Pricing and Advertising Strategies in Conceptual Waste Management Planning

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Abstract:

The paper presents a new model for integration of circular economy strategies into the municipal solid waste management. The goals are to reduce the waste produced, recycle at the highest rate as possible (material recovery) and to use the resultant residual waste for energy recovery. Such a strategy utilizes both pricing and advertising principles in the mixed integer linear programming model while accounting two criterions - assessment of greenhouse gas (GHG) and cost minimization. The aim is to design the optimal waste management grid to suggest a sustainable economy with environmental concerns. The government, municipalities and/or authorized packaging company decide about the investments to the propagation of waste prevention and to advertising of waste recycling, while investors decide about new facility location and technological parameter. The availability of waste is projected in pricing method as well as in the location of the facility. The mathematical model will consider randomness in the form of waste production. The suggested non-linear functions of pricing and advertising are replaced by piecewise linear approximation to reduce computational complexity. The proposed multi-objective model is applied in a case study for the Czech Republic in the area of waste treatment infrastructure planning to support decision-making at the micro-regional level. The integration of circular economy principles, considering also the total amount of produced GHG, revealed the existing potential in waste prevention. On the other hand, the increase of recycling is limited, landfills are not supported and the energy recovery is preferred. However, the planning of the complex system relies on the decision-maker.

Keywords

Waste management, pricing, advertising, waste hierarchy, modelling, MIP

Highlights

- Waste treatment hierarchy principles utilized in mathematical modelling.
- Pricing and advertising as the features of waste prevention and recycling.
- Investor point of view for the evaluation of sustainable facility location.
- Greenhouse gases and cost minimization as the decision-making criterions.

1. Introduction

Waste treatment has gained major attention in recent years (Liu et al., 2018). Although material and energy recovery from waste has been steadily growing (Malinauskaite et al., 2017), many countries still resort to landfilling (Lino et al., 2017). Sadly, many countries refuse to deal with the issue of waste treatment altogether (Wang et al., 2018). Some of the most startling examples may be seen in the oceans which are filled with plastics; this plastic then enters the food chain of sea animals (Gutow and Bergmann, 2018). In addition to that, the decrease in the availability of primary sources has become a subject of serious discussion (Hofmann et al., 2018). Several countries have taken steps to amend relevant legislation in order to reduce inefficient waste treatment and consequently also the negative impact of waste on the environment (Gharfalkar et al., 2015). At the same time, there are strong efforts to use a hidden potential of waste as the secondary source of materials and energy (Silva et al., 2017). Circular Economy Package (Directive (EU) 2018/849, 2018/850, 2018/851, 2018/852) may serve as an example of these efforts. This package aims to shift from a linear pattern (raw material, product, waste) to the circular pattern which strives for maximum reuse and minimum amounts of residual flows (Tomić and Schneider, 2018).

Circular economy (CE) provides a powerful approach to combat environmental challenges and promote sustainable development (Korhonen et al., 2018). Some developed European as well as Asian countries have advanced in the development of policies that support the CE in their society (Ormazabal et al., 2018). Waste treatment hierarchy defined in EU (Directive 2008/98/EC) must be observed to comply with the targets of the CE. The waste hierarchy prioritizes prevention to waste production, followed by waste recycling, material and energy recovery and last - waste disposal (Fonseca et al., 2018).

The efficient CE requires the establishment of necessary processing infrastructure. Mathematical modelling may serve as a powerful tool for its start and design. This issue is rather complex and covers all stages of waste hierarchy, siting of processing capacities, the design of transportation infrastructure, including transfer stations and so on. Therefore, sophisticated methods and tools are required. The paper by Barbosa-Póvoa et al. (2018) provides an in-depth research study for planning in supply chain systems, including waste management (WM). Papers discussed in the research study discuss various types of sustainability of the system. Specific decision-making criteria relate to the following aspects.

- **Economic aspects**

Minimization of total costs is a basic and most frequently used indicator of economically oriented calculations of the sustainable supply chain (Tong et al., 2014). Costs seem to be a sufficient indicator, especially if the network is stable and only tactical decisions are made; moreover, costs are the easiest metric value. Net Present Value or Internal Rate of Return are less frequently assessed (Amin and Zhang, 2012), especially when strategic decisions, i.e. new facility establishment, are made.

- **Environmental aspects**

There is a significant difference between indicators in terms of environmental assessment of the system. A lot of attention is paid to emissions of carbon dioxide, by direct evaluation of carbon footprint (Byrne et al., 2010), or by calculation of greenhouse gases (GHGs), see (d'Amore and Bezzo, 2016). Global warming potential (GWP) is an indicator used for comparison of the impact of particular pollutants on the environment changes, see (De Meyer et al., 2015). Climate change is another commonly applied indicator, see (Boukherroub et al., 2015). All of these indicators help evaluate the environmental impact of the systems in relation to global warming. Waste reduction and recycling is another important category of environmental impacts, see (Gilli et al., 2018). The papers and publications mentioned above focus exclusively on one of the indicators; however, this may significantly distort final results. The so-called life cycle assessment (LCA) approach usually incorporates more than one environmental aspect and the method is crucial for transition to a CE, see (Cellura et al., 2012). LCA represents a complex method for environmental impact assessment.

- **Social aspects**

Job creation, safety, health and others are among the most frequently assessed indicators of the social aspects category, see (Bouchery et al., 2012). In addition, the so-called NIMBY (Not-In-My-BackYard) effect becomes evident as mentioned by (Ren et al., 2016). The public perception of modern waste infrastructure is investigated by (Kirkman and Voulvoulis, 2017).

- **Multi-criteria approaches**

There are several decisions that have to be made when operating an integrated system of WM; these include waste collection planning, siting of processing facilities, selection of proper waste treatment technologies, etc (Yadav et al., 2017). A complex approach to the whole system has to consider more than just one aspect discussed above. Hu et al. (2017) examined a bi-objective model for the design of Waste-to-Energy (WtE) plants siting. The authors analyse economic and environmental aspects; total costs and emission production are minimized in the objective function. Multi-objective model is explored by (Asefi and Lim, 2017) for the design of integrated solid WM. The authors strive to minimize waste transport related costs. Suitability of the whole system is further assessed by evaluation of system components which include social and environmental criteria. A model presented in a paper by (Jabbarzadeh et al., 2016) represents another multi-objective method for design of a WM system consisting of customers, transfer stations, landfills and waste collection vehicles. The model incorporates three objective functions: minimization of total costs, minimization of total GHG production, and the total rate of energy consumption.

Many papers usually focus only on particular fractions of municipal solid waste (MSW) and related technologies which are suitable for their processing. Residual MSW (RES) is the main waste flow suitable for processing by the energy recovery infrastructure, see (Fiorentino et al., 2015). Biowaste is another topic that deserves mentioning, see (Neri at al., 2018). Some of the studies aspire for a more complex method and assume MSW as a whole, see (Chen et al., 2019) in China or (Malinauskaite et al., 2017) in certain European countries. These authors consider the separation of utilizable fractions (for material recovery) and subsequent energy recovery of RES. Relatedness of waste prevention, material recovery, energy recovery and waste disposal are only theoretical in these papers; the authors may only focus on small, aggregated areas with little practical applicability. Following sections of this paper presents a new complex method for design of optimization of MSW treatment related to WM hierarchy. Figure 1 displays a scheme of intended borders of the MSW processing system which includes economic and environmental aspects. Since ignoring uncertainties often leads to insufficient results (Yadav et al., 2017), uncertainty in the amount of produced waste is expressed using a scenario-based approach which leads to a stochastic model.

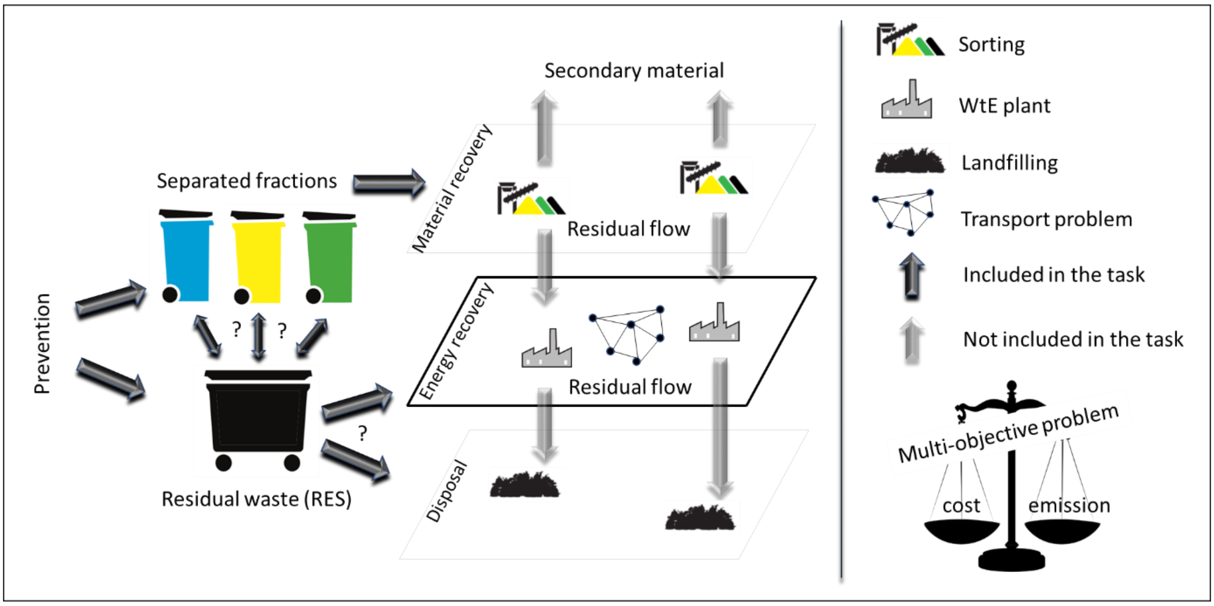


Figure 1: Scheme of the MSW processing system includes economic and environmental criteria

Basic layer analysed in this paper is related to RES and relevant optimization of processing infrastructure. Pricing and advertising methods are used to describe relationships between this RES layer and its surroundings, incl. layers focused on prevention of waste production, material recovery, and waste disposal. Figure 2 shows a complex view of the balance for one node of the network. The method combines economic and environmental criteria, a detailed description is in Section 3. The aim is to design an effective plan for waste transport and subsequent waste processing, provided that the total waste production (reduced thanks to prevention) and recycling rate (material recovery) may be affected by targeted investments.

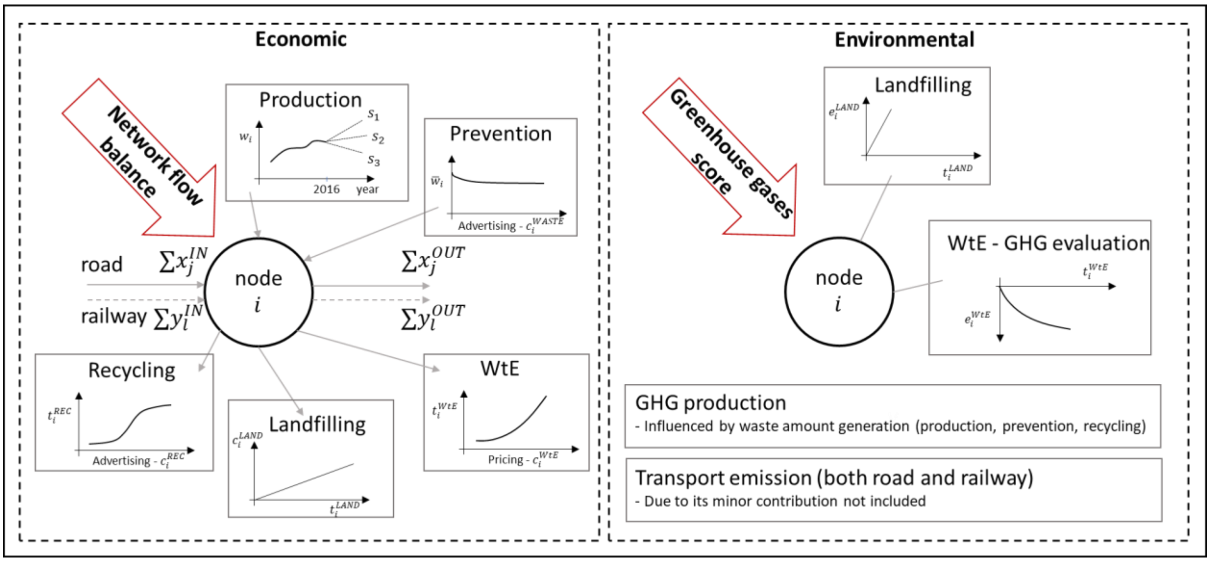


Figure 2: Scheme of the proposed integrated system consisting of an economic and environmental component

Prevention of waste production and recycling is usually taken into account very generally in most of the studies that determine the means for change, i.e. assessment of main factors using regression in (Gilli et al., 2018). However, there is not a quantification of links between economic factors and real data about waste production and its management.

This paper presents functional relationships based on real data about waste production and processing in the Czech Republic in 2015, see Section 2. The introduced dependencies are inputs to the mathematical model (see Section 3) for WM planning, which takes into account both economic and environmental aspects. Next part (Section 4) of the paper presents the case study on waste data from the Czech Republic and the current situation in the year 2015 is analysed. Finally, the paper concludes with Section 5.

2. Description of economic and environmental relationships in the system

The aim is to suggest the optimal waste strategy for waste suitable processing and to find an optimal waste transportation scheme with respect to the total cost and GHG. The proposed procedure assumes the possibility of influencing the waste production and recycling investments in advertising. Economic sustainability of the new projects is a crucial aspect for actually implemented case studies. Functional dependencies from Figure 2 were estimated based on the real data.

Motivation based solely on economic profitability has limited opportunities for more efficient MSW management. Since there is a link to the environment and the quality of life, state intervention is needed to support material and energy recovery. Non-profit organizations and associations can also play an important role in fulfilling the waste management hierarchy (Fonseca et al., 2018).

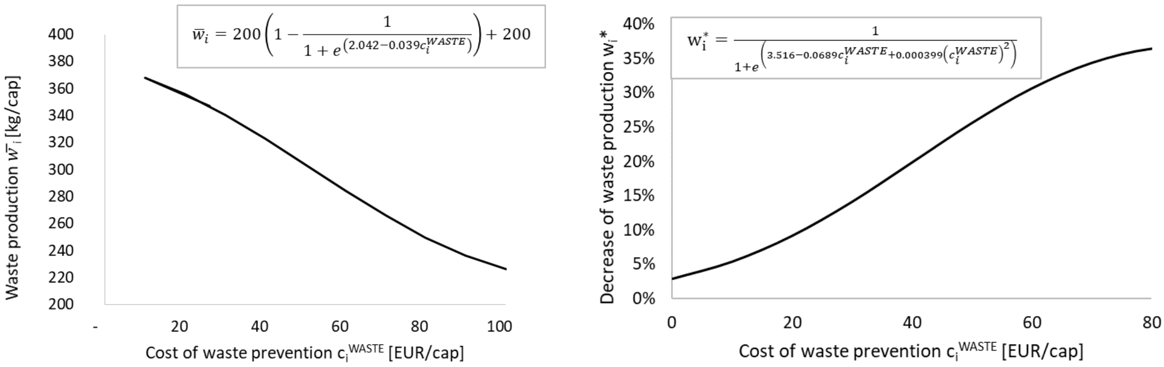
- **Waste prevention**

One of the influencing factors of waste generation is a certain extent by investment to prevent waste production such as education and environmental projects (washable cups for events, etc.), (Corvellec, 2016). Now, there is still a serious potential for improvements in waste prevention, which may be held back by lack of public awareness, willingness and absence of relevant information, see (Zorpas and Lasaridi, 2013). Investments in waste prevention can be approached by pricing-like principles (Hrabec et al., 2016).

S-curves are usually used in waste management for modelling by regression (Ghinea et al., 2016) and forecasting of waste generation (Lu et al., 2016). Waste production is in obvious relation with the waste prevention. Amount of waste production as a dependent variable is described by a regression model in the form of logistic function (S-shaped curve) Eq(1):

$$\overline{w}_i(c_i^{WASTE}) = (w_{max} - w_{min})\left(1 - \frac{1}{1 + e^{-(a+bc_i^{WASTE})}}\right) + w_{min}, \qquad (1)$$

where $\overline{w}_i$ is the estimation of waste production based on the independent variable c_i^{WASTE} which indicates the investment in the waste prevention at node i and a, b are regression parameters. The parameters w_{min} and w_{max} sets the minimum and maximum possible waste generation. Estimate of minimum and maximum MSW* production (MSW* is a sum of particular MSW fractions: paper, plastics, glass, RES) in the Czech regions is set to 200 kg/cap respectively 400 kg/cap, which corresponds to the best and worst regions in applying a prevention strategy. Similar situation was also observed in Austria, see (Lebersorger and Beigl, 2011). Waste processing price has a major impact on the amount of produced waste (MSW*). S-curve (see Eq(1)) was selected due to nature of modelled prevention on the basis of waste management experts. Data from Czech regions in 2015 were used to estimate regression parameters a and b (see supplementary materials and Figure 3a). In general, it is assumed that higher costs spent on public awareness raising are included in total costs (one of the aspects of higher unit costs). Figure 3 illustrates the regression model of the dependence between waste prevention cost and percentage decline of waste production (see supplementary materials). The model stems from dependence illustrated at Figure 3a. It is assumed that if additional costs (additional to current costs) are spent on waste prevention, the final effect will be at least the same as in Figure 3a. The goal of further analysis is to improve the prevention cost definition and calculation. The S-shaped curve in Figure 3b should lead through the point of 0% decrease of waste production in the case of no waste prevention investment. The w_i^* corresponds to MSW* production decrease for a specific node, which is further used in the model. This regression function leads to poor approximation around the point $c_i^{WASTE} = 0$ (see Figure 3b). This inaccuracy will be reduced in a mathematical model using the special order set of type 2 (SOS2) variables, see Section 3. The mean absolute percentage error of function from Figure 3b equals to ca 6.5 % (against ca 9.7 % for linear function).



a) Dependence of the waste production on the waste prevention cost

b) Dependence of waste production decline on the waste prevention cost

Figure 3: Impact of waste prevention investments on waste production

It must be noted, that the data comes from the regional level although the case study is targeted at the micro-regions. Unfortunately, the economic data are available only on a regional level, more detailed data are not accessible concerning business secrets between producer and waste processors. The regression model assumes the same decision in all regions, but some of the nodes lie under the regression model. To prevent the solution from getting worse than the current situation, the local constraint is added to prohibit deterioration of waste production.

- **Recycling**

The preference of the waste processing method is controlled by the hierarchy that is anchored in Directive 2008/98/EC. The most desirable way is to prevent and reuse waste followed by waste recycling, so the waste is shifted from RES to recycled MSW. A number of control mechanisms and investments were identified by authors to increase recycling. They can be divided based on the target side: producer of products side, consumer side and operator side. An illustrative division into qualitative and quantitative groups is based on different points of view of participants in the system.

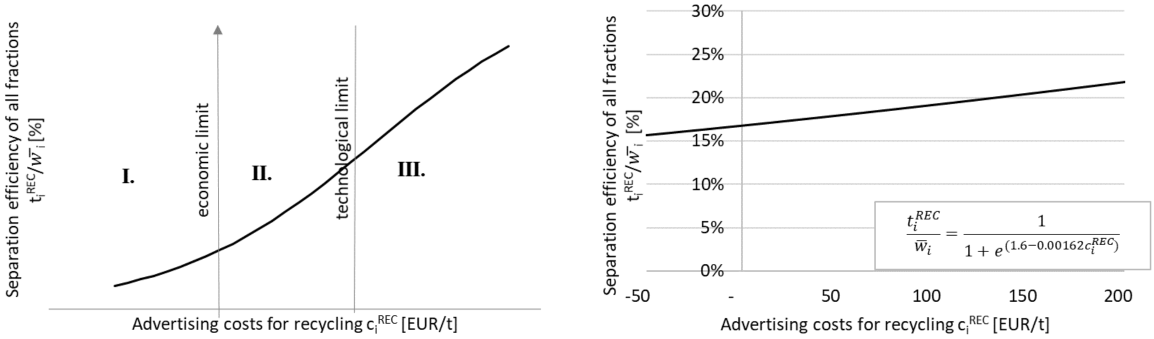
- Quantitative

  - Producer of products – Adequate size packaging with regard to the product; Aggregation of products into a smaller number of packages.
  - Consumer – Denser net of containers.
  - Operator – Separation of larger amounts of fractions.
- Qualitative
  - Producer of products – Eco-design and utilization of recyclable materials.
  - Consumer – Changes in the collection system; Fees related to production: PAYT – pay as you throw (Elia et al., 2015); Separation of larger amounts of fractions.
  - Operator – The technological level of the facility.

The investments are described by advertising cost in this text. The term is generally used in mathematical programming. In the context of recycling, it expresses investment and operating costs associated with a larger number of collection points, the cost of a deposit refund system (e.g. returning PET, cans, glass bottles) and/or the costs of school promotion etc. The advertising efficiency is commonly described by S-shaped function, see (Hrabec et al. 2017). The dependence of the separation efficiency on investment is characterized according to Figure 4a by three phases:

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 RES.

Figure 4b shows the S-shaped regression model of the relationship between recycling ratio and advertising costs based on real data. Curve at Figure 4b models efficiency of separation of consumer's part. Increase in separation depending on investments is very slow, which reflects the need to focus on other participants of the chain.



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

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

Figure 4: Functional relationships associated with the recycling rate in terms of investment in increased recycling

As the separation efficiency increase, the composition of the residual RES changes which is processed in WtE, see (Ferdan et al., 2017). Waste composition, which is treated in the WtE, is at the same time linked with high impact on GHG contribution. As stated by Chen (2018) incinerating plastic MSW emitted the most GHG followed by paper waste, whose GHG production is almost negligible compared to plastic. The waste composition is valuable information in a number of applications and is the subject of research (Baawain et al., 2017), especially with regards to the amount of plastic which leads to the increased contribution of GHG. In the case study, the authors worked with the average waste composition in the Czech Republic where plastics represented 9.32 percent in 2015.

Based on real data in the Czech Republic, about 16.7 % of waste can be separated without additional investment, so-called advertising cost for recycling (see Figure 4b), which corresponds to the current separation efficiency. This value is marked as an economic limit in the scheme in Figure 4a. Figure 4b shows a segment of the S-shaped regression model for 14 regions in the Czech Republic. Only selected components of MSW are considered for the purposes of this paper. The analysis is targeted at sorted paper, plastic, glass and RES; other types of waste represent a completely new flow of produced waste in the Czech Republic. The relationship between the amount of separated biowaste or metal and quantity of RES has not been established. Others waste types, such as textile, wood, etc. constitute only negligible parts of MSW.

- **Treatment**

The treatment cost is determined as dependent on WtE facility capacity, see (Hrabec et al., 2018). In the case of landfills, the processing cost is assumed constant. The treatment cost is based on the so-called gate fee, which is given as a cost per unit of processed waste. In this paper, the annual treatment cost is considered and it has to be assessed for each locality separately due to dependence on the local heat demand and on attributes of WtE facility, see (Putna et al., 2018b). The following figures describe the annual treatment cost depending on the capacity of WtE plant for a particular territory. The area covers ca. 40,000 inhabitants and advanced industrial production with total heat supply of ca. 1,900 TJ/year. Figure 5 illustrates treatment cost as a function of WtE capacity in particular locality. Both the investment and operating costs are included. These costs are different for each (see supplementary material). Construction is expected in the premises of existing heating plants (see supplementary material for potential sites), where it is possible to ensure the sales of heat produced. In addition, some old boilers are expected to be shut down.

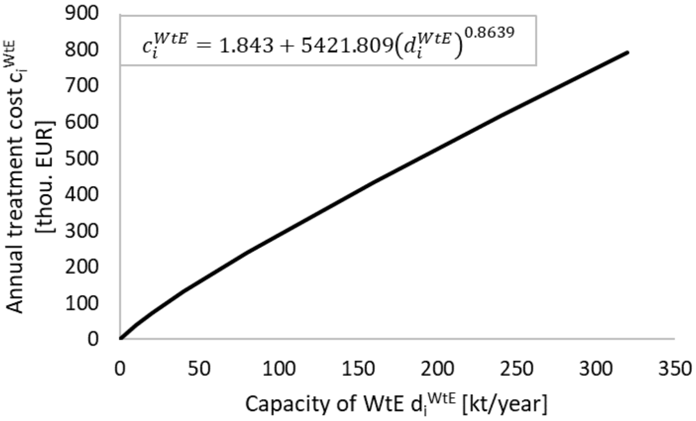
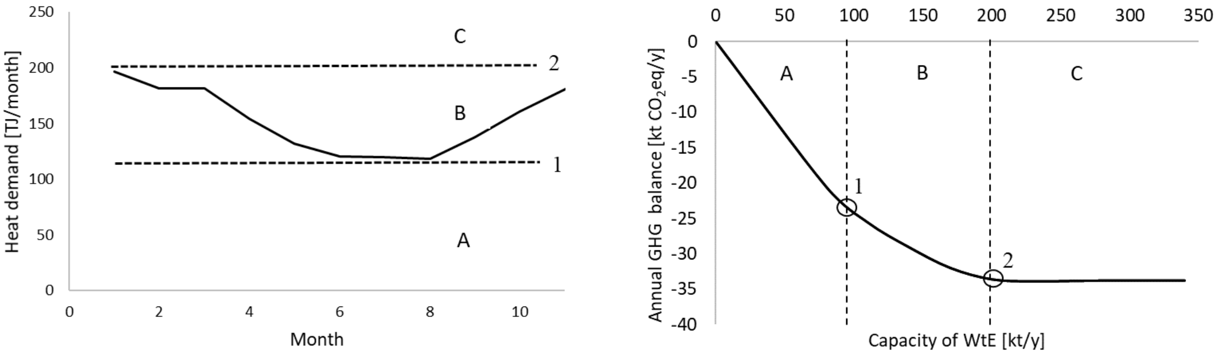


Figure 5: Annual treatment cost as a function of WtE facility capacity

(Fan et al., 2018b) further examined the efficiency of the process and its integration in the plant for cleaner production. In the waste processing as well as in other businesses, there is an emphasis on emissions as GHG. The amount of GHG is given by a function of waste amount processed in the WtE facility. This dependence has a different course for each area because it depends on the heat demand (Putna et al., 2018b) as depicted in Figure 6.

Figure 6a illustrates the heat demand during a year for the same area as in Figure 5 with an obvious decrease in summer months, marked by line 1. The increased heat demand, when covered by WtE, has the positive effect on the GHG contribution, see Figure 6b, which describes the reduction of GHG contribution when replacing fossil fuels (gas, coal) for heating. In addition, several heat supply levels from WtE are displayed by horizontal lines in Figure 6a. Two break points 1 and 2 are highlighted and indicate three parts of graph A, B and C. In part A, the all heat produced in the WtE is absorbed. WtE covers the base, whereas peaks are supplied by additional heat sources. In some months, the demand is lower than WtE maximum capacity. As a result, some heat cannot be utilized. In part C, the heat demand is completely covered by WtE. Since that point, heat delivery reached its maximum. Annual GHG production does not change with increased WtE capacity considering power production is GHG neutral, see (Ferdan et al., 2018). The electricity production does not change and balance is approximately zero. So higher WtE capacity is not beneficial from GHG point of view.



a) Heat demand during a year

b) Annual GHG balance as a function of the amount of processed waste in the WtE facility

Figure 6: Functional dependence between the capacity of WtE and GHG contribution with respect to heat demand

The most significant cost and environmental impact come from MSW processing. The preferred form of energy use is considered in the model, but the model also includes the possibility of landfilling. This cost was set to 160 EUR/t. It includes processing costs itself (about 30 EUR/t) and landfill tax, which is the main motivator for better ways to use RES, see (European Commission (DG ENV). 2012).

In the case of WtE facility, it is necessary to determine the gate-fee with regard to the disposition of the site. This is mainly about demand and the price of heat (Putna et al, 2018a). The link between WtE capacity and gate-fee is described by function separately for each locality. GHG contribution is evaluated in terms of GWP, based on specific attributes of each WtE plant. Therefore, it is assessed for each territorial area apart.

- **Transportation**

Waste transport is planned using both roads and railways, while rail transport is preferred for the transportation of large quantities of waste over long distances. The economic aspect of these modes of transport is taken into account by the transportation costs (Gregor et al., 2017). Traffic emissions are neglected in the model due to its minor production compared to a processing facility. A respective air emission analysis has been proposed by (Fan et al., 2018a).

For the road transport, a constant price is considered 0.16 EUR/km.t. In view of the disposition of the regional calculation, the effect of the distance and the quantity transported on the unit price is minimal (Gregor et al., 2017). In the case of rail transport, the distance plays a key role in unit prices. The following equation was used to describe the price:

$$c_l^{RAIL} = 0.005 + 6.26h^{-1}, \tag{2}$$

where parameter h represents the distance in km and c_l^{RAIL} defines the unit cost in EUR/t. The relationships are set according to information from company ČD Cargo, a.s. The unit cost decreases with distance, which is due to the lower weight of the total cost for cargo handling. Furthermore, it is possible to optimize the use of the rail more effectively, making transport more efficient and reducing unit prices. Compared to disposal methods, transport also plays a minor role in terms of GHG production for WM strategy planning (Ferdan et al., 2017). The reason is that GHGs from transport are the same for every kind of waste processing.

3. Modelling approach

In this section, a mathematical model for transport planning and WM is introduced. The previously mentioned contexts are taken into account due to both economic and environmental impacts. Therefore, the objective of the model is to create appropriate waste transport and management plan with minimal cost and emission production.

3.1 Notation used

The following notation is used in the model to formulate the general scheme as was described before. The main goal of the model is to identify decision variables and SOS2 variables. SOS2 variables corresponds to the established capacity of WtE plant, investments for recycling and investments for prevention of waste generation. Other decision variables mostly define the waste flows on edges and the amount of waste processed in a certain way.

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 representing the amount of waste production
$k \in K$	points for linearization – for each k the value on axis x and axis y is defined

Decision variables

f	weighted multi-objective function
f_1, f_2, f_3, f_4	individual parts of objective function
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
w_i^s	waste production in the node i in the scenario s
d_i^{WtE}	planned capacity of WtE plant in the node i
$\overline{w}_i$	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

M	big constant
$a_{i,j}$	incidence matrix for road transportation
$b_{i,l}$	incidence matrix for rail transportation
c_i^{LAND}	cost of landfilling in the node i

$c_i^{WtE,PEN}$	cost of loss within electricity 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
d_i^{LAND}	existing capacity of landfill in the node i
A_l	minimal amount of waste transported through rail edge l
ϵ_i^s	random value generated for scenario s in the node i
p^s	probability of scenario s
λ	weight of the objective functions
w_i^C	current production in the reference year in the node i
$f_{i,k}^{WtE}$	potential capacities of each linearization point k for WtE plant in node i
$f_{i,k}^{REC}$	possible advertising investments k for recycling in node i
$f_{i,k}^{WASTE}$	possible advertising investments k for waste production reduction in node i
$c_{i,k}^{WtE}$	cost for processing in the WtE plant in node i
$c_{i,k}^{REC}$	cost for recycled waste in the node i,b
$c_{i,k}^{WASTE}$	cost for waste reduction in the node i
$e_{i,k}^{WtE}$	GHG contribution in the WtE plant in the node i
e_i^{LAND}	GHG contribution for landfilling in the node i

SOS2 variables

$\alpha_{i.k}^{WtE}$	the variable of special order set 2 type; indicates the activation of specific capacity k of WtE for all nodes i
$\alpha_{i,k}^{REC}$	the variable of special order set 2 type; indicates the use of specific advertising investment k for recycling in all nodes i

$\alpha_{i,k}^{WASTE}$ the variable of special order set 2 type; indicates the use of specific advertising investment for prevention of waste production k in all nodes i

3.2 Model formulation

On the basis of the above notation, a model consists of multi-objective function Eq(3) – Eq(7) and set of constraints Eq(8) – Eq(17).

Objective function

The mathematical model is built as a multi-objective optimization problem. It involves objective functions, listed below, which minimize total cost Eq(3) – Eq(5) and GHG contribution Eq(6) which are weighted in the objective function Eq(7).

Each functional relationship described in the Section 2 given by non-linear expression disrupt the model linearity and hence solvability. All of these non-linear functions are substituted by piecewise linear function using SOS2 variables to restore the linear property of the model in the way as was described in (Hrabec et al., 2018).

The linearization mentioned uses the so-called SOS2 variables, which ensures that at most two adjacent in the ordering given to the set can be non-zero and they must add up to 1.

$$f_1 = \sum_{i \in I} \sum_{k \in K} \alpha_{i.k}^{WtE} c_{i,k}^{WtE} + \sum_{i \in I} \omega_i^{WtE;s} c_i^{WtE,PEN} \tag{3}$$

$$f_2 = \sum_{l \in L} y_l^s c_l^{RAIL} + \sum_{l \in L} \delta_l c_l^{RAIL,PEN} + \sum_{j \in J} x_j^s \, c_j^{ROAD} \tag{4}$$

$$f_3 = \sum_{i \in I} \sum_{k \in K} \alpha_{i,k}^{REC} c_{i,k}^{REC} + \sum_{i \in I} \sum_{k \in K} \alpha_{i,k}^{WASTE} c_{i,k}^{WASTE} + \sum_{i \in I} t_i^{LAND;s} c_i^{LAND} \tag{5}$$

$$f_4 = \sum_{i \in I} \sum_{k \in K} \alpha_{i,k}^{WtE} e_{i,k}^{WtE} + \sum_{i \in I} t_i^{LAND;s} e_i^{LAND} \tag{6}$$

$$f = \sum_{s \in S} p_s \left[\lambda(\mathrm{f}_1 + f_2 + f_3) + (1 - \lambda) f_4\right] \tag{7}$$

The Eq(3) is an objective function for presents the processing cost in WtE plants, where the first summation is the linearized price. In the case of unused capacity $\omega_i^{WtE;s}$, the penalty is paid as a loss in electricity and heat generation, the amount is a result of balance according to Figure 2. Within the minimization of the cost, the optimal location and capacities of WtE plants are suggested. The Eq(4) includes the transportation cost for both types of transport considered (road and rail). The operation fees for the use of railways $c_l^{RAIL,PEN}$ are also taken into account. The objective function Eq(5) summarizes the advertising investments for recycling and waste prevention. The relations for these investments (introduced in Section 2) were linearized again using SOS2 variables. The last summation in this objective function f_3 includes the cost for landfilling. The Eq(6) deals with emissions, so it includes GHG contribution from WtE plants and landfilling, while the replacing of fossil fuels is considered. The methodology is described in more detail in (Ferdan et al., 2018). The last part, Eq(7) is the weighted multi-objective function which connects all mentioned objective functions Eq(3) – Eq(6). Depending on the value of the weight λ, the objective function moves its focus between the costs (corresponding to higher values of λ) and emissions (lower values of λ).

The waste production is modelled in the form of scenarios s with the probability p^s. In this way, the stochasticity is included in the model so the parameters and variables can acquire different values for individual scenarios.

Constraints

$$w_i^s + \sum_{j \in J} a_{i,j} x_j^s + \sum_{l \in L} b_{i,l} y_l^s = t_i^{WtE;s} + t_i^{REC} + t_i^{LAND;s} \qquad \forall i \in I, \tag{8}$$

$$\delta_l A_l \leq y_l^s \leq \delta_l M \qquad \forall j \in J, \qquad (9)$$

$$w_i^s = \bar{w}_i \epsilon_i^s \qquad \forall i \in I, \qquad (10)$$

$$\bar{w}_i \leq w_i^C \qquad \forall i \in I, \qquad (11)$$

$$t_i^{WtE;s} + \omega_i^{WtE;s} = d_i^{WtE} \qquad \forall i \in I \qquad (12)$$

$$t_i^{LAND;s} \leq d_i^{LAND} \qquad \forall i \in I, \qquad (13)$$

$$y_l^s \geq 0 \qquad \forall l \in L, \qquad (14)$$

$$x_j^s \geq 0 \qquad \forall j \in J, \qquad (15)$$

$$t_i^{WtE;s}, t_i^{REC}, t_i^{LAND;s}, \bar{w}_i, w_i^s, \omega_i^{WtE;s} \geq 0 \qquad \forall i \in I, \qquad (16)$$

$$\delta_l \in \{0,1\} \qquad \forall l \in L. \qquad (17)$$

The first constraint Eq(8) defines the total balance of each node. The amount of waste that is transported to the node i and produced in the node i has to be equal to amount transported from the node i and processed there in some way (WtE, REC, LAND). The summations $\sum_{j \in J} a_{i,j} x_j^s$ and $\sum_{l \in L} b_{i,l} y_l^s$ define flows to the node and also from the node through incidence matrix $a_{i,j}$ and $b_{i,l}$. The inequality Eq(9) gives the minimum waste transport by rail in order to reduce the density of road transport. The Eq(10) defines waste production w_i^s, which is given by average waste production $\bar{w}_i$ and random value generated for each scenario ε_i^s. The waste production is determined on the basis of an average value $\bar{w}_i$ (its change by investing to the waste prevention is further decribed) and it is randomized for each scenario s by ϵ_i^s. Eq(11) forbids the increase of waste production beside the current production w_i^c (for the explanation, see Section 2). In Eq(12), the planned capacity of the facility is set and divided into utilised and not used according to individual scenarios. The Eq(13) indicates the maximum amount of landfilled waste which is limited by the capacity d_i^{LAND}. All flows have to be non-negative both for the road Eq(14) and for the rail Eq(15). The amount of processed waste, production, average production, and non-utilised capacity have to be non-negative as stated in Eq(16). Activation of rail edge l is performed by binary variable δ_l Eq(17).

Additional constraints for SOS2

The constraints listed below are added due to the linearization of the non-linear expressions from Section 2.

$$d_i^{WtE} = \sum_{k \in K} \alpha_{i,k}^{WtE} f_{i,k}^{WtE} \qquad \forall i \in I, \tag{18}$$

$$t_i^{REC} = \sum_{k \in K} \alpha_{i,k}^{REC} f_{i,k}^{REC} \qquad \forall i \in I, \tag{19}$$

$$\overline{w}_i = \sum_{\mathrm{k} \in \mathrm{K}} \alpha_{i,k}^{WASTE} f_{i,k}^{WASTE} \qquad \forall i \in I, \tag{20}$$

$$\sum_{\mathrm{k} \in \mathrm{K}} \alpha_{i,k}^{WtE} = 1, \sum_{k \in K} \alpha_{i,k}^{REC} = 1, \sum_{\mathrm{k} \in \mathrm{K}} \alpha_{i,k}^{WASTE} = 1 \qquad \forall i \in I. \tag{21}$$

Eq(18) gives the WtE plant capacity d_i^{WtE} based on SOS2 variable $\alpha_{i,k}^{WtE}$ in order to linearize the cost function. In the same way, Eq(19) and Eq(20) deal with linearization of functions which describe advertising for recycling and investments for waste reduction. Eq(21) indicate conditions for SOS2 variables.

4. Case study

The introduced approach given by Eq(3) – Eq(21) is applied to the data from 2015 in the Czech Republic. The analysed area includes 206 nodes with existing WtE plants in 4 of them, with a combined capacity of 741 kt. In the rest of nodes, the model allows the construction of new facilities. The input data is shown in Figure 7, including the 1,898 road edges connecting the individual nodes. The considered railway network consisted of 2,966 possible edges (these are not included in Figure 7 as it would make it rather hard to read). There are 48 possible places for new WtE plants in 32 different nodes (in some of the nodes, it is possible to build more WtE plants). The details regarding the input data are provided in the supplementary materials.

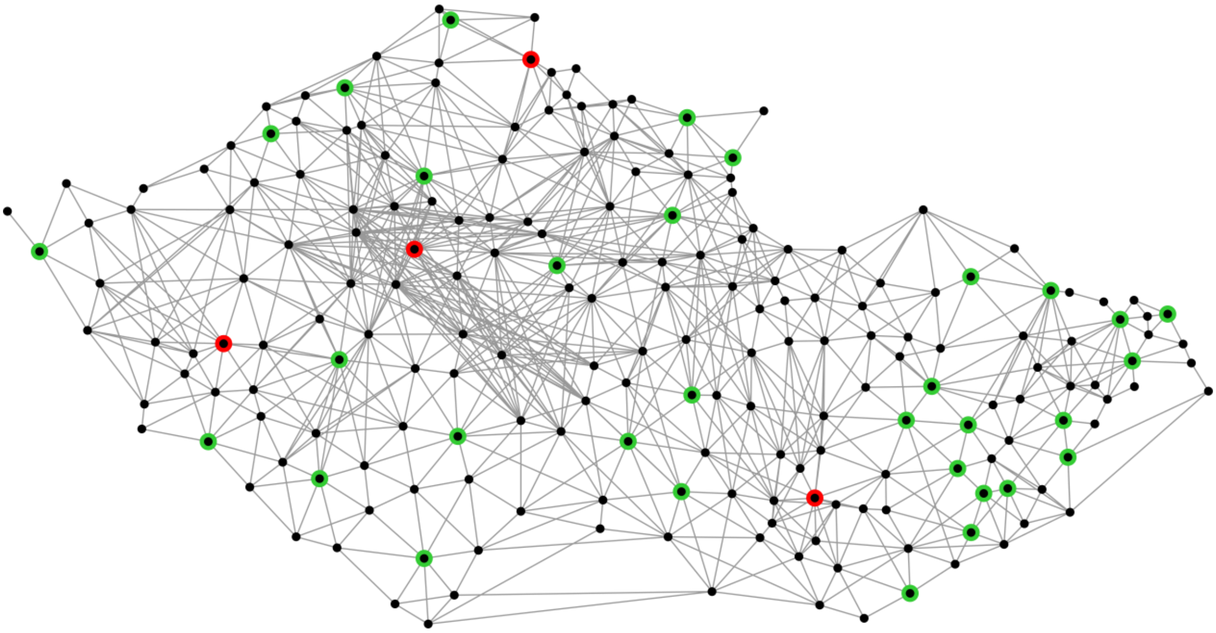


Figure 7: Problem layout. Nodes are denoted as black dots, existing WtE plants as red rings, possible places for new WtE plants as green rings. Road network (incidence matrix $\boldsymbol{a}_{i,j}$*) is marked by grey lines.*

The model considered 500 different waste production scenarios to adequately capture the uncertainty involved. The uncertain values ϵ_i^s are drawn from a uniform distribution on the interval [0.9,1.1]. The probability of a scenario is the same for all scenarios $p^s = \frac{1}{|S|}$. The problem was solved for varying values of λ (cf. the numerical results) to identify the trade-off between the overall optimal costs and the amount of produced GHG emissions. The algorithm that was used to solve the problem was the Benders decomposition scheme, thoroughly reviewed in (Rahmaniani et al., 2017), utilizing the warm-start cuts developed in (Kůdela and Popela, 2017). The optimization model and the decomposition algorithm were programmed in the high-performance dynamic language JULIA (Bezanson et al., 2017) with the JuMP package for mathematical optimization (Dunning et al., 2017), that is well suited for large-scale scientific computing. The solver CPLEX 12.6.3 (CPLEX, 2019) was used to compute the consecutive mixed-integer problems (in the Benders decomposition scheme). The optimality gap was set to 1.5% and the computations took around 8 hours to complete (for each value of λ) on an ordinary machine (3.2 GHz i5-4460 CPU, 16 GB RAM). The resulting optimal decisions were subsequently tested on a separate set of 10,000 different scenarios and the average costs, the amount of produced emissions are reported in Table 1, whereas the average amount of waste prevented, recycled, treated and landfilled are reported in Table 2 (the reference average waste production is a constant value 2,661 kt). The tests took around 1.5 hours to compute (for each value of λ).

Table 1: The numerical results for different values of **λ** *– decisions and costs.*

λ	Cost [MEUR]	Emissions [Mt]	# of rail connections	Transport by rail [%]	Additional recycling costs [MEUR]	Additional prevention costs [MEUR]	Installed new WtE capacity [kt]	# of new WtE plants
0	801.262	134.400	2,966	42.27	16.084	31.614	1,280	4
0.001	209.340	134.401	31	22.41	0	29.722	1,280	4
0.25	202.078	134.487	16	19.76	0	23.231	1,280	4
0.375	197.089	135.097	37	27.15	0	19.086	1,280	4
0.5	193.796	137.419	47	29.76	0	15.128	1,280	4
0.625	181.931	153.050	49	29.49	0	0.033	1,320	5
0.75	160.303	204.275	46	29.99	0	0.033	1,320	7
0.875	148.850	255.371	28	19.00	0	0.033	1,320	9
1	146.445	307.757	26	15.86	0	0.054	1,326	15

Table 2: The numerical results for different values of **λ** *– waste disposal.*

λ	Prevention [kt]	Prevention [%]	Recycling [kt]	Recycling [%]	Energy recovery [kt]	Energy recovery [%]	Landfilling [kt]	Landfilling [%]
0	89.98	3.38	604.57	22.72	1,966.61	73.90	<0.01	<0.01
0.001	87.55	3.29	602.57	22.64	1,971.03	74.07	<0.01	<0.01
0.25	71.59	2.69	602.57	22.64	1,986.99	74.66	<0.01	<0.01
0.375	60.69	2.28	602.57	22.64	1,997.19	75.05	0.72	0.03
0.5	49.45	1.86	602.57	22.64	2,006.38	75.39	2.78	0.10
0.625	5.68	0.21	602.57	22.64	2,048.79	76.99	4.14	0.16

0.75	5.68	0.21	602.57	22.64	2,048.79	76.99	4.14	0.16
0.875	5.68	0.21	602.57	22.64	2,048.79	76.99	4.14	0.16
1	5.81	0.22	602.57	22.64	2,050.47	77.05	2.32	0.09

The results of the computations are summarized in Table 1 and 2. Although the optimal decisions depend quite profoundly on the chosen value of λ, they have one thing in common – in all the cases (and all the considered scenarios) the amount of installed WtE capacity is robust enough to process nearly all of the generated waste and less than 0.2% of the waste is being landfilled. It means that the decision to build and use the WtE plants is both economic and ecological (in terms considered in this paper). The two extreme cases for the value of the weight λ correspond to the two opposite solutions. For $\lambda = 0$ the model emphasizes the amount of produced emissions over everything else, resulting in rather disastrous transporting decisions and enormous costs. On the other hand, the model with $\lambda = 1$ completely disregards the production of emissions and advises to build a comparatively large number of smaller WtE plants. These two, in fact, single-objective, solutions are useful as reference points rather than grounds for actual decision support, as the main strength of the model comes from the possible trade-off between these two extremes. Small capacities of WtE have economic advantages due to easier slag waste management, flue gas cleaning etc.

As depicted in Figure 8, even very small deviations from the boundary values of λ yield solutions that are much better in one of the objectives while being only marginally worse in the other objective. These trade-off decisions retain some of the qualities of the extreme ones – i.e. the decision to build a small number of high-capacity WtE plants and increased spending in prevention for the lower values of λ. The solution for $\lambda = 0$ is not depicted in Figure 8, since it would distort the overall insight – compared to all other solutions, it has extremely high cost with very marginal improvement in the amount of produced emissions.

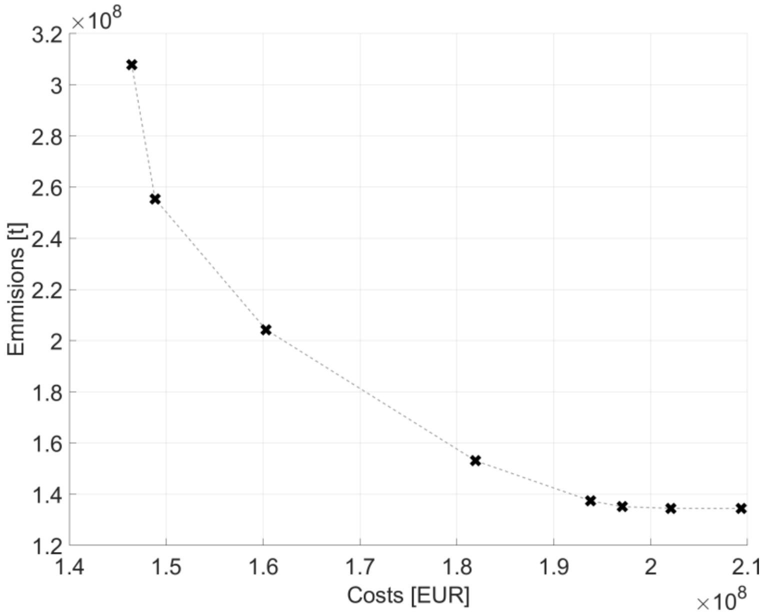
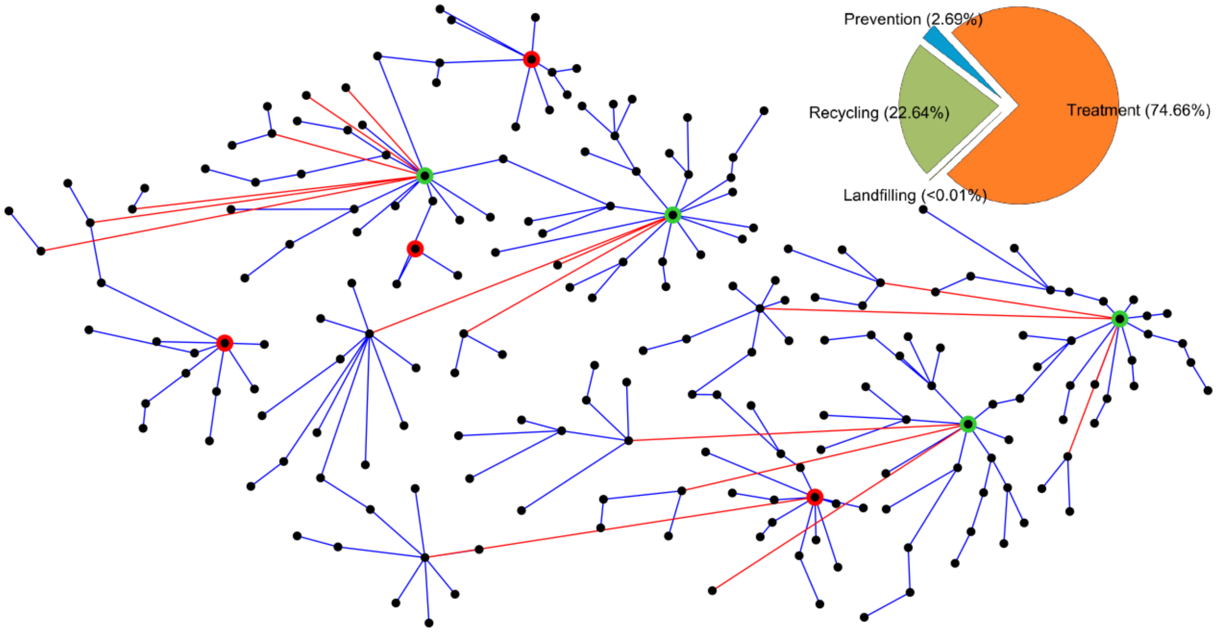


Figure 8: The Pareto frontier describing the trade-off between the optimal costs and the amount of produced emissions. The dashed line has only a visual purpose.

The considered railway transport is utilized in all the solutions. Because of the relationship for the computation of the railway transport costs Eq(2) the model seems to prefer longer and medium-sized journeys to be conducted by the trains, whereas the shorter ones are left for the road transport. This can be seen in Figure ***9*** and Figure 10. What can also be seen (especially in



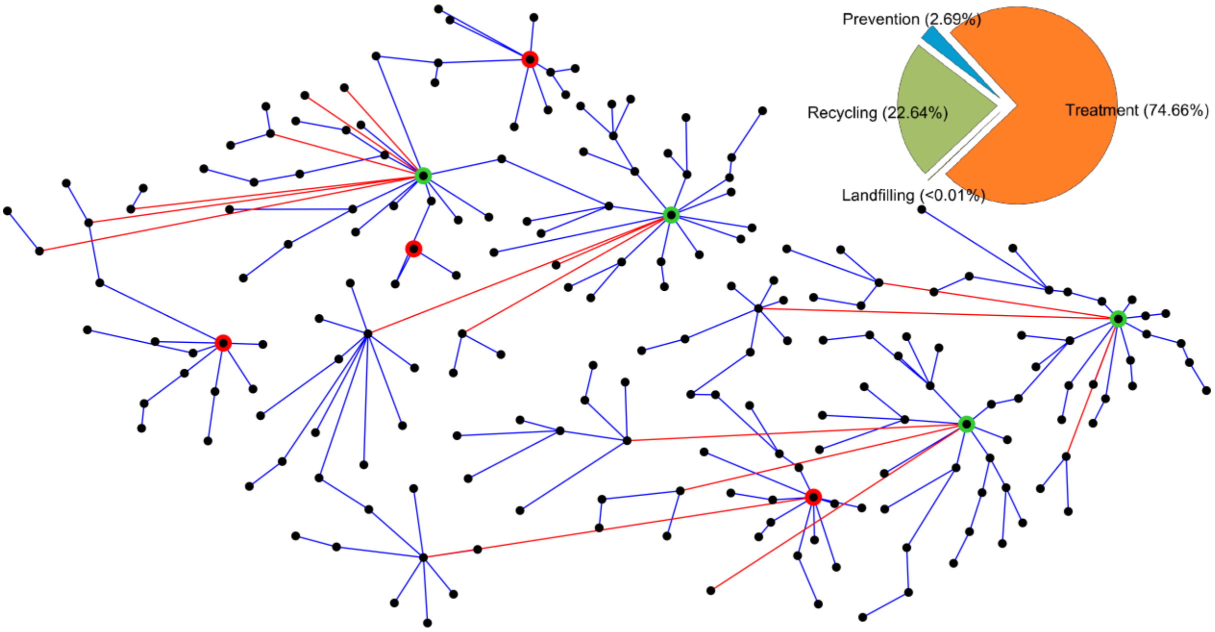


Figure ***9***) is that some of the nodes serve as a “transfer hubs” where the waste is being concentrated from nearby nodes by the road transport and subsequently loaded on a train and shipped to a node with a WtE plant.

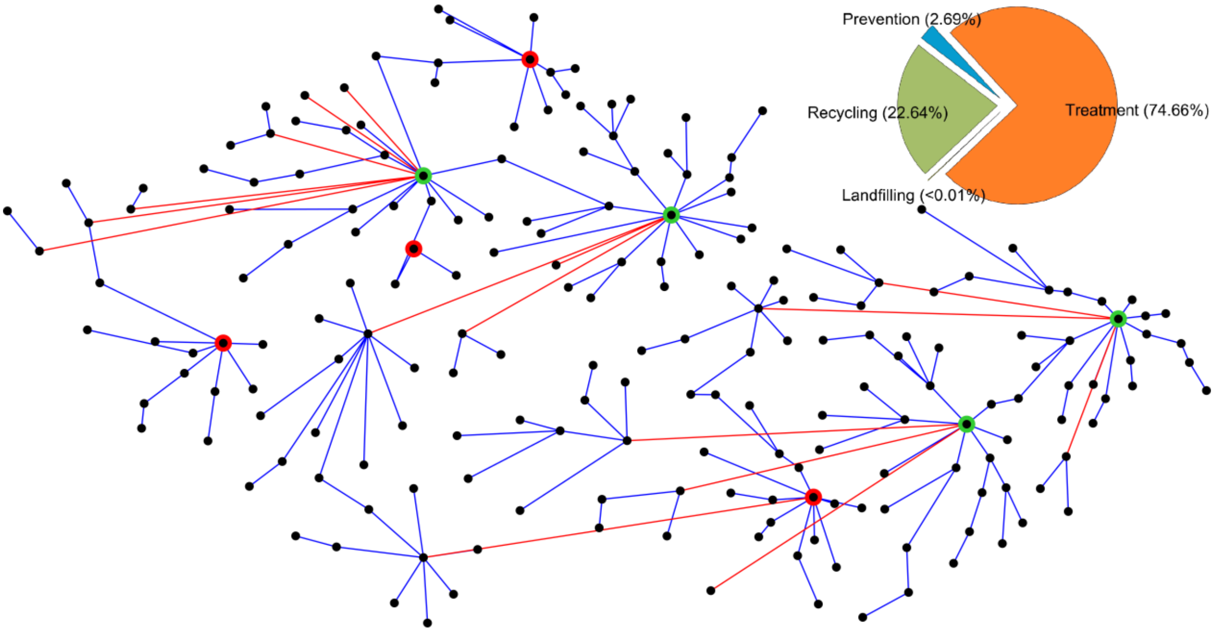


Figure 9: The optimal solution for $\boldsymbol{\lambda}$*=0.25 (one scenario). Red lines correspond to the used rail connections, blue lines to the road connections. Green rings denote the newly build WtE plants, red rings the already existing ones.*

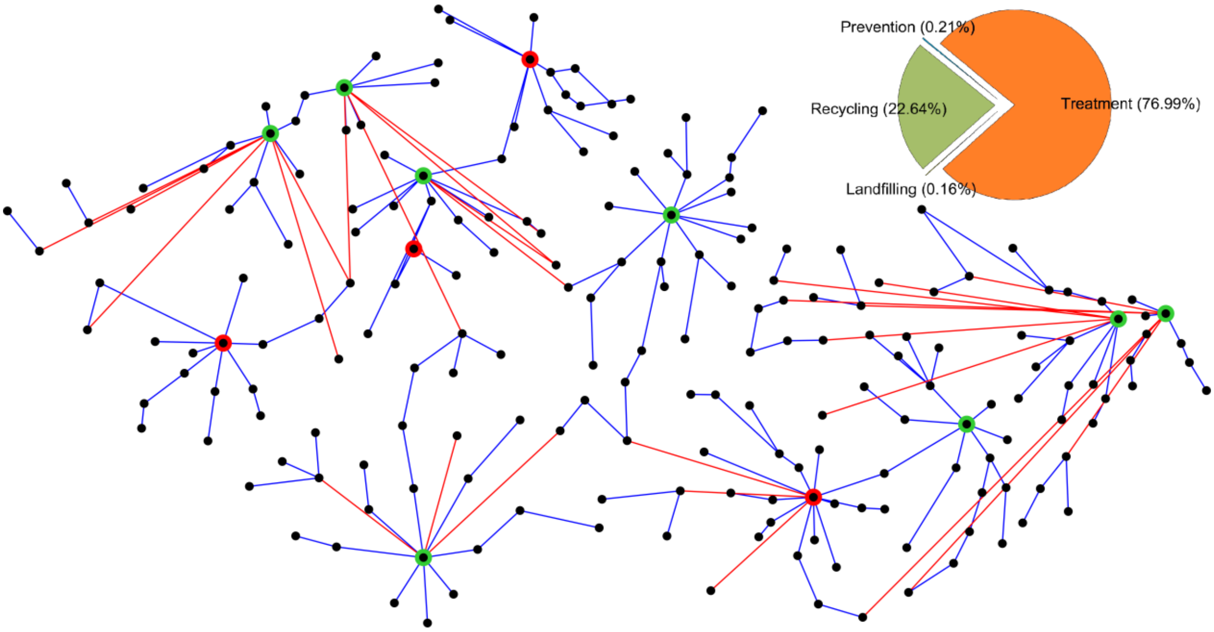


Figure 10: The optimal solution for $\boldsymbol{\lambda}$*=0.875 (one scenario).*

The usage of different advertising investments varies greatly. The recycling investments (at least in the presented form) are too expensive to be used and, therefore, are advised only when costs are completely neglected. On the other hand, the waste-prevention investments are utilized to a greater extent, mainly in places with high per capita waste production, as the investment in waste prevention in these places has a higher impact compared to places with already low per capita waste production (see Figure 3a). What can be seen from the results in Table 1 is that the waste-prevention investments are being used to decrease the need for landfilling, without the need to increase the WtE capacity. These investments are most prominent for lower values of λ as they help to decrease the amount of GHG emissions while being rather costly.

As it is with most optimization computations, especially the ones that are working with random quantities, the results should be taken cautiously. It is up to the decision-maker to choose the desired trade-off between expected costs and environmental impacts and to carefully weigh the advantages, disadvantages, and applicability of the decisions suggested by the results of the optimization.

5. Conclusion

The paper presents a new method to apply some of CE concepts within the WM sector. The approach is based on the multi-objective mixed integer linear model, which comprises both the economic and environmental aspects. It utilizes the pricing and advertising principles in the form of waste prevention and recycling investments. These principles are implemented through the developed dependencies defined in the Section 2. The functions are further approximated by piecewise linear functions to reduce the computational complexity and thus to ensure the solvability of the problem. Moreover, the approach contains the stochasticity in the unknown future waste production, which also makes the model more robust and complex. The resulting large-scale problem was subsequently solved with the well-known Benders decomposition.

The developed methods were applied in a case study for municipalities from the Czech Republic. The results revealed the existing potential in the waste prevention (a few percent according to the λ parameter). On the other hand, the increase of recycling is limited, at least from the economic point of view. The recommendation to make an investment was only for λ equal to 0, which corresponds to the absolute preference of the environmental aspect. Energy recovery is at a high level irrespective of preference. Landfilling is not supported, resulting in less than one percent utilization for all considered situations. However, the final realization is upon the decision-maker.

Since the CE way of thinking receives a rapidly increasing attention, the proposed model has also some limitations, such as it does not cover the whole cycle and it also misses other objectives (besides used economic and environmental aspects) that are recently used. The main such objective is the social aspect(s) including, e.g., harmful effects of waste processing, nuisance or people density and resistance; see, e.g., (Asefi and Lim, 2017).

Acknowledgements

The authors gratefully acknowledge the financial support provided by the project Sustainable Process Integration Laboratory – SPIL, funded as project No. CZ.02.1.01/0.0/0.0/15_003/0000456, by Czech Republic Operational Programme Research and Development, Education, Priority 1: Strengthening capacity for quality research, and by the project “Computer Simulations for Effective Low-Emission Energy” funded as project No. CZ.02.1.01/0.0/0.0/16 026/0008392 by Operational Programme Research, Development and Education, Priority axis 1: Strengthening capacity for high-quality research.

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