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Biowaste separation of household waste. Case study of the city of Brno.

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Abstract
The paper presents an analysis and design of a model system of biowaste management in a model city of middle or north European Union countries. Biowaste is considered as a biodegradable component of household waste, evaluated in four types of built-up areas of the city: rural (suburban) area; villa area; panel housing estates and block-house estate areas. Generation of biowaste in and outside the growing season is also considered and, subsequently, also all-season potential. Biowaste is considered to be specified by the European List of Waste, in particular the codes: 20 01 08 biodegradable kitchen and canteen waste (specifically from households); 20 02 01 biodegradable waste (waste from gardens in apartment and family houses) and biowaste from mixed municipal waste (code 20 03 01). The economic model of generation, collection and treatment of biowaste is developed and potential scenarios of biowaste management are evaluated from the economic point of view.
A case study of the current biowaste management system of the city of Brno in the Czech Republic is presented. The evaluation of economic costs and benefits of the various proposed models for the city of Brno is also presented, including the quantity of generated waste (the cost of rental of containers, collection costs, costs for material recovery facilities etc.). Finally, a design of the best solution for biowaste management of the city of Brno is presented, with proposals and recommendations for the next steps, including the design of areas suitable for the application of different types of biowaste management.

Keywords
biowaste modelling, household waste, economic analyses, case study, the city of Brno.

Introduction

Every city provides an array of service, residential, and industrial functions. How these services are arranged in relationship to one another is what we call urban structure, or land use structure. Europe and Middle Eastern cities each have a lot of history behind them, which of course often gives them no easily identifiable city structure today[1]. These cities have often evolved from previously large towns and have seen their borders continually expand.

Let us consider a hypothetical large city (from 250,000 to 1,000,000 inhabitants) in the European Union (EU) with the introduced system of municipal waste management which fulfils EU waste management legislation [1-5]. We can recognize here four types of built-up area of the city: rural (suburban) area; villa area; panel housing estates and block-house estate areas.

Biowaste is defined as biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, and comparable waste from food processing plants. It does not include forestry or agricultural residues, manure, sewage sludge, or other biodegradable waste such as natural textiles, paper or processed wood [1].

We consider waste classification based on the European List of Waste (ELW) [2], where we will take into account as biowaste the following waste codes in the hypothetical large city:

- 20 01 08 Biodegradable kitchen and canteen waste (specifically from households),
- 20 02 01 Biodegradable waste (waste from gardens near apartment and family houses),
- 20 03 01 Mixed municipal waste.

We suppose that biowaste (codes 20 01 08 and 20 02 01) is partly collected by inhabitants in collecting yards and waste collection centres in the city and transported to a central composting plant. However, a large part of biowaste remains in mixed municipal waste (MMW), which citizens store in small or large containers close to their dwelling. Let us suppose that MMW is collected and transported to treatment facilities in the city.

The amount of biowaste changes in the growing season (generation of biowaste from vegetation in the spring and autumn months) and outside the growing season (winter months).

We suppose that this city treats biowaste from MMW in an incineration plant with energy recovery and in a composting plant with separated biowaste (i.e. codes 20 01 08, 20 02 01).

We suppose that the administration of the city has accepted the development of the new Waste Management Plan following the Commission Methodological Guidance Note [5]. It enables improving the system of biowaste collection and declining this from MMW with the support of composting. For decision-making it is necessary to perform an economic analysis of the current situation of biowaste management in the city and to assess the possible scenarios of biowaste management from an economic and environmental point of view.

In the first part of the paper a developed model of generation, collection and treatment of biowaste is introduced with appropriate constant and variable parameters. Further an application of the model for the development of potential scenarios of biowaste management from the economic point of view is presented. A case study of the current biowaste management system of the city of Brno in the Czech Republic is presented in the second part of the paper. The evaluation of economic costs and benefits of the various proposed scenarios for the city of Brno is also presented, including the quantity of generated biowaste, the number of collected containers, the cost of rental of containers, collection costs, and costs for material recovery facilities, etc.

Material and methods

For the support of decision-making in a hypothetical European city with an energy recovery incineration and composting plant the model for analysing and improving the system of biowaste management is developed. It included following consequent modelling steps:

1. Identification of the four types of structures of the city (built-up area): rural (suburban) area; villa area; panel housing estates and block-house estate areas and the number of inhabitants there.
2. Identification of potential biowaste generation from MMW in the four types of built-up area of the city and computation of its amounts, including analysis of the composition of mixed municipal waste there.
3. Identification of the system of collection of biowaste from MMW to different types of containers and costs of their collection and transport to treatment facilities.
4. Construction of the model of biowaste generation with different systems of collected containers and their economic assessment.

[1] https://citybuildingcrashcourse.wordpress.com/2014/08/27/city-structure-models/

Identification of the four types of built-up areas of the city

We assume that in most large cities and towns in the EU four types of structure of the city (built-up area) can be distinguished:

1. *Villa built-up area* - characterized by family houses without productive gardens, usually only with decorative features (lawns, shrubs and trees). Biowaste and MMW from houses in the villa built-up area can be collected in small containers (typically 120 l) located at each house individually. The placement of a composter in most cases is possible, but one can expect a lower willingness for composting because of the poor quality of the substrate consisting mostly of grass and tree leaves and branches (inappropriate C/N ratio).
2. *Rural (suburban) built-up area* - characterized by family houses with productive gardens, where one can place a composter. Biowaste and MMW from houses in rural built-up areas can be collected in small containers (typically 120 l) located at each house individually (owned by the waste collection company or property owner). Location of a composter is possible in most cases. Currently experiencing gradual conversion of part of the rural built-up area to a villa built-up area in several EU countries.
3. *Panel housing estate area* – characterized by panel housing estates and residential buildings constructed without interior courtyards and gardens. Here there is typical collection of biowaste and MMW from large-volume containers (1,100 l) and an inability to operate the compost.
4. *Block house estate area* - characterized by older residential houses carefully articulated in the intensive development of the city centre. Collection of MMW is mostly in small containers (120 l) placed in individual houses with a larger numbers of flats that are shared by the inhabitants. The location of a composter in block buildings is possible in inner blocks and courtyards of apartment buildings, but one can expect the population to be less willing to compost because of more flats sharing one composter and inhabitants with more difficult opportunities in producing compost.

Citizen denotes the number of inhabitants in the city. Cities usually have an administrative division of the city into city districts. For each type of built-up area in the city it is necessary to establish the number of inhabitants (according to the latest data available from the statistical Census of Eurostat or a given EU country) and the proportion of the population living in these built-up areas. Let us denote the numbers Cit_i, *i=vil,rur,pan,blo* of inhabitants and the ratio $Z_i = Cit_i/Citizen$, *i=vil,rur,pan,blo* of inhabitants living in a villa built-up area, a rural built-up area, a panel housing estate area and block house estate built-up area. These numbers are necessary to estimate statistics from the city districts. We denote *C* and *Z* arrays/vectors with elements Cit_i and Z_i for future implementation in the program MS Excel.

Let us denote δ as the ratio of the population involved in the system of biowaste management, where δ is a number from 0 to 1 (from 0% to 100%). It indicates how much of the population will be involved in the separation and collection of biowaste from MMW. This ratio depends on the (non-) separate biowaste collection obligations of the city and on information and incentive campaigns explaining the system of biowaste management. The ratio includes all residents who will participate in separate biowaste collection from MMW and home composting or will be interested in it (but for objective reasons, are not able to become involved, see below).

Identification of potential biowaste generation during the year in the four types of built-up area of the city

Let us identify the following input parameters in the designed BIOWASTE model specific for the given city:

- *The annual generation of mixed municipal waste (MMW) per capita in each built-up area*. We denote these variable MMW_i, *i=vil,rur,pan,blo*. They are calculated in the unit [kg/inhabitant/year]. We denote the *MMW* array/vector with elements MMV_i for future implementation in the program MS Excel. Usually they can be taken from the annual waste reporting of the city, which is obligatory from waste legislation [1,2].
- *The portion of biowaste contained in MMW in the given built-up area of the city*. For the whole of the city it is specified by four coefficients k_i, *i=vil,rur,pan,blo*. We denote the *K* array/vector with elements k_i for future implementation in the program MS Excel. They are quoted as the number of percentages i.e. from 0 % to 100 %. This usually results of analysis of MMW composition in built-up areas of the city, see [6-9, 11-13].
- *The distribution of generated biowaste in individual months of the year in built-up areas*. It is measured as the proportion of full-year production, i.e. as the number of percentages (i.e. from 0 % to 100 % from January to December in the built-up areas. These parameters are denoted as

$d_{j.i}$, i=1,…,12, j=*vil,rur,pan,blo*,. We denote the matrix *D* of 12 rows and 4 columns which contains $d_{j.i}$ elements. They are usually the result of analysis of MMW composition in built-up areas during the year [14].

The above parameters *Cit, Z, MMW, K, D* are assumed as constant and valid in the designed model for all considered variants of the system of collection of biowaste and MMW and their transport to the biowaste treatment facility.

Identification of the system of collection of biowaste in different types of containers and costs of collection and transport to treatment facilities.

Moreover, the designed BIOWASTE model enables each of the variations to separately set out detailed parameters on specific types of containers (for simplification volumes of 120 l and 1,100 l are considered), their placement, for calculation of the potential amount of collected biowaste and its treatment.

Let us denote model variable input parameters:

- *The willingness of inhabitants to participate in the collecting/composting biowaste to the given type of containers in the built-up area*. These parameters indicate the proportion of inhabitants of the given built-up area willing to use that type of container (small or larger) or composter, i.e. as a percentage number (i.e. from 0% to 100%). These parameters are denoted as $wil_{j.i}$, *i=small,large,comp, j=vil,rur,pan,blo*. We denote the matrix *WIL* of 3 rows and 4 columns which contains $wil_{i.j}$ elements. They are usually estimated from questionnaires completed by inhabitants of built-up areas or from other sociological investigation [14]. The willingness of inhabitants to have large containers can be assumed 100%, because it depends usually on the city administration decision and does not depend directly on the willingness of inhabitants.
- *The reachable (optimal) proportion of small or large containers and composters in different built-up areas*. These proportions are specified between 0% and 100% and are denoted as $opt_{j.i}$, *i=small,large,comp, j=vil,rur,pan,blo.* We denote the matrix *OPT* of 3 rows and 4 columns which contains $opt_{i.j}$ elements. We assume $opt_{pan.comp} = 0$, it characterises that in the panel building built-up area it is not possible to cover the compostable biowaste by composters, because it is not technically possible to have a place for them.
- *The volume of large container* Vol_{large} specified in unit [l] and the maximum frequency f_{large} of the collection of large containers in the year with unit specified as [number of days].
- *The volume of small container* Vol_{smal} specified in unit [l] and the maximum frequency f_{smal} of the collection of small containers in the year with unit specified as [number of days].
- *The average volume of the composter* Vol_{comp} specified in unit [l] and the frequency f_{comp} of the variations of the contents of the composter in the year. The unit is specified [number of days].
- We denote arrays/vectors *VOL* and *F* with elements Vol_i and f_i, *i=small,large,comp*.
- *The density* ρ of biowaste in the unit of [kgm^{-3}].

All the above input parameters are summarized in the following table.

Table 1. Summary of basic input parameters of the BIOWASTE model. Source: Authors

Parameter [unit]	*Villa area*	*Rural area*	*Panel estate area*	*Block estate area*
Number of inhabitants living in the built-up area	Cit_{vil}	Cit_{rur}	Cit_{pan}	Cit_{blo}
Ratio of inhabitants living in the built-up area [%]	Z_{vil}	Z_{rur}	Z_{pan}	Z_{blo}
Generation MMW per capita [kg/year]	MMW_{vil}	MMW_{rur}	MMW_{pan}	MMW_{blo}
Proportion of biowaste in MMW in the year [%]	k_{vil}	k_{rur}	k_{pan}	k_{blo}
Proportion of biowaste in MMW in January [%]	$d_{vil.1}$	$d_{rur.1}$	$d_{pan.1}$	$d_{blo.1}$
Proportion of biowaste in MMW in February [%]	$d_{vil.2}$	$d_{rur.2}$	$d_{pan.2}$	$d_{blo.2}$
Proportion of biowaste in MMW in March [%]	$d_{vil.3}$	$d_{rur.3}$	$d_{pan.3}$	$d_{blo.3}$
Proportion of biowaste in MMW in April [%]	$d_{vil.4}$	$d_{rur.4}$	$d_{pan.4}$	$d_{blo.4}$
Proportion of biowaste in MMW in May [%]	$d_{vil.5}$	$d_{rur.5}$	$d_{pan.5}$	$d_{blo.5}$
Proportion of biowaste in MMW in June [%]	$d_{vil.6}$	$d_{rur.6}$	$d_{pan.6}$	$d_{blo.6}$
Proportion of biowaste in MMW in July [%]	$d_{vil.7}$	$d_{rur.7}$	$d_{pan.7}$	$d_{blo.7}$
Proportion of biowaste in MMW in August [%]	$d_{vil.8}$	$d_{rur.8}$	$d_{pan.8}$	$d_{blo.8}$
Proportion of biowaste in MMW in September [%]	$d_{vil.9}$	$d_{rur.9}$	$d_{pan.9}$	$d_{blo.9}$
Proportion of biowaste in MMW in October [%]	$d_{vil.10}$	$d_{rur.10}$	$d_{pan.10}$	$d_{blo.10}$

Proportion of biowaste in MMW in November [%]	$d_{vil.11}$	$d_{rur.11}$	$d_{pan.11}$	$d_{blo.11}$
Proportion of biowaste in MMW in December [%]	$d_{vil.12}$	$d_{rur.12}$	$d_{pan.12}$	$d_{blo.12}$
Willingness to place a large container [%]	$wil_{vil.large}$	$wil_{rur.large}$	$wil_{pan.large}$	$wil_{blo.large}$
Willingness to place a small container [%]	$wil_{vil.smal}$	$wil_{rur.smal}$	$wil_{pan.smal}$	$wil_{blo.smal}$
Willingness to place a composter [%]	$wil_{vil.comp}$	$wil_{rur.comp}$	$wil_{pan.comp}$	$wil_{blo.comp}$
Reachable (optimal) proportion of large containers [%]	$opt_{vil.large}$	$opt_{rur.large}$	$opt_{pan.large}$	$opt_{blo.large}$
Reachable (optimal) proportion of small containers [%]	$opt_{vil.smal}$	$opt_{rur.smal}$	$opt_{pan.smal}$	$opt_{blo.smal}$
Reachable (optimal) proportion of composters [%]	$opt_{vil.comp}$	$opt_{rur.comp}$	$opt_{pan.comp}$	$opt_{blo.comp}$
Density of biowaste [kgm^{-3}]				ρ
Volume of large container [l]				Vol_{large}
Maximum frequency of collection of large containers in the year [day]				f_{large}
Fixed costs per large container [€]				Fc_{large}
Variable costs per large containers [€]				Vc_{large}
Volume of small container [l]				Vol_{smal}
Maximum frequency of collection of small containers in the year [day]				f_{smal}
Fixed costs per small container [€]				Fc_{smal}
Variable costs per small container [€]				Vc_{smal}
Biowaste treatment costs (depending on waste facility) [€/t]				Tc

Construction of the model of biowaste generation from MMW

Based on the above parameters an interactive BIOWASTE model was designed and implemented in MS Excel. The model is described as follow:

BIOWASTE(*Citizen, Cit, MMW, k, D, WIL, OPT, VOL, F, Fc, Vc, δ, ρ, Tc, P, opt, L, S, C, CC, CT*)

where *Citizen, Cit, MMW, k, D, WIL, OPT, VOL, F, Fc, Vc, δ, ρ* and *Tc* are input parameters described above. The outputs of the BIOWASTE model *P*, *opt, L, S, C, CC, CT* are described below.

The potential amount p_m of biowaste generation from MMW in the city and the individual calendar months is defined as

$$p_m = Z_{vil}k_{vil}MMW_{vil}d_{vil.m} + Z_{rur}k_{rur}MMW_{rur}d_{rur.m} + Z_{pan}k_{pan}MMW_{pan}d_{pan.m} + Z_{blo}k_{blo}MMW_{blo}d_{blo.m} \quad (1)$$

where index *m* represents a calendar month (from 1 to 12). The total potential *P* of biowaste generation from MMW in the city is

$$P = \sum_{m=1}^{12} p_m \,. \quad (2)$$

Let us denote *the optimal ratio* opt_{large} *of biowaste collected in large containers* (situated usually in public collecting nests for separated components of municipal waste) in the city, *the optimal ratio* opt_{smal} *of biowaste collected in small containers* (individual location for real estate) in the city, both declared as a relative proportion between 0% and 100%, and *the ratio* opt_{comp} *of biowaste processed in composters* in the city. These ratios are specified between 0% and 100%. Now, we can specify the opt_{large}:

$$opt_{large} = (Z_{vil}k_{vil}MMW_{vil}opt_{vil.large} + Z_{rur}k_{rur}MMW_{rur}opt_{rur.large} + Z_{pan}k_{pan}MMW_{pan}opt_{pan.large} + Z_{blo}k_{blo}MMW_{blo}opt_{blo.large})/P, \quad (3)$$

where Z_i, k_i and MMW_i are input constant parameters and $opt_{i.j}$ input variable parameters for *i=vil,rur,pan,blo* and *j=large, small*. Similarly, we determine the optimal share of biowaste opt_{smal} collected in small containers and the optimal share of biowaste opt_{comp} composted in composters.

Now, we can specify the number of containers or composters which enable collection of the total potential *P* of biowaste from MMW in built-up areas.

The number of large containers L_i, *i=vil,rur,pan,blo,* for the given type of built-up area can be estimated from the knowledge of the real proportion of biowaste collected in large containers in *i*-th built-up area and the willingness of the inhabitants to place a large container at their house (specifically in the case of large containers, $wil_{i,large}$ is expected to be equal 100%, since the containers are placed on public places and managed by the municipality):

$$L_i = \min(opt_{i.large}; wil_{i.large}) \cdot Citizen \cdot Z_i MMW_i \cdot k_i / (Vol_{large}/1000 \cdot \rho)/(365/f_{large}) \tag{4}$$

Then the number L of total large containers in the city is

$$L = L_{vil} + L_{rur} + L_{pan} + L_{blo} \tag{5}$$

The number $S = S_{vil} + S_{rur} + S_{pan} + S_{blo}$ of small containers in the city and the number $C = C_{vil} + C_{rur} + C_{pan} + C_{blo}$ of composters in the city can be estimated similarly; however the number C_{pan} of composters in panel housing estate areas will be close to zero (because of very low willingness $wil_{pan.comp}$).

While the costs of biowaste collection depend mainly on the above computed numbers of small and large containers and their collection frequency, the costs Tc of biowaste treatment depend on the real amount of collected biowaste on input to the treatment facility.

The costs of collected biowaste usually consist of a fixed cost (expenditures associated with the container itself, such as initial costs, leasing, cleaning etc.) and a variable cost depending on the frequency/ period of the biowaste collection. We can express the overall costs CC_i , i=*large, small* of the collection of biowaste in the large, small containers as follows:

$$CC_i = Fc_i \cdot L + Vc_i \cdot L \cdot 365/f_i \tag{6}$$

where Fc_i and Vc_i denotes fixed and variable costs of biowaste collection (price list items according to a biowaste collection company), see Table 1.

The costs CT_i, of the waste treatment in i-the built-up area $i=vil,rur,pan,blo$ are dependent only on the amount of the waste and the entry price to the waste treatment facility:

$$CT_i = Tc\left(\frac{\min\left(\left(L_i \cdot \frac{Vol_{large}}{f_{large}} + S_i \cdot \frac{Vol_{smal}}{f_{smal}}\right) \cdot \frac{365}{1000} \cdot \rho; Citizen \cdot Z_i \cdot k_i \cdot MMW_i\right)}{1000}\right) \tag{7}$$

where the minimum value is selected from the maximum capacity of the biowaste collection system consisting of sum of large and small containers (it is not possible to collect more biowaste than was generated or than the capacity of the system) and the lower amount from the maximum possible biowaste generation in the given villa built-up area.

Application of the BIOWASTE model in decision-making

The above designed BIOWASTE model enables the efficient evaluation of different scenarios with the above constant and variable input parameters *Citizen, Cit, MMW, k, D, WIL, OPT, Vol, f, Fc, Vc, δ, ρ* and *Tc*. For example, we can consider the following potential scenarios, which cover most reasonable biowaste management systems:

- *Scenario 1:* Collecting biowaste especially in large containers Vol_{large}=1,100 l located in public spaces with absolute willingness of inhabitants to sort biowaste from MMW, where we choose parameters $wil_{i.large}$=100%, $wil_{i.smal}$=0%, $opt_{vil.large}$=100%, $opt_{vil.smal}$=0%, $i=rur,pan,blo$. It assumes an idealized situation where all the inhabitants involved in the biowaste management system with a total preference of large containers are willing to sort biowaste. There is, therefore, no collection in small containers located at each of the properties or any home composting. In this case, we can assume that the number of containers will be based only the needs of the collection of biowaste that residents are willing and able to sort from MMW and the distribution of containers in the city will be optimized so that the containers are sufficiently filled and avoid being overfilled. Denote output parameters P^1, opt^1, L^1, S^1, C^1, CC^1 and CT^1.
- *Scenario 2*: Collecting biowaste in small containers located at individual properties in addition to housing estates and half of the block estates, where we choose the parameters $wil_{rur.smal}$= 100%, $wil_{vil.smal}$=100%, $wil_{blo.smal}$=50%, $wil_{pan.smal}$=0%,$wil_{i.large}$=100%, $opt_{i.smal}$= 100%, $i=vil,rur$, $opt_{i.large}$=0%, $i=vil, rur,pan,blo$. We consider only small containers with the capacity Vol_{smal} =120 l, located at individual estate houses (one container may be shared by more flats, we assume that the average flat is occupied one and half persons). Denote output parameters P^2, opt^2, L^2, S^2, C^2, CC^2 and CT^2.
- *Scenario 3:* Combination of large containers in the panel built-up areas with half of small containers, in block built-up areas and only small containers in the villa and rural built-up areas (according to the number of households), i.e. $wil_{pan.large}$=100%, $wil_{blo.smal}$=50%, $wil_{vil.smal}$=100%, $wil_{rur.smal}$=100%. This is identical to Scenario 2 with the collection of biowaste in large containers

from panel housing estates and 50% of block house estate, which are not covered by small containers. This covers the whole included part of the population by either large or small containers. We obtain output parameters P, opt, L, S, C, CC and CT. The costs roughly correspond to the total costs of Scenarios 1 and 2, decreased in the area of family houses, where biowaste is not collected in large containers. Denote output parameters P^3, opt^3, L^3, S^3, C^3, CC^3 and CT^3.

- *Scenario 4*: Combination of large containers in the panel built-up areas with half of composters in the block built-up areas and only composters in the villa and rural built-up areas (according to the number of households). This is identical to Scenario 3, in which small containers are replaced with the same numbers of composters with zero cost to the collection of biowaste from MMW. Denote output parameters P^4, opt^4, L^4, S^4, C^4, CC^4 and CT^4.

Now we can compare and evaluate the output parameters P^i, opt^i, L^i, S^i, C^i, CC^i and CT^i, i=1,…,4 and choose an optimum scenario and the most appropriate biowaste management system for the city.

Case study of the city of Brno

The current biowaste management system of the city of Brno is described here and the potential amount of generated waste (quantities in tonnes for the period/year) is evaluated with the distribution of biowaste [14].

Brno demography

Brno is the second largest city in the Czech Republic by population and area, the largest Moravian city, and the historical capital city of the Margraviate of Moravia. Brno is the administrative centre of the South Moravian Region in which it forms 29 separate districts (Brno-City District)[2].

Figure 1 Administrative divisions of city districts of the city Brno. Source: https://en.wikipedia.org/wiki/Administrative_divisions_of_Brno

The city districts of Brno significantly vary in their size by both population and area, see Fig. 1. The most populated city district of Brno is Brno-střed which has over 91,000 residents and the least populated are the districts Brno-Ořešín and Brno-Útěchov with about 500 residents. By area, the largest is the city district Brno-Bystrc with 27.24 square kilometres and the smallest is Brno-Nový Lískovec with 1.66 square kilometres.

We analysed all the districts of the city of Brno to determine their four built-up areas. We used the last statistical census of the city Brno from the Czech Statistical Office[3], as the interactive map of each

[2] https://en.wikipedia.org/wiki/Administrative_divisions_of_Brno
[3] https://www.czso.cz/csu/xb/sldb_2011_vybrane_vysledky_podle_mestskych_casti_brna

district of the city of Brno[4]. These maps are based on the technology of Google Maps and allow online viewing with a variety of benefits. They have interactive zooming, enabling us to determine for each district the required part of built-up area, see for example Fig. 2 and Table 2 for the district Brno Žebětín.

Table 2. Basic demography of the city district Brno Žebětín. Source: Authors

Item	number
Number of inhabitants 2011	3,577
Inhabited houses	839
Occupied dwellings	1,236
Occupied dwellings in family houses	912
Occupied dwellings in panel housing estate area	339
Occupied dwellings in other buildings	13
Villa built-up area	22%
Rural (suburban) built-up area	50%
Panel housing estate area	25%
Block house estate area	3%

Figure 2 Satellite map of city district Brno-Žebětín.
Source: http://www.mapa-brna.cz/brno-zebetin

On the basis of the above analysis, we can summarize that from the overall population *Citizen*=385,913 of the city of Brno live: Z_{vil}=9.9% of the population in a villa built-up area of Brno, Z_{rur}=11.2% of the population in a rural (suburban) built-up area of Brno, Z_{pan}=58.6% of the population in a panel housing estate area of Brno and Z_{blo}=20.3% of the population in a block house estate area of Brno.

Brno waste management system

The city of Brno is also the centre of the South Moravian Region in waste management. Major companies operating in the field of waste management have their seat there, including waste treatment facilities such as the SAKO incinerator [5], the SUEZ Využití zdrojů composting plant[6], sorting units of waste paper and plastics, units for the processing of recyclable waste, etc.

[4] http://gis.brno.cz/jsviewer/mapa_mesta/
[5] http://www.sako.cz/en/
[6] http://www.centralnikompostarna.cz/

The company SAKO is a Czech joint-stock company which is one hundred percent owned by the City of Brno. It provides services for the city that are related to the collection and transport of municipal waste – collection, transport and energy recovery of waste (black refuse bins and dumpsters), collection, transport and reuse of recoverable municipal waste components (colour bins) and operation of waste collection centres including the transport of waste from waste collection centres. SAKO is a company with a tradition. Its history dates back to 1905 when the first incineration plant in the former Austro-Hungarian Empire was built in Brno and already at that time it was designed to generate electricity [10]. Currently it processes waste for its subsequent recovery and has a capacity of 240,000 t/year. It is among the most modern incinerators in Europe. It converts MMW into heat and electricity for the city of Brno.

SAKO also operates a modern sorting and post-processing unit for separated waste (paper, plastics and beverage cartons) with the input capacity of 10,000 t/year.

The SUEZ Využití zdrojů composting plant has been in operation since 2007 and uses the technology of controlled intensive composting in heaps with aeration. It has a capacity of 7,000 t/year of input biowaste.

The waste management system of the city of Brno consists of three basic subsystems:

- The subsystem of collection of MMW (black MMW containers are located at individual properties) on a 230 km^2 area of the city by the company SAKO, (Fig. 3a), whose MMW energy is recovered by in its incinerator.
- The subsystem of the collection by SAKO of separated material recyclable components of municipal waste in special containers placed on publicly accessible locations throughout the whole territory of the city (blue for paper, green and white for glass, and yellow for a mixture of PET-bottles, beverage cartons and aluminium beverage containers), (Fig. 3b), which passes through sorting units and is recycled.

a) b)

Figure 3 Containers for MMW and for paper, plastics and glass. Source: [11]

- The subsystem of 37 waste collection centres (WCC)[7], operated by SAKO, where residents can place biowaste (in 9 and 14 m^3 containers), bulky waste (which due to its size and nature cannot be stored in MMW collection containers), construction and demolition waste, material recycling components of municipal waste (paper, PET bottles, beverage cartons, glass, metals, biowaste, etc.) and hazardous components of municipal waste, Fig. 4.

The waste is treated in accordance with the terms of the EU and Czech waste legislation, i.e. material recovery in recycling plants, energy recovery in the SAKO incinerator and disposed of at landfills close to the city of Brno (only for waste from collection centres that do not perform material or energy recovery).

Brno biowaste management system

The city of Brno currently allows residents to submit all sorted biowaste only to the WCC. Biowaste collection through the WCC was launched in 2007. From this year all WCC were equipped for the collection of biowaste. The following table shows the total amount of biowaste on the SSO in the years 2012–2015. For comparison, the overall production of MMW is listed here, including production per capita.

Table 3. Amount of biowaste placed in the WCC and MMW collected in the city of Brno in the years 2012–2015 [t]. Source: SAKO

[7] http://www.sako.cz/page/en/608/waste-collection-centre/

year	2012	2013	2014	2015
Generation of biowaste [t]	2,148	2,530	2,451	2,322
Generation of biowaste per capita [kg/inhab.]	5.67	6.69	6.49	6.30
Generation of MMW [t]	68,582	67,522	66,866	66,684
Generation of MMW per capita [kg/inhab.]	180.97	178.48	177.12	176.67

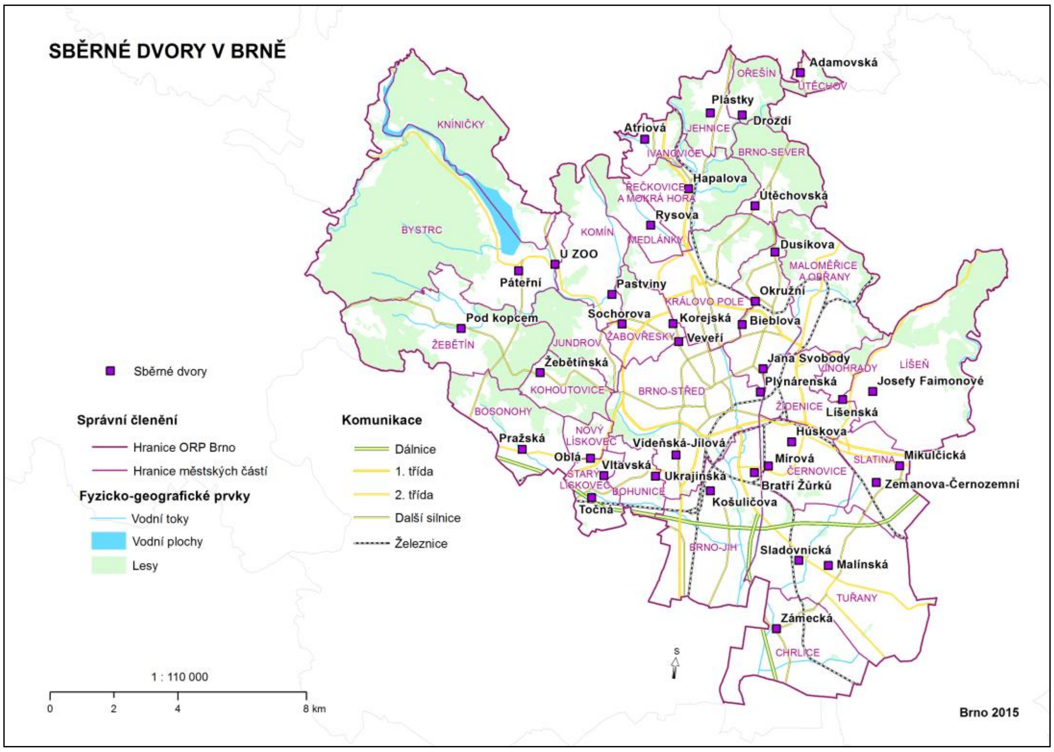

Figure 4 Map of waste collection centres in Brno. Source: http://www.sako.cz/sberna-strediska/en/

Composters in the city of Brno

The city of Brno, within the framework of the international project Miniwaste[8] "Design, implementation and evaluation of an innovative and sustainable strategic plan leading to minimizing urban organic waste in EU countries" implemented the pilot project aimed at promoting domestic composting, together with the cities of Rennes Métropole (France), and Lipor (Belgium) on different scales. The selected location for implementation in the city Brno was the city district of Žebětín with 3,577 inhabitants [14], see Table 2. Within the framework of the project 360 composters were placed at properties in Žebětín. For the duration of the project 350 composters (volume of 390 l) were deployed at family houses and 10 composters (volume of 720 l) on panel housing estates. In the following year, 2013, in the context of the sustainability of this project, the city of Brno purchased 500 composters (400 l) and 30 composters (900 l) suitable for family houses and panel housing estates. In 2015 the city of Brno purchased 200 (volume 1000 l) composters. On 13 September 2016 the council of the city of Brno approved the purchase of an additional 150 composters (400 l) and 290 composters (950 l).

The following Table 4 summarizes the number and volume of composters purchased by the city of Brno in 2010-2016.

Table 4. Number and volume of composters purchased from 2012 to 2016. Source: The city of Brno

Composter\Year	*2012 [units]*	*2013 [units]*	*2015 [units]*	*2016 [units]*	*Sum of volume [l]*
K390	350				784,680
K720	10				7,200

8 http://www.miniwaste.eu/

K400		500		150	260,000
K950				290	275,500
ThermoKing900		30			270,00
Thermostar1000			200		200,000
Total composter volume [l]	*791,880*	*227,000*	*20,0000*	*335,500*	*1,554,380*

Content of biowaste in mixed municipal waste

Biowaste is a quantitatively significant part in MMW in the city of Brno. Determining the exact proportion of biowaste in the MMW is problematic [6-9, 11-13]. Its amount varies depending on the season, the type of built-up area and the living standards of the population.

However, many analyses of the composition of the MMW have been processed in the city of Brno by the company SAKO since 1999 [11-12]. We evaluated these analyses from 2010 and obtained the proportion d_{vil}=34% of biowaste in MMW in the villa built-up areas of the city of Brno, the proportion d_{rur}=22.2% of biowaste in MMW in the rural built-up areas of the city of Brno, the proportion d_{pan}=16.4% of biowaste in MMW in the panel housing estate areas of Brno and the proportion d_{blo}=16.4% of biowaste in MMW in the block house estate areas of Brno [14].

We estimated the proportion of biowaste in MMW in individual months of the year 2015, see Table 5.

Input data to the model

The following tables show the input constant and variable parameters to the BIOWASTE model, which were collected in collaboration with the city of Brno and the company SAKO.

Table 5. Input constant parameters to the BIOWASTE model. Source: City of Brno, SAKO, [14].

Parameter [unit]	*Villa areas*	*Rural areas*	*Panel estate areas*	*Block estate areas*
Ratio of inhabitants living in built-up area [%]	9.9	11.2	58.6	20.3
Generation MMW per capita [kg/year]	186.7	166.7	176.7	176.7
Proportion of biowaste in MMW in year [%]	34.1	22.2	16.4	16.4
Proportion of biowaste in MMW in January [%]	1.7	1.7	1.7	1.7
Proportion of biowaste in MMW in February [%]	1.2	1.2	1.2	1.2
Proportion of biowaste in MMW in March [%]	8.1	8.1	8.1	8.1
Proportion of biowaste in MMW in April [%]	8.9	8.9	8.9	8.9
Proportion of biowaste in MMW in May [%]	10.1	10.1	10.1	10.1
Proportion of biowaste in MMW in June [%]	10.3	10.3	10.3	10.3
Proportion of biowaste in MMW in July [%]	7.0	7.0	7.0	7.0
Proportion of biowaste in MMW in August [%]	7.9	7.9	7.9	7.9
Proportion of biowaste in MMW in September [%]	11.8	11.8	11.8	11.8
Proportion of biowaste in MMW in October [%]	13.0	13.0	13.0	13.0
Proportion of biowaste in MMW in November [%]	16.0	16.0	16.0	16.0
Proportion of biowaste in MMW in December [%]	3.9	3.9	3.9	3.9
Willingness to place a large container [%]	100	100	100	100
Willingness to place a small container [%]	70	70	0	50
Willingness to place a composter [%]	50	75	0	25
Reachable (optimum) proportion of small containers [%]	5	5	100	5
Reachable (optimum) proportion of large containers [%]	55	30	0	70
Reachable (optimum) proportion of composters [%]	40	65	0	25
Density of biowaste [kgm^{-3}]				270
Volume of large container [l]				1,100
Maximum frequency of the collection of large containers in the year [day]				14
Fixed costs per large container [€]				50
Variable costs per large container [€]				250
Volume of small container [l]				120/240
Maximum frequency of the collection of small containers in the year [day]				7/14
Fixed costs per small container [€]				5

Variable costs per small container [€]	25
Biowaste treatment costs (depending on waste facility) [€/t]	14

Let us consider the input variable parameters *WIL* and *OPT* in the scenarios described above. We consider the parameters *WIL* constant in all scenarios, see the following Table 6.

Table 6. Input variable parameters *WIL* to the BIOWASTE model in Scenarios 1, 2, 3 and 4. Source: [14].

Parameter [unit]	*Villa areas*	*Rural areas*	*Panel estate areas*	*Block estate areas*
Willingness to place a large container [%]	0	0	100	50
Willingness to place a small container [%]	100	100	0	50
Willingness to place a composter [%]	0	0	0	0

The parameters *OPT* are different in the scenarios, see the following Table 7.

Table 7. Input variable parameters *OPT* to the BIOWASTE model in Scenario 1, 2, 3 and 4. Source: [14]

Parameter [unit]	*Villa areas*			*Rural areas*			*Panel estate areas*			*Block estate areas*		
Scenario	1	2,3	4	1	2,3	4	1,3	2	4	1	2,3	4
Reachable (optimum) proportion of large containers [%]	100	0	0	100	0	0	100	0	100	100	50	50
Reachable (optimum) proportion of small containers [%]	0	100	0	0	100	0	0	100	0	0	50	0
Reachable (optimum) proportion of composters [%]	0	0	100	0	0	100	0	0	0	0	0	50

We use the above input parameters from Tables 5, 6 and 7 in the BIOWASTE model for the calculation of the four scenarios and obtain the results which are summarized in the following table.

Table 8. Outputs of the BIOWASTE model in Scenarios 1, 2, 3 and 4. Source: authors.

Scen.	Collected biowaste [t]	Eff. [%]	Number of large containers [units]	Number of small containers [units]	Number of composters [units]	Biowaste collection costs [€]	Biowaste treatment costs [€]	Costs per ton [€/t]
1	7,191	56	472	0	0	64,134	100,677	22,92
2	6,231	49	0	33,566	0	887,391	87,242	156,40
3	8,199	64	150	33,566	0	907,773	114,797	124,71
4	2,232	18	150	0	33,566	20,382	31,537	23,05

We introduce the third column in Table 8 with efficiency [%] of collection of 12,755 tons of potential generated biowaste from MMW. We can now propose an optimal variant of biowaste management for the city of Brno.

Proposal of an optimal variant of biowaste management

Let us specify the following optimal variant of the biowaste management covering the entire territory of the city of Brno with the following assumptions:

- Home composting in the mode of waste prevention will be preferred over separate biowaste collection and its processing, where technically possible, the operation of the domestic composters;
- In the case of biowaste collection in separate containers, they will not be placed on the ground outside the premises of the owners of property, i.e. mostly these containers apply only in villa and rural built-up areas (small containers up to 240 l) or panel housing built-up areas, where it is possible to place the containers into collection nests (large containers 1,100 l);

- Coverage of rural and villa built-up areas will be 100% made up of small containers, in block building areas, of 50% of small containers and 50% in large containers and in panel built-up areas, of 100% of large containers;
- Distribution of small containers will comprise 25% with a volume of 120 l and 75% with a volume of 240 l, large containers will all have a volume of 1,100 l;
- The number of small containers in villa, rural and partly in block built-up areas will be defined by the number of houses (1 container per 1 house), in panel built-up areas and part of the block built-up areas the number of containers is defined by the estimated generation of biowaste;
- In the period December to February monthly biowaste collection will take place, the rest of the year a two-week biowaste collection period will take place.

Conclusion

The developed BIOWASTE model of generation, collection and treatment of biowaste with appropriate constant and variable parameters is presented here in the paper. The potential of biowaste is considered as the biodegradable component of household waste, evaluated in four types of built-up areas of the city: rural (suburban) areas; villa areas; panel housing estates and block-house estate areas. The distribution of biowaste in the growing season (the generation of waste from the green) and outside the growing season (winter months) is also considered and, subsequently, the all-season potential. The willingness of inhabitants to collect and separate biowaste is also incorporated into the parameters of the BIOWASTE model. Biowaste is considered to be specified by the European List of Waste, in particular the codes: 20 01 08 biodegradable kitchen and canteen waste (specifically from households); 20 02 01 biodegradable waste (waste from gardens in apartment and family houses) and biowaste from mixed municipal waste (code 20 03 01). In addition the general application of the BIOWASTE model is presented, enabling the analysis of potential scenarios of biowaste management from the economic point of view. A case study of the current biowaste management system of the city of Brno in the Czech Republic is presented in the second part of the paper. The evaluation of economic costs and benefits of the various proposed scenarios for the city of Brno is also presented, including the quantity of generated biowaste, the number of collected containers, the cost of container rental, collection costs and costs for material recovery facilities, etc.

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