites contributes to global greenhouse gas emissions by approximately 4% (Papageorgiou et al., 2009). A directive which has a crucial value from this perspective and which is fully integrated with Czech legislation is referred to as the Council Directive on Landfill 1999/31/EC (known familiarly as the 'Landfill Directive'). Landfill Directive 1999/31/EC establishes targets which should result in a decrease in the quantity of bio-waste that is disposed in landfill. In 2010, around 75% of the total bio-waste mass produced in 1995 should be stored in landfill sites, while in 2013 the figure should be 50% of this amount, and by 2020 only 35% of bio-waste from 1995 should remain in landfill sites. In the Czech Republic, a total of 1,530,000 tons of bio-waste was produced in 1995, and in 2010 there were 1.5 million tons of bio-waste being stored in landfill sites instead of the admissible 1.15 million tons. The precautions set out by the directive should take care of the materials and energy-related use of the waste from the perspective of a solid waste management system (Vehlow et al., 2007). Waste collections form one of the most visible activities in a waste solid management system, and it is one that the public highly perceives. Although the goal of waste collection is to keep a city clean, the activity needs to deal with budgetary challenges, logistical constraints, public acceptance, and a reduction of environmental and health impacts, as well as being capable of reaching collection and recycling targets which have been set by Landfill Directive 1999/31/EC (Rogge & De Jaeger, 2013; Usón et al., 2013; Williams & Cole, 2013).

The services for PCMSW and BMSW collection are defined as being a combination of a certain form of technology and human labour (Bilitewsky et al., 1997). This action corresponds not only to waste collection from certain types of source, but also includes the transportation of this waste to locations at which waste management lorries are loaded up (Tchobanoglous & Kreith, 2002). PCMSW and BMSW collection systems which are applied within the Czech Republic can form a kerbside collection, where recyclables are placed by members of the public on the kerbside outside their houses for collection by a lorry on an appointed day, or by means of a drop-off collection, where recyclables are taken by members of the public to drop-off points at various localities in their vicinity and then are picked up by lorry at an identified frequency. Both kerbside and drop-off systems are characterised by a diversity of implementation technologies (sometimes including especially-designed collection vehicles), and different collection frequencies and logistics are needed to support them. The way in which each region operates its PCMSW and BMSW collection depends upon socio-economic conditions, available infrastructure, and service provision (Timlett & Williams, 2011; Martinho et al., 2017).

More studies of waste collection systems are needed to generate a greater knowledge base of such collection systems and to understand how they should be adapted in order to be more successful. Waste collection services which separate the PCMSW and BMSW parts from municipal solid waste could be analysed according to their performance in terms of cost (Teerioja et al., 2012; Rogge & De Jaeger, 2013), environmental impact (Powell, 1996; Maimoun et al., 2013; Teixeira et al., 2014; Yildiz-Geyhan et al., 2016), recycling/collection rates (Wilson & Williams, 2007), and public participation and behaviour (Oskamp et al., 1996; Wang et al., 1997; Bolaane, 2006; Martin et al., 2006; Shaw et al., 2006). When focusing on operations, Huang et al. (2011), for example, developed key performance indicators in order to assess the efficiency of the MSW collection.

The main aim of this paper consists of a basic description of a better collection strategy, taking into account the analysis of two selected collection schemes for sorted BMSW and PCMSW waste from the perspective of its diversion from landfill. In the first stage data is collected, treated, and statistically analysed, based on some selected variables and performance indicators from one selected urban area in the Czech Republic. It provides conclusive information regarding whether selective waste collection behaviours and trends follow the same direction for all type of sorted waste collected under each collection scheme. The second stage focuses on a more detailed analysis and comparisons between possibly significant impacts which may be caused by the increased production of selected sorted waste on its relative volume in the rest of the MSW stream (RMSW), which is sent to landfill sites.

MATERIALS AND METHODS

Collection area

The methodology was applied to two selected kerbside collection services for paper and biodegradable waste in a medium-sized city in the Vysočina region. The collection area consisted of a typical city centre, mainly one with apartment buildings or residences with a rather high population density. The total surface area occupied by the city is 56 km^2. By the year 2016, it had grown to include 36,630 inhabitants, who are permanently domiciled in 5,304 houses and 14,779 flats. This corresponds to a mean spatial distribution of about 704 inhabitants per km^2 and they are distributed throughout seventeen different city districts. Ten of them are located directly in the urban area and the other seven are in the vicinity of the integrated village. Gas is the most common heating medium.

Economic activities for this population include industry (50%), trade and business (46%), and agriculture (4%). MSW production per capita is only about 2.3 kg per day. Most of the municipal solid waste production is deposited in landfill sites.

Separate collection of PCMSW and BMSW can be considered to be fully developed, with good access throughout the whole of the urban area. The collection BMSW here is applied as a combination of drop-off and kerbside systems. The situation regarding a separate collection of PCMWS also includes the kerbside system and drop-off system.

Data collection

Data collection was carried out in order to obtain a representative sample which was able to produce accurate generalisations about the performance of both of the kerbside collection systems. Data was collected through measurements from the urban area which were taken by the local collection company (ESKO-T s.r.o.) over the course of three years (2014–2016 inclusive). Above all, data related to production, the number of containers, and the volume of each container, describing the frequency of the collection within the selected reference period. The total volume of BMSW and PCMSW is shown in Table 1. For the other purposes of this paper these total amounts were calculated on a monthly basis during each year of the survey. This conversion also took into account the available volume of containers by frequency of collection.

The values given in Table 2 were provided by the collection company which carried out regular RMSW analysis at monthly intervals within the city being surveyed. A substance analysis of RMSW has been carried out since 2012. For the purposes of evaluation, use was made of the total volumes of BMSW (20 02 01) and PCMSW (20 01 01) in RMSW data from January to December in the years 2014–2016.

Table 1. Waste production in 2014–2016 in the urban area under study

Year	Total volume of waste, t	Amount of MSW, t	Amount of RMSW, t	Amount of BMSW, t	Amount of PCMSW, t
2014	192,200	31,074	16,239	149	580
2015	193,693	31,169	16,230	274	591
2016	235,374	31,484	16,676	545	620

Source: research ESKO-T s.r.o.

Table 2. Rest municipal solid waste composition – average mass fraction in 2014–2016

Type no	Waste component	Mass fraction, kg
20 01 01	Paper and cardboard (PCMSW)	12.17
20 01 08	Food waste	12.71
20 01 39	Plastics	10.31
20 01 10	Clothes	1.75
20 01 11	Textiles	2.09
20 01 38	Wood	1.18
20 02 01	Biodegradable waste (BMSW)	5.62
20 03 01	Glass	1.03
20 03 02	Metals	1.28
20 03 07	Other	43.60

Note: type no – the code for each type of waste in the Czech Republic's waste catalogue; Source: research ESKO-T s.r.o.

The density of the waste was evaluated by measuring any increase in weight for empty containers of a size of 1.1m^3 and 0.66m^3 once they had been filled with PCMSW and BMSW (Table 3). The identified density was used to determine the total capacity utilisation of the containers.

Table 3 Results of our own measurements of density for both kinds of segregated municipal solid waste in the collection containers

Waste	Density*, kg m^{-3}
BMSW	300
PCMSW	50

** average.*

Statistics methods

In this work we present a methodology which aims to support the assessment of waste collection performance. The determination of the volume of BMSW and PCMSW in RMSW is based on the results of composition analysis which was carried out by the local collection company. Average values of the content of individual RMSW components are calculated by derived relation (1), where the formula for the arithmetic mean is adjusted from progressively-performed RMSW analysis in 2014 and 2016. For the calculations being considered, the methodology also allows for the relation (2), which determines the relative volume of PCMSW and BMSW in RMSW.

Average relative content of type of waste in RMSW, %

$$\overline{p}_D = \frac{\sum_{i=1}^{n}(\frac{m_{Di}}{m_{Ci}})}{\text{n}} \cdot 100 \quad (1)$$

where $\bar{p}_D$ – average relative content of the type of waste in RMSW, %; m_{Di} – content mass of the type of waste in one RMSW sample, kg; m_{Ci} – one whole RMSW sample mass, kg; n – number of performed RMSW analyses, (-).
Relative amount of PCMSW and BMSW in RMSW, %

$$P_{PCMSW/BMSW} = \frac{m_{PCMSW/BMSW}}{m_{sample}} \cdot 100 \quad (2)$$

where $p_{PCMSW/RCMSW}$ – relative amount of PCMSW and BMSW in RMSW, %; $m_{PCMSW/RCMSW}$ – content mass of the type of waste in one RMSW sample, kg; m_{sample} – one whole RMSW sample mass, kg.

In addition, a methodology for producing descriptive statistics was used to process the RMSW composition results, involving standard deviation, dispersion, maximum and minimum averages, an error allowance for the 95% base file of reliability, and a variation coefficient.

The methodology for determining the total capacity utilisation of PCMSW and BMSW containers was based on relations 3, 4, and 5.
Total available volume of PCMSW and BMSW containers, dm^3 $year^{-1}$

$$TAVc_{PCMSW/BMSW} = nc_{PCMSW/BMSW} \cdot nj_{PCMSW/BMSW} \cdot Vc_{PCMSW/BMSW} \quad (3)$$

where $TAVc_{PCMSW/BMSW}$ – total available volume of PCMSW and BMSW containers, dm^3 $year^{-1}$; $nc_{PCMSW/BMSW}$ – the number of PCMSW and BMSW containers, (number); $nj_{PCMSW/BMSW}$ – the number of rides to empty the PCMSW and BMSW containers, (number); $Vc_{PCMSW/BMSW}$ – volume of PCMSW and BMSW containers, dm^3.
Total capacity of PCMSW and BMSW containers, kg $year^{-1}$

$$TCc_{PCMSW/BMSW} = \frac{TAVc_{PCMSW/BMSW}}{\rho_{PCMSW/BMSW}} \cdot 100 \quad (4)$$

where $TCc_{PCMSW/BMSW}$ – total capacity of PCMSW and BMSW containers, kg $year^{-1}$; $TAVc_{PCMSW/BMSW}$ – total available volume of PCMSW and BMSW containers, dm^3 $year^{-1}$; $\rho_{PCMSW/BMSW}$ – identified density of PCMSW and BMSW, kg m^3.
Utilisation of the total capacity of PCMSW and BMSW containers, %

$$UCc_{PCMSW/BMSW} = \frac{Q_{PCMSW/BMSW}}{TCc_{PCMSW/BMSW}} \cdot 100 \quad (5)$$

where $UCc_{PCMSW/BMSW}$ – utilisation of the total capacity of PCMSW and BMSW containers, %; $TCc_{PCMSW/BMSW}$ – total capacity of PCMSW and BMSW containers, kg $year^{-1}$; $Q_{PCMSW/BMSW}$ – total volume of PCMSW and BMSW, kg $year^{-1}$.
The STATISTICA 8 program was used to analyse the data and obtain the necessary characteristics of simple regression and analyses of variances (F-test in regression). These statistical methods were used to describe the dependence between the relative monthly volume of sorted waste in RMSW and its average monthly productions.

RESULTS AND DISCUSSION

The totals for PCMSW and BMSW production were shown on a monthly basis for each year of the survey. These monthly production values were completed by adding in values for the total available volume of PCMSW and BMSW containers. Figs 1 and 2 reflect the same trend regarding how the total available volume corresponds with the production of both kind of waste.

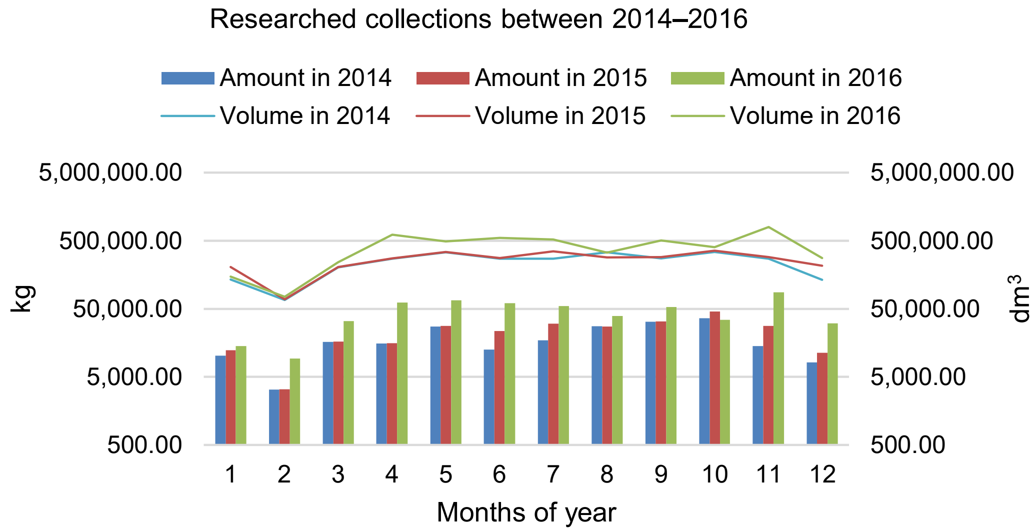

Figure 1. BMSW production and total available volume of BMSW containers.

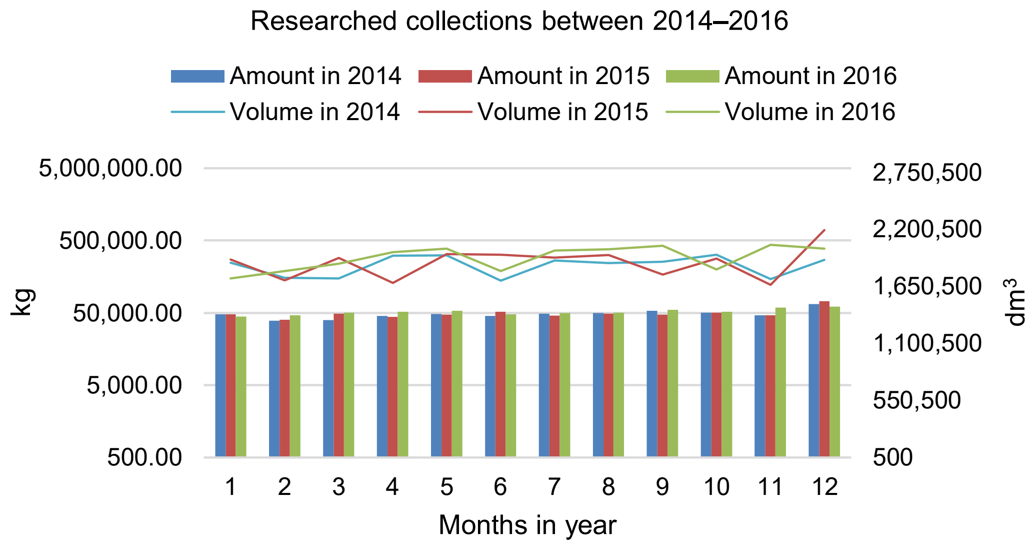

Figure 2. PCMSW production and total available volume of PCMSW containers.

The percentages calculated for PCMSW and BMSW collections by methodology for determining the total capacity utilisation of containers used are presented in Fig. 3. For BMSW, the percentage of use is very low. This is caused by too-frequent a waste collection. From the perspective of PCMSW the percentages are slightly higher, but overall these are also low. In the PCMSW containers, distributed packaging boxes often appear, and they then fill a large proportion of the container.

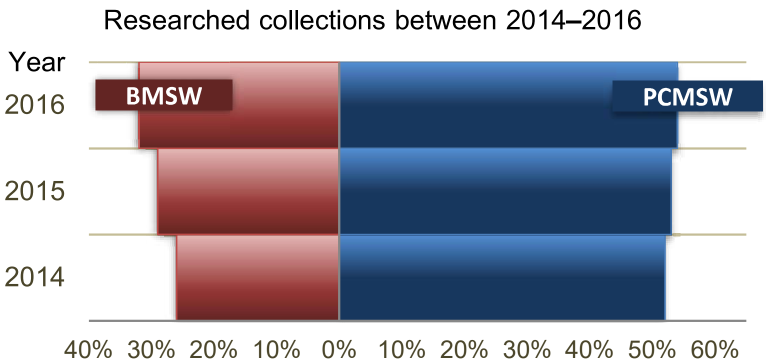

Figure 3. Utilisation of the total capacity of BMSW and PCMSW containers.

The successful evaluation of PCMSW and BMSW collections by means of the results of the composition analysis of RMSW is shown in Fig. 4. This figure shows that, in the area being researched, the percentage of BMSW in RMSW is increasing, and the percentage of PCMSW in RMSW has a tendency to decline. Table 4 shows the value of individual calculations of descriptive statistics relating to the average checked values of PCMSW and BMSW in RMSW.

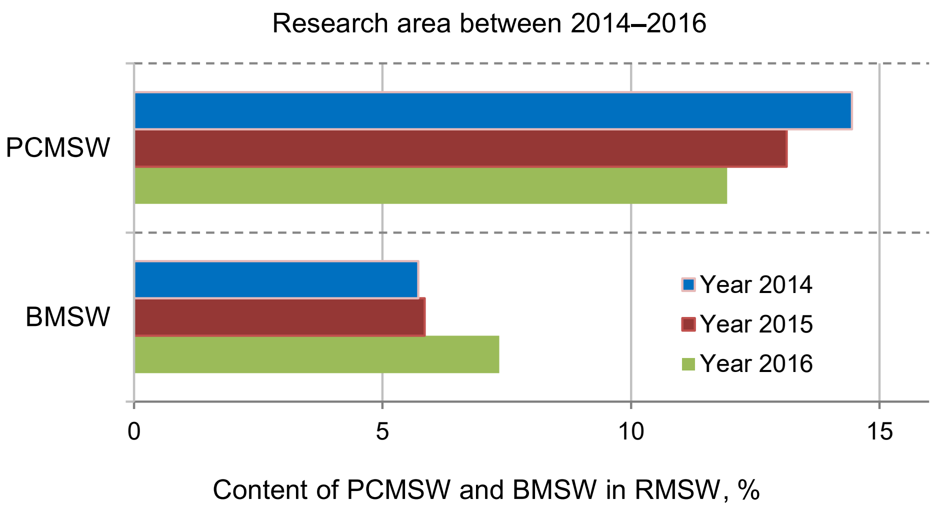

Figure 4. Relative amount of PCMSW and BMSW in RMSW between 2014–2016.

Table 4. Overview of descriptive statistics (PCMSW and BMSW values)

Year	Dispersion, (-)	Standard deviation, (-)	Coefficient of variation, (-)	Δ*, %	Minimum average, %	Maximum average, %
2014	9.71	3.12	55.94	1.98	3.59	7.55
2015	6.21	2.49	34.43	1.58	5.66	8.82
2016	6.21	2.49	34.43	1.58	5.66	8.82

** error for 95% base file of reliability.*

The sites which had a separate collection for BMSW placed four types of BMSW containers in the built-up area. Their usage is as follows:

- containers measuring 0.66 m^3, 0.44 m^3, and 1.1 m^3 – BMSW from residences,
- containers measuring 14 m^3 – BMSW from public green areas.

The situation regarding separate collection of PCMWS placed only one type of container with an available volume of 1.1 m^3 alongside all collections points.

The year-by-year development of the number of PCMSW and BMSW containers and their collection inside the surveyed area is presented in Table 5, below.

The increasing numbers of PCMSW containers (and the associated increase of the number of collections) influenced the total amount of collected PCMSW between 2014 and 2016 during kerbside collections with effective separation procedures taking place. The summarised values also show that collections especially tend to increase with a small number of collection containers. The increasing numbers of collection containers and collections can be seen from the perspective of BMSW collections with the same level of influence between 2014–2016. However, non-effective separation also exists in the comparison of relative volumes of BMSW in RMSW. This is due to the fact that the increasing number of collection containers is not gradual on the kerbside in relation to apartment buildings or houses. A large increase is only seen in relation to large-volume containers which are collected from public green areas. The collection company has deployed these containers primarily in marginal areas (which can be labelled using the phrase ‘gardening colonies’) within the urban area, where there is no large-scale RMSW production.

Table 5. Average number of collections and the average number of collected containers per month

Year/ Volume	0.66 m^3	0.77 m^3	1.1 m^3	14 m
PCMSW				
2014	-	-	9/1,681	-
2015	-	-	11/1,709	-
2016	-	-	13/1,750	-
BMSW				
2014	-	2/206	-	-
2015	-	4/341	-	-
2016	3/9	4/331	3/9	7/10

**average number of collections/average collected containers per month (PCMSW and BMSW containers).*

Therefore only one more effective separation has been used for the next calculation (which covers the average number of collections per month).

The first of result of the analysis by STATISTICA 8 focuses on the simple regression summary that is presented in Table 6. The determination coefficient R^2 can be considered as a percentage of the total variability of the response variable, as explained by the regression model. However, use of the adjusted determination coefficient R^2 is recommended (Šmilaur, 2007).

Table 6. Results of regression for the average number of collections per month

	Regression Summary for dependent variable: [%] (waste composition) R = 0.67521326 R^2 = 0.45591294 Adjusted R^2 = 0.43991038 F(1.34) = 28.790 p < 0.00001 Std.Error of estimate: 2.3979					
	Beta	Std.Err.	*B*	Std.Err.	*t*(14)	*p* level
N =36		of Beta		of B		
Intercept,			23.10718	2.086260	11.07589	0.000000
%	-0.675213	0.126501	-0.97875	0.183369	-5.33760	0.000006

Notes: The R field contains the correlation coefficient, which is the positive square root of R-squared. The R^2 field contains the determination coefficient, which measures the reduction in the total variation of the dependent variable due to the independent variables; the adjusted R^2 is interpreted similarly to the R^2 value except that the adjusted R^2 takes into consideration the number of degrees of freedom.
The F value, df, and the resultant p value are used as an overall F test for the relationship between the dependent variable and the set out independent variables. The standard estimate error measures the dispersion of the observed values about the regression line.
The intercept field contains the intercept value if a choice was made to include the intercept in the model on the 'Model Definition - Advanced'.
The 'Std.Error' field contains the standard error for the intercept. The t value with the resulting p value are used to test the hypothesis that the intercept is equal to zero.
The beta coefficients are the regression coefficients which would have been obtained had all of the variables first been standardised to a mean of zero and a standard deviation of one.
The N is the total number of observations.

'*F* statistics' which result from the analysis of the variance regression model were carried out as an intermediate step of the selected regression function (Table 7).

Table 7. ANOVA results

	Variance analysis; *DV*: % (waste composition)				
N = 36	Sums of Squares	*df*	Mean Squares	*F*	*p* level
Regress	163.8105	1	163.8105	28.49000	0.000006
Residual	195.4917	34	5.7498		
Total	359.3022				

Note: The N is the total number of observations.

The values for mean squares in Table 7 were used for testing the significance of the regression model, whereas the key value used was the ratio of the model mean square and the residual mean square. In the case of the null hypothesis, the value of this ratio should be relatively close to one (ie. the explained and unexplained variability should be of a similar size). More precisely (for this particular model), it should originate from the F disturbance with a parameter value of 1.34 (for the model being presented). Nevertheless, the probability that the true value of this ratio, ie. the *F* statistic (with a value of 28.4900), originates from this F disturbance is less than 0.000001 or equal to 0^6, as confirmed by the values in the '*p* level' column. Hence H_0 can be rejected with this probability of a Type I error (at the concerned level of significance).

We present below a graphical representation of the regression line (Fig. 5).

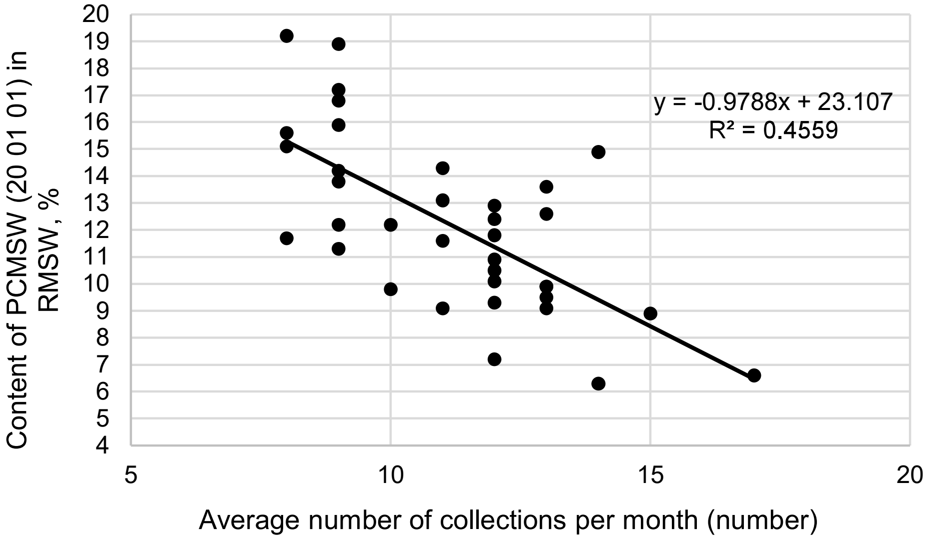

Figure 5. Graphical representation of regression.

According to Fig. 4 but in more detail, there is a decrease in the relative content of PCWSW (20 01 01) in RMSW, from approximately 14.45% to 11.93% here in the years being monitored, 2014–2016. This corresponds to the opposite course of utilisation of the total capacity of PCMSW containers. There utilisation rose to 54% from 51%. However, the percentages calculated for paper are evaluated as being unsatisfactory. This state is achieved by a lack of discipline during the disposal of waste by members of the public. It is stated that the paper volume after pressing is only 20% of the total volume. In this example, it may be possible to achieve substantial savings in logistics costs for these processes by consistent deformation. The role of the public is fundamental in achieving this goal. In fact, the correct source separation of PCMSW is at the basis of any successful collection scheme (Dhokhikah et al., 2015). For example, members of the public can be interviewed to assess their willingness to pay as a function of the separate collection services, in order to work out which socio-demographic characteristics influence the production of waste as well as the identification of proposals for the promotion of recycling (Challcharoenwattana & Pharino, 2016; Giovanni et al., 2017). On the other hand, there was no reflection of any separate BMSW collection in RMSW composition. The representation of BMSW in RMSW is still rising, from 5.72% to 7.35% in the period being monitored. The utilisation of the total capacity rose too. Values have increased from 26% to 32% but they are lower than those for paper. The BMSW collection is carried out once a week. It is therefore possible to reduce the frequency of collections without there being a risk of overfilling the containers or damaging the efficiency of separation.

In view of a comparison between both of these areas, a collection through the use indicator of waste generation per capita per year (Teixeira et al., 2014, and CML et al., 2014) also evidences a difference in the achieved value of 16.2 kg per person^{-1} year^{-1} (PCMSW collection) and 8.3 kg per person^{-1} year^{-1} (BMSW collection) in the last year of measurement – 2016 – from the perspective of production from apartment buildings or houses.

An assessment of the mean values of input data (regarding the PCMSW collection) further proves a statistically significant relation that the relative volume of PCMSW in RMSW depends upon the average number of collections per month by settings of collection parameters, from the perspective of the overall size of this site. The positive relationship was furthermore enriched by regression analysis; however this does not necessarily reflect a causal relation (in fact, only non-manipulated areas were observed). Therefore, the relative volume of PCMSW in RMSW is influenced by non-measured factors. Furthermore, as the distribution of regression residuals around the *x* axis shows, there exist some differences between the real (observed) and predicted (fitted by the regression model) values of the variables in the regression equation. These differences could have been caused by increasing numbers of collections with a small number of collected containers.

CONCLUSIONS

The principal objective of the present study was to conduct a comparison of PCMSW and BMSW collections in one selected urban area from the perspective of its diversion from landfill (during the 2014–2016 period). The authors also studied the influence of the average number of PCMSW collections per month, it corresponds to increasing PCMSW production in terms of the relative volume of this form of waste in RMSW for kerbside paper collections.

The study proves that the average number of PCMSW collections per month influences the relative amount of PCMSW in RMSW, and mathematically defines this dependence. Available data for individual quarters of 2014–2016 confirm the following regression compensation straight line of the average monthly PCMSW production **p** and the relative amount of PCMSW in RMSW **T** for kerbside paper collections A: T = 23.107–0.9788.p.

The decrease of PCMSW in RMSW for on-site paper collection indicates that the directive on landfills can be followed with well-chosen technological parameters in regard to a separate BMSW collection. It confirms the statistically significant relation. Improperly adjusted technological parameters for on-site BMSW collections indicate that this site has total monitored results which are parallel to areas without any separate collection. It means then that the collection has only an increase in costs for BMSW disposal without any of the concrete positive effects of a separate BMSW collection or any equivalent benefit towards the environment.

Hence it is necessary to continually analyse the collection data, rigorously evaluate and carry out immediate remedial measures, and optimise the technological parameters at the given site with both separate forms of collection.

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