Decision support tools in the waste management field. Conceptual modelling of mixed municipal waste generation and treatment in the Czech Republic

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Abstract: The Czech Republicwill have to fulfil requirements of the Landfill Directive 1999//31/EC in 2020, which demand 65% diversion of bio-waste amounts from landfills compared to 1995 ones. Furthermore, the Waste Framework Directive 2008/98/EC requiresto reach 50% material recovery rate of recyclable municipal waste in 2020.

Towards achievement of these goals, decision makers of the Czech Ministry for the Environment (MoE) needed appropriate decision support tools. TheMoE had asked the Masaryk University for developing conceptual models of municipal solid waste (MSW) generation and treatment in the Czech Republic, which enables forecastingMSW until 2024. This model was finished in 2014 and we have continued in its further development.

In the paper a comparison of two modelsis presented: the developedmodel M1 for the MoEat 2014 as a normative waste flows model of MSW, the new developedmodel M2 as a linear programming optimization model.Both modelsare based on the time series analysis of previous MSW generations and treatments in the Czech Republic and on planned capacities of energy recovery plants (1.47Tg in 2024 compared with 0.64 Tg in 2015) of the Waste Management Plan of the Czech Republic. Both

modelsissuefrom the assumption of future economic development of the Czech Republic and information on the current MSWflows composition. The models follow forecasts and analyses of Kalina et al. (2014) and Hřebíček et al. (2012)with surprisingly similar results.

Introduction

Modelling themunicipal solid waste (MSW)generation and treatment is rather complex incomparisonwith other waste flows. Not only MSW generation and treatment vary quantitatively in time, but also its composition changes due to a socio-economic development (Cherian & Jacob2012, Kalina&Hřebíček 2012, Kalina et al. 2014). The typical socio-economic precursors of MSW generation are the household consumption, changing range of goods on the market, willingness to sort municipal waste, changes in a type of heating, favourite packages etc.

The normative waste flows model (M1) was prepared as a part of preparation of the Waste Management Plan of the Czech Republic for the period 2015–2024 to predict waste generation and treatment in this period(Hřebíček, Kalina&Soukopová 2013, Kalina, Hřebíček&Bulková2014).

Forecasting MSW generation

The MSW generation model consisted of three parts: time-series linear and exponential regression submodelsanda structuralmultilinearsubmodel.The MSW treatment model usingwaste flows submodelsis discussed later.

In the first two submodels, a method of least squares linear regression was used to derive both linear and exponential trends of MSW generation in four main (overlapping) waste flows (Kalina, Hřebíček&Bulková2014), see Fig. 1:

- *biodegradable waste* (BMW) consisting of remains of food, kitchen waste, green waste from gardens (grass, leafs etc.), but also wooden waste (incl. disposed furniture), paper (packaging, newspapers, magazines, books etc.) and biodegradable part of clothes and other textiles;

- *recyclable waste* (RMW) consisting of packaging, destroyed products, ashes and rubbish, used or unwanted consumer goods, including shoes and clothing. This flow was divided on plastic, glass and metal containers, biodegradable part (wood and printed matter) and the rest;
- *mixed municipal waste* from households (MMW) defined as a waste flow, which is disposed in households, collected and disposed without any further treatment (such as sorting, mechanical and/or biological treatment etc.). This waste flow covers both the rest of waste which does not belong to BMW or RMW and also part of these flows which could be sorted, but it was not;
- *municipal solid waste* (MSW) in general which encompasses these three defined overlapping flows as well as marginal (by their amount) flows of hazardous municipal waste (waste from electrical and electronic equipment, drugs, chemicals etc.), bulky waste and rest (waste from municipal maintenance);

These flows were described as the sums of different wastes in terms of European List of Waste (Commission Decision 2000/532/EC) and Annex III to Directive 2008/98/EC. In the case of MMW, several more detailed analyses (Kalina&Hřebíček 2012) were used for the distinction between different components of the MMW flow.

Figure 1 here

Theannual data of time series of the MSW generation from the period 2008–2012 (from all 6,245 municipalities over the Czech Republic)were used for the construction of MSW generation trends of selected waste flows (total MSW, MMW, BMW, RMW). Several MSW expert changes were also made in these trends due to expected development of waste management in the Czech Republic in near future (Kalina et al. 2014).Finally, an empirical approach was chosen to describe the future development MSW generation as a weighted average of linear and exponential trends.

The structural multilinearsubmodel of MSW generation was built on the fact that MSW generation is affected by a plenty of municipal parameters (part of which could be however difficult to analyze and describe (Beigl et al. 2008, Hejč&Hřebíček 2008, Soukopová&Kalina 2012, Cherian & Jacob 2012). The dependence between MSW generation and a scale of known municipal parameters (20 parameters was analyzed, such as population, different acreages and land use inside the municipalities, civic amenities, living standards etc.) was created (Soukopová&Kalina 2012, Hřebíček, Kalina&Soukopová 2013, Kalina, Hřebíček&Bulková2014). This model forecasts the future development of MSW generation using expected trends of the socio-economic parameters (all from expertises, e.g. Vejměleket al. (2013) and time series analysesofthe Czech Statistical Office (2014)).

The final forecast of above waste flows was constructed from the forecasts of all three submodelsand the result was obtained as the sum of one half ofthe average of time series submodels and one half of the structure multilinearsubmodel.

Forecasting MSW treatment

For the forecastingMSW treatment in the model M1, it was necessary to outline main processes of waste recovery and disposaltogether withEuropean Union (EU)waste management objectives to 2020,environmental policies (7EAP, 2013) and legislation. Firstly, we assessed the initial (infrastructure) conditions of waste management in 2012 in the Czech Republic and all EU legislative and environmental objectives (usually in the form of thresholds/limits)to formulate a mathematically applicable structure of the model M1.

The MSWtreatmentsubmodelwas defined for the same four principal MSWflows (total MSW, MMW, BMW and RMW) as was done in the MSW forecastingsubmodels. Due to the fact, that these waste flows are overlapping and size of their intersections change in time (see Fig. 1), the construction of the treatment submodel required the division of MSW to more detailed distinct subflows. In total 8subflowsand 4 their sums were defined.

For each of eight subflows, we considered at most five different treatment options: *landfilling, material and energy recovery, composting (anaerobic digestion)* or *combustion without sufficient efficiency of energy generation*. This proposal provided 40 variablesin total to solve the forecast separately for each year (2014-2024).These variables were expanded by variables representing the composition of MMW, the capacities of appropriate treatment facilities and the convergenceof times series of subflowsaccording to waste legislation. We obtained 75 independent variables in total with nonlinear (in general) relations.

It was necessary to derive the same number of equations to solve thisforecasting problem as a set of derived equations. We derived with the collaboration of decision maker of the MoElogical relations (such as sums of subsets within a set), treatment capacities and legislative demands, which provided only 60 equations and remaining 15 equations had to be designed appropriately to keep the solution of the forecast with a real possibilities of the waste management of the Czech Republic.

It was necessary to considerthis submodelwith rather uncertain estimations and simplifications in order to characterize the MSW management system in all its details and to obtain a correct solution.

Nevertheless, there was also considera different approach how to solve the system ofnon-linearequations with higher numbers of variables with non-linear dependencies. We used software Maple(Maple 2015) providing a powerful computational tool how to obtain the feasible solution respecting all (also non-linear) relations without the necessity of detailed specification of all (and maybe unknown) relations between the waste flows. Further, we try to use non-linear programming tool and implemented this again in Maple, as described in the next section.

Materials and methods

Wedecided to use the non-linear programming (NLP) package of Maple(Maple 2015) in the new formulated model M2, in order to solve the set of 58 fundamental equations and 2 inequalities describing in each year (2014-2024) the state of Czech MSW management.Therefore, it was not necessary to add 15 more equations to obtain the fully determined set of equations. The successful useof the NLP method in waste management field in form of different waste flow models was proven in the last decade (Costi et al. 2004, Pires et al. 2011), but was never usedin the Czech Republic. Further, we introduce our new approach and the model M2.

The NLP method is able to solve undetermined set of (in)equalities by searching one from an infinite number of solutions with some optimal property (optimization). This means, that further 40 inequalities (8 subflows multiplied by 5 treatment options) ensuring a non-negativity of all waste flows had to be added to the set to obtain a correct result.The NLPmethod usually involves computing the minimum (or maximum) of the real-valued objective function, possibly subject to constraints.The local minimum of the objective function is returned unless the problem is convex and the objective function and the constraints are twice continuously differentiable. We analysed and proved that theseconditions were fulfilled by all equations entering the optimization.

Equations describing the logical structure of municipal waste management

The first set of equations involves all relations of the mentioned 8 subflows and their 4 sums, which are apparent directly from the structure of sets, deriving the variables (by the principle of exclusion and inclusion). It comprises the description of waste flows composition, see Fig. 1:

$$msw = rmw + bmw + mmw - brmw - bmmw - mrmw + bmrmw + rest \quad (1)$$

$$bmw = bmw0 + brmw + bmmw - bmrmw \quad (2)$$

$$mmw = mmw0 + mrmw + brmw + bmrmw \quad (3)$$

$$rmw = rmw0 + bmrw + mrmw + bmrmw \quad (4)$$

where:$bmw0$, $rmw0$, $mmw0$ represent subflows BMW, RMW, MMW which are not included in any other waste flow; $brmw$represents an intersection of BMW and RMW – esp. paper and wood out of MMW;$bmmw$represents an intersection of BMW and MMW – esp. kitchen and garden waste;$mrmw$represents an intersection of MMW and RMW – esp. recyclable wastes in MMW;$bmrmw$denotes the waste paper, which is contained in BMW, RMW and MMW;$rest$ is the remaining part of MSW (bulky waste, hazardous parts, electro waste etc.);bmw denotes a sum of entire BMW including all possible subflows;rmw denotes a sum of entire RMW including all possible subflows;mmw denotes a sum of entire MMW including all possible subflows;mswa sum of the overall MSW.

Besides these equations, also 40 inequalities ensuring the non-negativity of all waste flowswas added to this set.

Equations arising from technical and legislation demands

The second set of equations follow minimal EU legislation and technical conditions such as the demanded diverse of biowaste from landfills in 2020, set up material recovery rate in the same year and the total expected capacity of necessary waste facilities. Since the legislation limits are set up only for one year within the predicted period, a linear gradual transition to their achieving was expected between 2014 and 2020.

The capacity of waste energyrecovery facilities was estimated by considering all available information on planned facilities under construction in 2014 and facilities in the phase of a pre-constructionpreparation.The probability of finishing construction of each facility was assessed and we took into account the present level of national andEU subsidies. The seven potential projects (A, B, …, G) were assessed to be viable during next decade with capacity: A: 2015 (95 Tg/year), B: 2019 (150 Tg/year), C: 2020 (150 Tg/year), D, E: 2021 (150 Tg/year), E, F: 2021 (100 Tg/year),G: 2023: (192 Tg/year).The total waste energy recovery capacity of them is 937 Tg/year.

Further, we have expected a maximal annual increase 50% of composting plants and biogas stations total capacity.

Equations describing properties of individual waste flows

The third set of equations covers all relations resulting from physico-chemical properties of MSW. Let us assumethat considered MSW subflows can undergo all five types of waste treatment and the overlapping parts between MMW, BMW and RMW changes continuously. This will followsocio-economic changes as the household consumption, range of goods on the market, consumer preferences, packages, etc.

There are equations treating these assumptions by putting relevant subflows equal zero:

- MMW flow will not be materially recovered or composted;
- the subflow of BMW, which is not in MMW or RMW, will not be burned or recovered;
- RMW flow will not be composted in any of its subflows.

Further assumptions are based on the expected development of the MSW composition derived from long-term observations and the composition analysis (Kalina, Hřebíček 2012).

We have introduced with decision makers of the MoE following assumptionsforthe next decade:

- fraction of polluted (and thus unusable) RMW will decrease from present 8% to final 2.6%;
- fraction of materially recovered RMW which is not in MMW or BMW will exceed 85%;
- fraction of materially recovered separately collected paper will reach 98%;
- amount of materially recovered MSW, which is not contained in the flow of RMW will remain constant (ca. 550,000 t/year);
- fraction of landfilled MSW will decrease linearly to zero in 2025;
- fraction of burned wastes in the flows is given by an extrapolation of previous development.

The above assumptions providethe set of 58equations and 42 inequalities of 75 variables.

In the last stage before the computation of NLP problem itself, it was necessary to make the crucial step of the selection of the optimized variable (the set of all solutions is the same, independently on the variable chosen for optimisation, but the unique optimal result is determined by this selection).

In principle any variable could be selected to be minimized or maximized to obtain the best solution respecting all (in)equalities. Nevertheless as the most important due to its environmental impact, the amount of landfilled BMW was chosen as the optimized variable.

ANLPsolve function of Maple 2015 (Maple 2015) was used for finding the solution of the above created nonlinear programming problem.

Results

Results of the models M1 and M2 are listed in Tab.1to enable mutual comparison of both models.The complete set of the graphic results of both models is given in Fig. 2.

Table 1 here

Figure 2 here

Discussion

The pressure to minimize the landfilling of BMW in the model M2 was reflected by a significant increase of other treatment options of this flow compared to the model M1. Especially the composting and anaerobic digestion (AD) increased to a maximal possible value, limited by the capacity of the facilities (in initial years). This showed, that the role of biodegradation of BMW is still underestimated in the Czech Republic, mainly due to economic reasons (very low sales and consumption of compost) and could be expanded by legislation and subsidies support.

The increase of BMW energy recovery is rather surprising, which is due to the combustion of common part of MMW and BMW, i.e. the unsorted rest of household waste as kitchen and green waste and partially textiles.The difference between M1 and M2 is probably caused by inexact expectations on the structure of the waste flows in M1 (there was expected to energy recovery 1,26Tg of MMW in 2024, but only 0,2 Tg of BMW in the same year). This looks as a more realistic result and also highlights the role of waste energy recovery plants in the MSWtreatment in the Czech Republic.

The results of RMW are practically the samefor both models, considering, that main limitations are given by a purity of the separately collected RMW and the willingness of the population to sort the household waste, which are the same for both models M1 and M2. The remaining portion of RMW is going to landfills and to energy recovery plants.It is represented by anunsorted portion of RMW within MMW.

The MMW flow is modelled as the total amount of waste, which becomes a part of MMW at present. This means, that the waste, which will be diverted from MMW flow in future, is presented in the overall result for MMW. It allows to see how a big part of MMW could be materially recovered/composted when the municipal sorting will improve.

The significant difference between the M1 and M2 model waste flows of MMW consist of the higher portion of composting, as is observable in the flow of BMW (intersection of BMW and MMW is rather high changing from 46% to 65% of MMW between 2015 and 2024). This is observable also for the overall flow of MSW.

Conclusion

The method of nonlinear programming (NLP) was used for modelling MSW treatment forecasting in the Czech Republic. It was implemented inthe form of waste flows optimization model M2 consisting of a set of 100(in)equalities. The model M2 was based on the same set of input data and assumptions on MSW future developmentas thepast developed model M1, which predictedMSWgeneration and treatment for purposes of the MoE. The model M1 was also adopted as the part of national Waste Management Plan in 2014. The both models give comparable resultsin the same period of ten years (2015–2024).

Although the results of models M1 and M2 are similar, the pressure on the minimization of the landfilled BMW amount in the model M2 leads to the significant increase in biodegradation technologies (i.e. composting and anaerobic digestion). A side effect of expected end of MSW landfilling is 2025 in the

Czech Republicwith a significant increase of MMW (this is same for both M1 and M2) induces also a massive growth of energy recovered BMW(only in M2).

The material recovery is practically the same for both models, which highlights an importance of energy recovery (i.e. building new waste energy recovery plants to multiply the present capacity several times) and also a persistent undervaluation of composting plants and biogas stations in the Czech Republic. The model M2 shows, that EU subsidiesandlegislative support is sufficient to build the new waste energy recovery plants of annual capacity 937 Tg and 50% annual increase of a composted/digested BMW could lead to the practical termination of BMW landfilling in 2022, i.e. three years before set up deadline.

References

Beigl, P., Lebersorger, S., &Salhofer, S.(2008) Modelling municipal solid waste generation: A review.*Waste Management*, 28, 200-214

Cherian, J., &Jacob, J. (2012) Management Models of Municipal Solid Waste: A Review Focusing on Socio Economic Factors. *International Journal of Economics and Finance*, 4, 131-139

Costi, P., Minciardi, R., Robba, M., Rovatti, M., &Sacile, R. (2004) An environmentally sustainable decision model for urban solid waste management. *Waste Management*, 24, 277-295

Czech Statistical Office (2014) Expected total population up to 2101. From: https://www.czso.cz/csu/czso/expected_total_population_up_to_2101 (May 31, 2015)

Hejč, M., &Hřebíček, J., Primary Environmental Data Quality Model: Proposal of a Prototype of Model Concept. In: Sànchez-Marrè, M.,Béjar, J., Comas, J., Rizzoli, A.E., &Guariso, G. (Eds.) Proceedings of the iEMSs Fourth Biennial Meeting: International Congress on Environmental Modelling and Software (iEMSs 2008), Barcelona,7-10July, pp. 83-90.iEMSS, Barcelona, Catalania

Hřebíček, J., Kalina, J., &Piliar, F. (2012).Measurement of performance of municipal waste management system in the Czech Republic. In:Špalková, D., &Furová, L. (Eds.) Proceedings of Modern and Current Trends in the Public Sector Research,Šlapanice,19 – 20 January,pp. 41-51.Masarykovauniverzita,Brno

Hřebíček, J., Kalina, J., &Soukopová, J.(2013) Vypracováníprognózyprodukcekomunálníchodpadů a prognózynakládání s nimi v Českérepublice v období 2014 – 2024.Část1.,Část 2.(Developing forecasts of waste production and waste treatment in the Czech Republic in the period 2014-2024.Part1., Part 2). Masaryk University, Brno

Kalina, J., &Hřebíček, J. (2012) Porovnáníanalýzskladby SKO v Brně s dalšímilokalitami v ČR, SR a Polsku.(Comparison analysis of the composition of the mixed municipal waste in Brno with other sites in the Czech Republic, Slovakia and Poland).In:Procházka,T. (Ed.)Symposium Odpadovéfórum 2012,KoutynadDesnou, 25 -27 April, pp. 54-63. CEMC, Praha

Kalina, J., Hřebíček, J., &Bulková, G.(2014) Case study: Prognostic model of Czech municipal waste production and treatment. In: Ames, D.P., Quinn, N.W.T., &Rizzoli, A.E. Proceedings of the 7th International Congress on Environmental Modelling and Software,San Diego, 15-19 June, pp. 932-939.iEMSS,San Diego

Maple 2015 (2015) What's New in Maple 2015. From:http://www.maplesoft.com/products/maple/new_features/(May 31, 2015)

Maple (2015) The Optimization Package. From: http://www.maplesoft.com/support/help/Maple/view.aspx?path=examples/Optimization (May 31, 2015)

Pires, A., Martinho, G., &Chang, N. (2011) Solid waste management in European countries: A review of system analysis techniques. *Journal of Environmental Management*, 92, 1033-1050

Soukopová, J., &Kalina, J. (2012) Mathematical model of economics of municipal waste management. In: Ramík, J. &Stavárek, D. (Eds.) Proceedings of the 30th International Conference Mathematical Methods in Economics,Karviná, 11-13 September, pp. 823–829, Silesian University in Opava, School of Business Administration, Karviná

Vejmělek, J.,Škop,, J. Frayer, M.,Adamkovič, M.,Dřímal, M.,Malíčková, J. (2013)Economic views(Ekonomickévýhledy). In Pomůženízkáinflacespotřebitelům?,Komerčníbanka, Praha

7EAP (2013) Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 “Living well, within the limits of our planet”. From: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:354:0171:01:EN:HTML(May 31, 2015)

Table 1: Results of models M1 and M2 for MSW in total											
Flow\Year		**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Combustion	**M1**	0,01	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
	M2	0,01	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
Composting and AD	**M1**	0,37	0,43	0,49	0,54	0,60	0,65	0,70	0,75	0,80	0,85
	M2	0,76	1,14	1,35	1,38	1,20	1,29	1,16	1,16	1,12	1,23
Material recovery	**M1**	1,91	1,94	1,96	1,99	2,03	2,07	2,12	2,17	2,23	2,31
	M2	2,02	2,05	2,07	2,11	2,16	2,20	2,26	2,31	2,37	2,37
Energy recovery	**M1**	0,68	0,72	0,72	0,72	0,80	0,95	1,15	1,15	1,37	1,47
	M2	0,68	0,72	0,72	0,72	0,80	0,95	1,15	1,25	1,37	1,47
Landfilling	**M1**	2,46	2,32	2,21	2,10	1,91	1,65	1,34	1,12	0,87	0,65
	M2	1,97	1,50	1,23	1,15	1,18	0,88	0,75	0,57	0,41	0,21

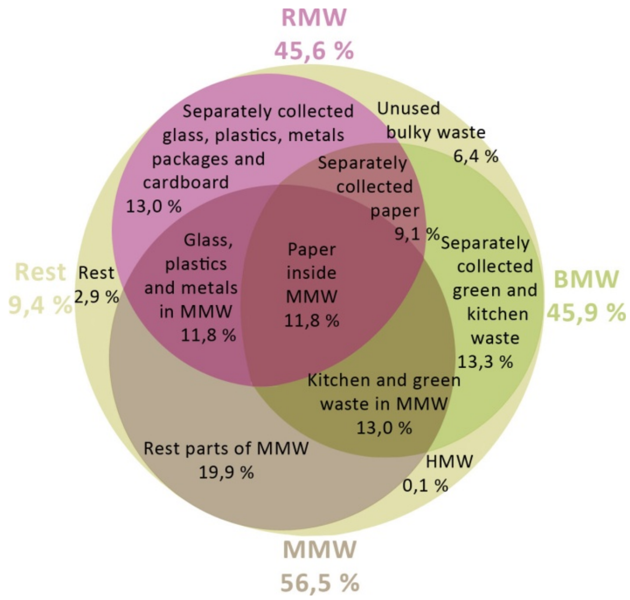
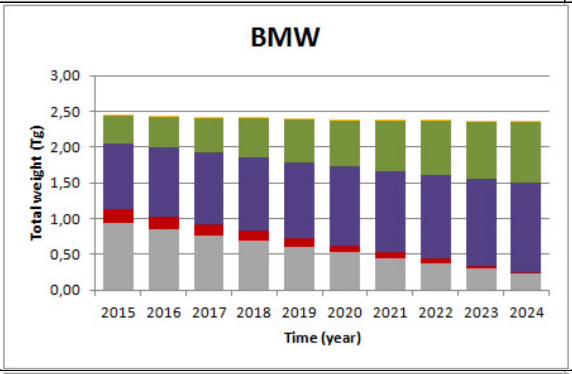
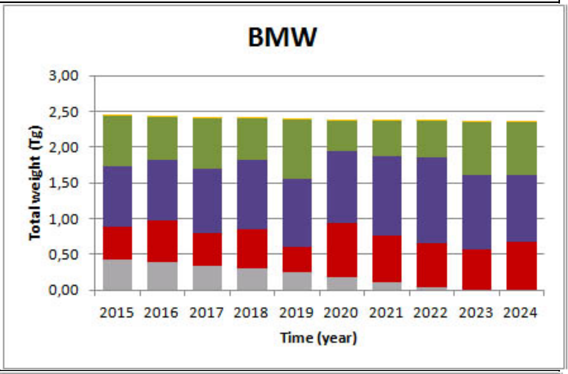
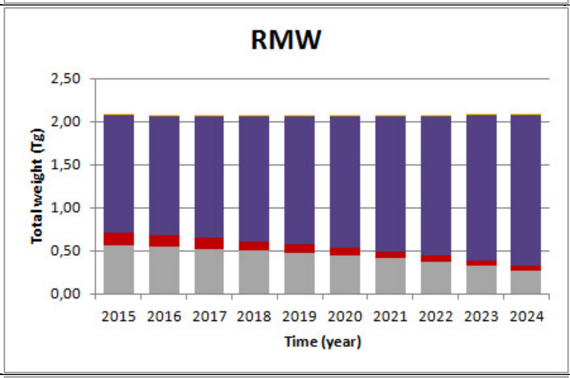
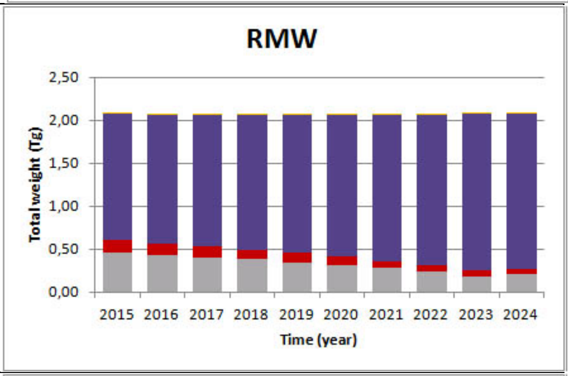
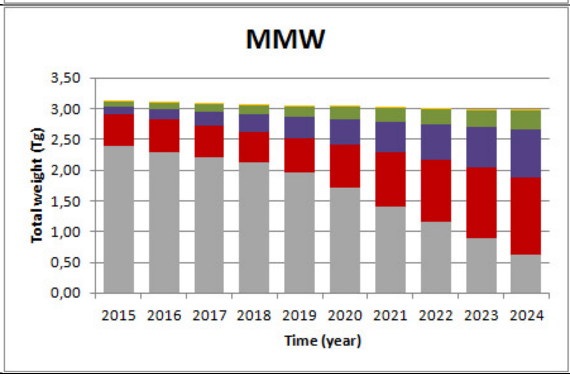
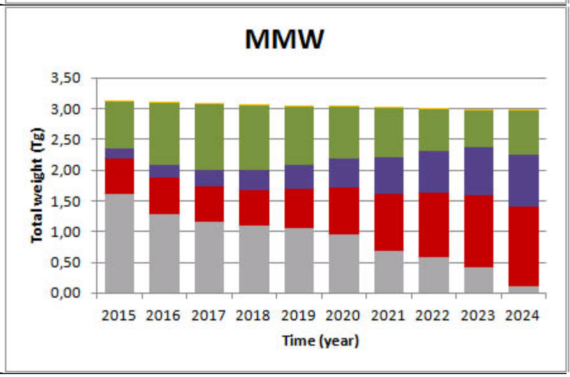


Figure 1.Composition of municipal waste in the Czech Republic in 2012 (Hřebíček, Kalina&Soukopová 2013).

M1 model	M2 model
	
	
	

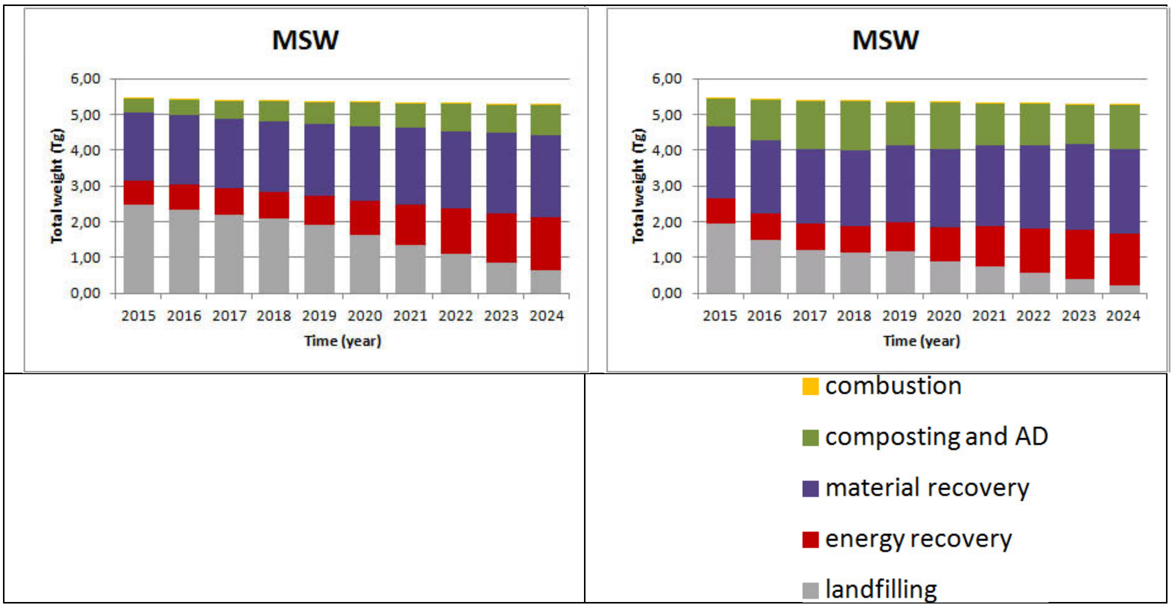


Figure 2. Forecasting principal waste flows treatment 2015–2024.