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Sustainable Model Integration of Waste Production and Treatment Process Based on Assessment of GHG

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The paper presents a new model for supporting strategic decision-making in the area of municipal solid waste management. The effort is to integrate the assessment of greenhouse gas (GHG) to a sustainable economy. The goals are (in the following order) to reduce the waste produced, recycle at the highest rate as possible (material recovery) and to use the resultant residual waste for energy recovery. These features will be implemented through both pricing and advertising-like principles. The resulting mathematical model proposes multi-objective approach considering GHG and cost minimisation. The aim is to design the optimal waste management strategy, where stakeholders decide about the investment to the propagation of waste prevention and to advertising of waste recycling, and investors decide about new facility location and technological parameter. The availability of waste is projected in pricing method as well as the location of the facility. The mathematical model will utilise randomness in the form of waste production. All of the non-linearities (advertising and pricing) in the objective function will be replaced by piecewise linear approximation. The results of the work are applicable to the area of waste treatment infrastructure planning and to support decision-making at the micro-regional level with regard to the GHG impact. The original obtained solution will further be utilised for analyses dealing with all types of combustible waste.

1. Introduction

During the last decade, the amount of solid waste has been growing year-by-year due to rapid urbanisation and increasing population growth (Wu et al., 2014). Therefore, new advanced trends appear in complex waste management systems nowadays. These require better and better waste handling that leads to the integration of new strategies such as waste prevention, integration of waste as raw materials in a circular economy or more effective waste separation and material recovery (Barbosa-Póvoa et al., 2018).

In the European context, waste prevention was promoted as the first priority for all EU member states; however, its actual implementation has often been hesitant (Hutner et al., 2017). The literature review emphasizes that the overall implementation status of waste prevention is low, which is partially due to an apparent lack of guidance for practitioners (Hutner et al., 2017). The EU 2020 strategy provides a guide for a sustainable society in the efficient use of resources since the European economy currently still loses a significant amount of potential secondary raw materials. Turning waste into a resource is one key to a circular economy. The objectives and targets set in European legislation have been key drivers to improve waste management, stimulate innovation in recycling, limit the use of landfills, and create incentives to change consumer behaviour (EC, 2010). Recycling of municipal solid waste (MSW) and subsequent material recovery play a fundamental role in the society (Expózito and Velasco, 2018). However, any modern and environment-friendly waste management system also has some bright sides. In this paper, we try to reflect the following issue: waste-to-energy (WtE) facilities, as well as transportation/collection vehicles, often pose some environmental disutility, such as atmospheric and greenhouse gas (GHG) emissions (Hu et al. 2017).

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This paper presents initial ideas for implementation of a complex waste management system that integrates the various decisions and its effects. It is assumed that the total waste produced can be influenced (reduced) by the so-called waste prevention investment. Two types of waste produced are considered in the paper: recycled and residual (i.e., mixed municipal waste (MMW)). The recycled represents a usable component, which is mainly subsidized by the company's fees for the production of packaging. Residual waste is then a purely economic burden on producers. Low-quality separated fractions have limited use, which is often subjected to high costs. Another decision considered is an investment in recycling; the relation between the investment and recycling is captured via an S-shaped curve and captures several aspects as the promotion of recycling or investments in recycling accessibility (e.g., containers installation). Then, the waste produced is assigned to a transport type and to a WtE facility. The transport type assignment decision means a transport type (road or rail transport) considering that rail transport is preferred for the higher waste amount and for longer distances (due to both costs as well as environmental impacts). Moreover, the cost of waste processed in WtE facility depends on its amount and the non-utilised capacity of the WtE facility is penalised. Only the remaining waste should be landfilled. The landfilling is limited by taxes that motivate to more efficient waste management.
This paper proposes a new multi-objective approach considering all ways of waste treatment (prevention, recycling, energy recovery and landfilling). It also suggests stochastic (scenario-based) modelling regarding waste production. The waste management system is described by a comprehensive approach with a focus on the circular economy. Both the road and rail transport are included. Therefore, the complete model that is a subject of further research will lead to a multi-objective stochastic mixed-integer nonlinear problem.

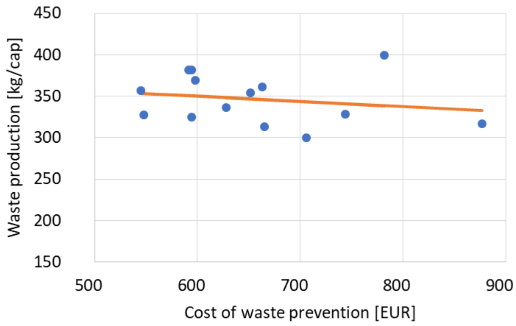
2. Costs and emissions: waste prevention, recycling, transportation and treatment

2.1 Waste prevention

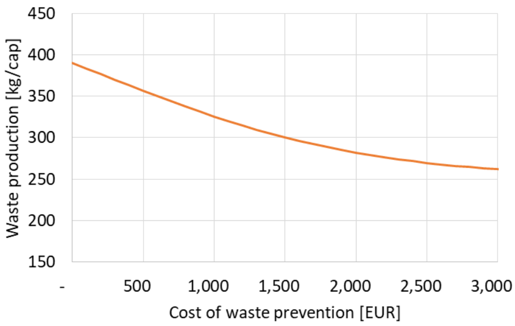
This subsection deals with a mathematical description of the waste prevention cost(s) as a decision variable that influences waste production amount, see (Nevrlý et al., 2016) for waste production identification details. The prevention cost is based on pricing approach, which is very often used in network problems, see (Hrabec et al., 2016). A minimal value for the MSW* (main fractions of MSW – paper, plastics, glass, bio-waste, MMW, bulky waste) production was determined to 250 kg/cap (i.e., when applying a suitable waste prevention strategy). Data available for regions of the Czech Republic show that waste production for the best regions corresponds with this value. Similar situation (i.e., waste production amount) was also observed in Austria (Lebersorger and Beigl, 2011).
The regression model is a logistic function (S-shaped curve) defined with a, b, c regression coefficients as

$$y = \frac{c}{1 + e^{-(a+bx)}} \tag{1}$$

Then, y is the production of MSW* and x represents cost(s) spent on the waste prevention (see Figure 1b for S-shaped function). The model considers that the decision is identical in all the regions; however, it is clear that such decision can lead to worsening for some nodes (see Figure 1a, where some nodes are under the regression function). Therefore, we employ a local constraint that does not allow worse solution than an actual state provides.



a) S-shaped regression: its segment for 14 real waste productions (regions in the Czech Republic)



b) Convex part of the S-shaped function (a wider perspective)

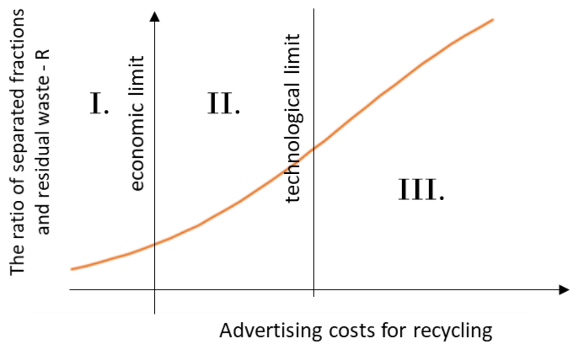
Figure 1: S-shaped function as a dependency between waste prevention cost and waste production amount

2.2 Recycling

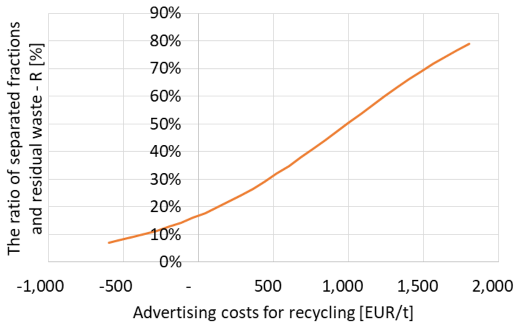
Another important tool for the optimization of the integrated waste management system is recycling. It will be further differentiated between two types of waste produced: recycled MSW and residual MMW. The effort is to recycle at the highest rate as possible. Any actual state of the rate between recycling and non-recycling can be increased by additional investment costs such as locating new containers for recycled waste, raising public awareness of recycling and its environmental advantages, etc. The idea is to describe the dependency between the investment and recycling ratio via an S-shaped curve, that is similar to a general S-shaped function commonly used for an advertising-demand dependency, see Hrabec et al. (2017).
Three following phases are further considered with regards to recycling-advertising dependency:

I. Phase, when it is advantageous to recycle. Such waste constitutes an income (material recovery).
II. Phase, when it is advantageous to support recycling, i.e., it is possible to increase the ratio of separated fractions and residual waste by investments in infrastructure and promotion for a general awareness of recycling benefits to the environment.
III. Phase presents an area of technological constraint for further increases of the recycling ratio, alternatively, it presents a depleted potential of separable components of the MMW.

The three abovementioned phases are illustrated in Figure 2a. Figure 2b shows real data from the Czech Republic that are based on a logistic regression. Around 18 % can potentially be separated without additional necessary costs (advertising of recycling), see Figure 2b, where the natural separation of inhabitants is depicted (this corresponds to collecting yards or paid fractions - mainly paper, metal). For the purposes of the paper, selected components of separated waste (paper, plastic, glass) and residual waste (MMW) are considered. Other components of the separated waste presented a new waste flow in the Czech Republic because no correlation between the reduction of residual waste and increasing of biowaste and metal waste was proven. Other fractions of MSW present negligible portions (e.g., textile, wood, etc.).



a) Three phases of dependency between waste separation investment and waste separation

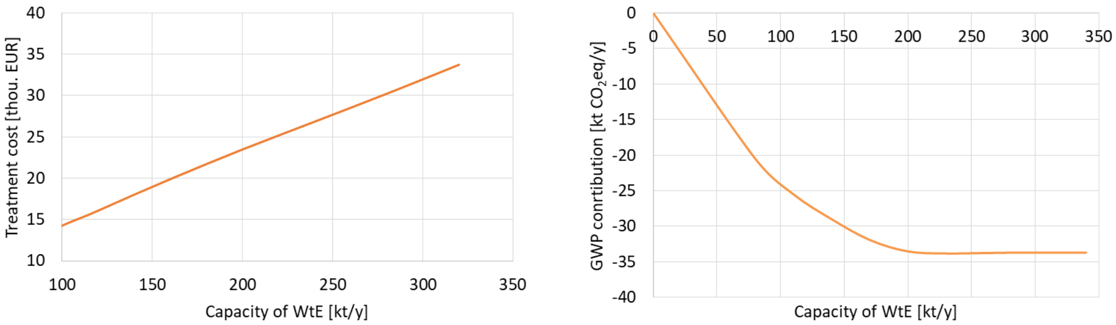


b) S-shaped regression function (based on real data)

Figure 2: S-shaped function as a dependency between recycling awareness increasing (via advertising among others) cost and recycling by itself (ratio of separated fractions and residual waste)

2.3 Transportation and treatment

In the integrated waste management system, both rail and road transportation options are considered. Both options have two crucial attributes influencing objectives or the model: transportation costs (Gregor et al., 2017) and emissions (Ferdan et al., 2017). Regarding both properties, rail transport is further preferred for longer-distance transport of higher-amount of waste. Regarding the waste treatment, similar properties/dependencies are defined: treatment cost as a function of WtE facility capacity (waste amount carried, respectively), constant treatment cost for landfilling and global warming potential (GWP) as a function of the amount of processed waste in the WtE facility. Figure 3a illustrates the so-called gate fee (treatment cost) as a function of WtE facility capacity. The figure illustrates one particular locality. This dependency must be analysed and established separately for each locality, since it depends on heat demand and on attributes of a local heating plant/source, see Putna et al. (2017). Fan et al. (2018) further examined the efficiency of the process and its integration in the plant for cleaner production. Figure 3a shows a locality with the total annual demand ca. 1,700 TJ/y. Similarly, with regards to emissions: it depends on the replacement of fossil fuels (coal, gas). Figure 3b illustrates a particular locality with a current coal heat source. The critical point around capacity 100 kt/y is caused by switching from heat only to combined heat production due to limited heat demand in the summer months. From capacity 200 kt/y WTE plant is not beneficial, since the heat demand is depleted.



a) Gate fee (treatment cost) as a function of WtE facility capacity

b) GWP as a function of the amount of processed waste in the WtE facility

Figure 3: S-shaped function as a dependency between recycling awareness increasing (via advertising among others) cost and recycling by itself (ratio of separated fractions and residual waste)

A change around 90 kt is because all of the energy cannot be used for heat production and the condensing turbine is utilised for greater power generation. See, e.g. Tabata et al. (2017), for an analysis of both economic and environmental impacts of waste management aspects.

3. Modelling approach

This section provides an insight into the modelling approach based on the previously mentioned and defined pricing, advertising and other principles. The goal is to propose a set of criterions upon the final model decides. The formulations are stated in general.

Sets

$i \in I$	nodes in the network
$l \in L$	edges which connect nodes i by railway
$j \in J$	edges which connect nodes i by road
$s \in S$	scenarios represent the amount of waste production

Decision variables

y_l^s	amount of flow on rail edge l in the scenario s
x_j^s	amount of flow on road edge j in the scenario s
$t_i^{WtE;s}$	amount of processed waste in the WtE plant in the node i in the scenario s
t_i^{REC}	amount of recycled waste in the node i
$t_i^{LAND;s}$	amount of landfilled waste in the node i in the scenario s
$\bar{w}_i$	average waste production in the node i
$\omega_i^{WtE;s}$	non-utilised capacity in the WtE plant in the node i and scenario s
δ_l	activation of rail edge l, a binary variable

Parameters

c_i^{LAND}	cost of landfilling in the node i
$c_i^{WtE,PEN}$	cost of loss within energy and heat generation in the node i in WtE plant
c_l^{RAIL}	cost of transportation on edge l
c_j^{ROAD}	cost of transportation on edge j
$c_l^{RAIL,PEN}$	penalization cost for railways
p^s	probability of scenario s
$\lambda_1, \lambda_2, \lambda_3, \lambda_4$	weights of the objective functions

Functions

f	weighted multi-objective function
f_1, f_2, f_3, f_4	objective functions
c_i^{WtE}	cost for processing in the WtE plant in node i

e_i^{WtE} GWP contribution in the WtE plant in the node i
c_i^{REC} cost for recycled waste in the node i
c_i^{WASTE} cost for waste reduction in the node i
e_i^{LAND} GWP contribution for landfilling in the node i
e_j^{ROAD} GWP contribution for road transportation
e_l^{RAIL} GWP contribution for railway transportation

The above-listed notation is used in the following to define and describe properties of designed functions.

$$f_1 = \sum_{i \in I} t_i^{WtE;s} c_i^{WtE}(t_i^{WtE;s}, \omega_i^{WtE;s}) + \sum_{i \in I} \omega_i^{WtE;s} c_i^{WtE,PEN} \quad (2)$$

$$f_2 = \sum_{i \in I} t_i^{REC} c_i^{REC}(t_i^{REC}) + \sum_{i \in I} t_i^{LAND;s} c_i^{LAND} + \sum_{i \in I} c_i^{WASTE}(\overline{w}_i) \quad (3)$$

$$f_3 = \sum_{l \in L} y_l^s c_l^{RAIL} + \sum_{l \in L} \delta_l c_l^{RAIL,PEN} + \sum_{j \in J} x_j^s \, c_j^{ROAD} \quad (4)$$

$$f_4 = \sum_{i \in I} t_i^{WtE;s} e_i^{WtE}(t_i^{WtE;s}) + \sum_{i \in I} t_i^{LAND;s} e_i^{LAND} + \sum_{j \in J} x_j^s e_j^{ROAD} + \sum_{l \in L} y_l^s e_l^{RAIL} \quad (5)$$

$$f = \lambda_1 f_1 + \lambda_2 f_2 + \lambda_3 f_3 + \lambda_4 f_4 \quad (6)$$

The objective function Eq(2) includes the pricing for the determination of the optimal locations and capacities for the WtE plants. It also calculates with the non-utilised capacity, which is penalised. The amount of non-utilised capacity $\omega_i^{WtE;s}$ is penalised due to loss ia n heat and electricity generation (the loss of income). The Eq(3) presents an advertising principles for the recycling and waste prevention. Cost for landfilling is also included and assumed linear. The objective function Eq(4) summarizes total price for transportation, which includes transportation by road and railway while the penalization of railway represents the transfer related and operation cost. In the Eq(5), the emission from WtE plants, landfills and both means of transport are calculated. They are aggregated in the form of GWP. For a detailed description of the methodology, see Ferdan et al. (2015). The Eq(6) is the weighted multi-objective function which includes previous four functions and the $\lambda_1, \lambda_2, \lambda_3$ and λ_4 represent the weights for the final contribution. These weights should be constructed to fulfil the specific requirements or constraints arising from the real applications. To be complete with the model, the usual capacity and balance constraints has to be defined. All of the non-linear expressions can be simplified by linearization and SOS2 variables.
When developing the final model, the stochasticity will also be included in the form of scenarios s. Each of the scenarios has its probability p^s. Among scenarios, the waste production and other parameters may vary. This randomness is used to follow up the real situations and progress in the waste management that can occur.

4. Conclusions

The aim of the work was to introduce an idea of a new integrated waste management system that should combine several decisions that are needed in order to optimize waste management strategy in the context of new EU strategies based on the circular economy scheme. The authors presented mathematical model objectives that lead to a multi-objective approach, where the objectives are, broadly speaking, based on both costs and emissions minimization. The investment to the propagation of waste prevention and to advertising of waste recycling are taken into account, while the investors decide about new facility location and technological parameters.
The main further research relates to the development of the complete mathematical model for such integrated waste management system. Since similar mathematical models often lead to computationally complex tasks, computational tools should be discussed, respectively suggested and tested. For some complex problems, it is appropriate to apply heuristic algorithms as proposed, e.g., in Pluháček et al. (2018). Therefore, a case study on real data will also be a subject of upcoming research work.

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