

1 Pricing and Advertising Strategies in Conceptual Waste

2 Management Planning

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16 Abstract:

17 The paper presents a new model for integration of circular economy strategies into the
18 municipal solid waste management. The goals are to reduce the waste produced, recycle at the
19 highest rate as possible (material recovery) and to use the resultant residual waste for energy
20 recovery. Such a strategy utilizes both pricing and advertising principles in the mixed integer
21 linear programming model while accounting two criterions - assessment of greenhouse gas
22 (GHG) and cost minimization. The aim is to design the optimal waste management grid to
23 suggest a sustainable economy with environmental concerns. The government, municipalities
24 and/or authorized packaging company decide about the investments to the propagation of waste
25 prevention and to advertising of waste recycling, while investors decide about new facility
26 location and technological parameter. The availability of waste is projected in pricing method

27 as well as in the location of the facility. The mathematical model will consider randomness in
28 the form of waste production. The suggested non-linear functions of pricing and advertising are
29 replaced by piecewise linear approximation to reduce computational complexity. The proposed
30 multi-objective model is applied in a case study for the Czech Republic in the area of waste
31 treatment infrastructure planning to support decision-making at the micro-regional level. The
32 integration of circular economy principles, considering also the total amount of produced GHG,
33 revealed the existing potential in waste prevention. On the other hand, the increase of recycling
34 is limited, landfills are not supported and the energy recovery is preferred. However, the
35 planning of the complex system relies on the decision-maker.

36

37 **Keywords**

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

39 **Highlights**

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

44

45 **1. Introduction**

46 Waste treatment has gained major attention in recent years (Liu et al., 2018). Although material
47 and energy recovery from waste has been steadily growing (Malinauskaite et al., 2017), many
48 countries still resort to landfilling (Lino et al., 2017). Sadly, many countries refuse to deal with
49 the issue of waste treatment altogether (Wang et al., 2018). Some of the most startling examples
50 may be seen in the oceans which are filled with plastics; this plastic then enters the food chain

51 of sea animals (Gutow and Bergmann, 2018). In addition to that, the decrease in the availability
52 of primary sources has become a subject of serious discussion (Hofmann et al., 2018). Several
53 countries have taken steps to amend relevant legislation in order to reduce inefficient waste
54 treatment and consequently also the negative impact of waste on the environment (Gharfalkar
55 et al., 2015). At the same time, there are strong efforts to use a hidden potential of waste as the
56 secondary source of materials and energy (Silva et al., 2017). Circular Economy Package
57 (Directive (EU) 2018/849, 2018/850, 2018/851, 2018/852) may serve as an example of these
58 efforts. This package aims to shift from a linear pattern (raw material, product, waste) to the
59 circular pattern which strives for maximum reuse and minimum amounts of residual flows
60 (Tomić and Schneider, 2018).

61

62 Circular economy (CE) provides a powerful approach to combat environmental challenges and
63 promote sustainable development (Korhonen et al., 2018). Some developed European as well
64 as Asian countries have advanced in the development of policies that support the CE in their
65 society (Ormazabal et al., 2018). Waste treatment hierarchy defined in EU (Directive
66 2008/98/EC) must be observed to comply with the targets of the CE. The waste hierarchy
67 prioritizes prevention to waste production, followed by waste recycling, material and energy
68 recovery and last - waste disposal (Fonseca et al., 2018).

69

70 The efficient CE requires the establishment of necessary processing infrastructure.
71 Mathematical modelling may serve as a powerful tool for its start and design. This issue is
72 rather complex and covers all stages of waste hierarchy, siting of processing capacities, the
73 design of transportation infrastructure, including transfer stations and so on. Therefore,
74 sophisticated methods and tools are required. The paper by Barbosa-Póvoa et al. (2018)
75 provides an in-depth research study for planning in supply chain systems, including waste

76 management (WM). Papers discussed in the research study discuss various types of
77 sustainability of the system. Specific decision-making criteria relate to the following aspects.

78 • **Economic aspects**

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

85 • **Environmental aspects**

86 There is a significant difference between indicators in terms of environmental assessment of
87 the system. A lot of attention is paid to emissions of carbon dioxide, by direct evaluation of
88 carbon footprint (Byrne et al., 2010), or by calculation of greenhouse gases (GHGs), see
89 (d'Amore and Bezzo, 2016). Global warming potential (GWP) is an indicator used for
90 comparison of the impact of particular pollutants on the environment changes, see (De Meyer
91 et al., 2015). Climate change is another commonly applied indicator, see (Boukherroub et al.,
92 2015). All of these indicators help evaluate the environmental impact of the systems in relation
93 to global warming. Waste reduction and recycling is another important category of
94 environmental impacts, see (Gilli et al., 2018). The papers and publications mentioned above
95 focus exclusively on one of the indicators; however, this may significantly distort final results.
96 The so-called life cycle assessment (LCA) approach usually incorporates more than one
97 environmental aspect and the method is crucial for transition to a CE, see (Cellura et al., 2012).
98 LCA represents a complex method for environmental impact assessment.

99 • **Social aspects**

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

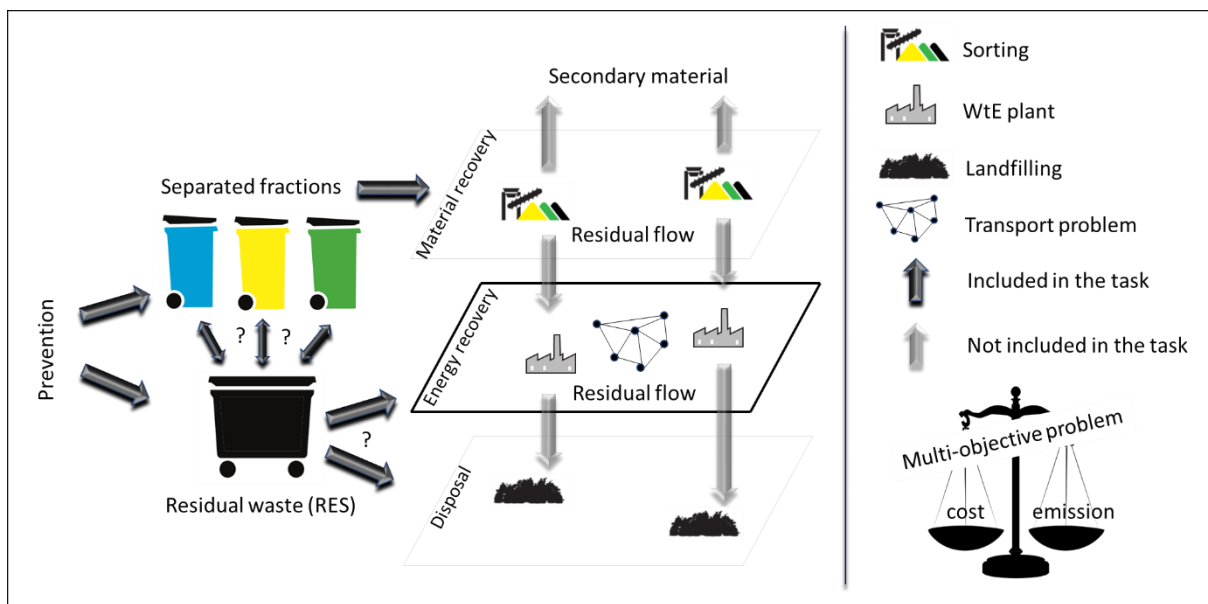
104 • **Multi-criteria approaches**

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

119

120 Many papers usually focus only on particular fractions of municipal solid waste (MSW) and
121 related technologies which are suitable for their processing. Residual MSW (RES) is the main
122 waste flow suitable for processing by the energy recovery infrastructure, see (Fiorentino et al.,
123 2015). Biowaste is another topic that deserves mentioning, see (Neri et al., 2018). Some of the
124 studies aspire for a more complex method and assume MSW as a whole, see (Chen et al., 2019)

125 in China or (Malinauskaite et al., 2017) in certain European countries. These authors consider
 126 the separation of utilizable fractions (for material recovery) and subsequent energy recovery of
 127 RES. Relatedness of waste prevention, material recovery, energy recovery and waste disposal
 128 are only theoretical in these papers; the authors may only focus on small, aggregated areas with
 129 little practical applicability. Following sections of this paper presents a new complex method
 130 for design of optimization of MSW treatment related to WM hierarchy. Figure 1 displays a
 131 scheme of intended borders of the MSW processing system which includes economic and
 132 environmental aspects. Since ignoring uncertainties often leads to insufficient results (Yadav et
 133 al., 2017), uncertainty in the amount of produced waste is expressed using a scenario-based
 134 approach which leads to a stochastic model.

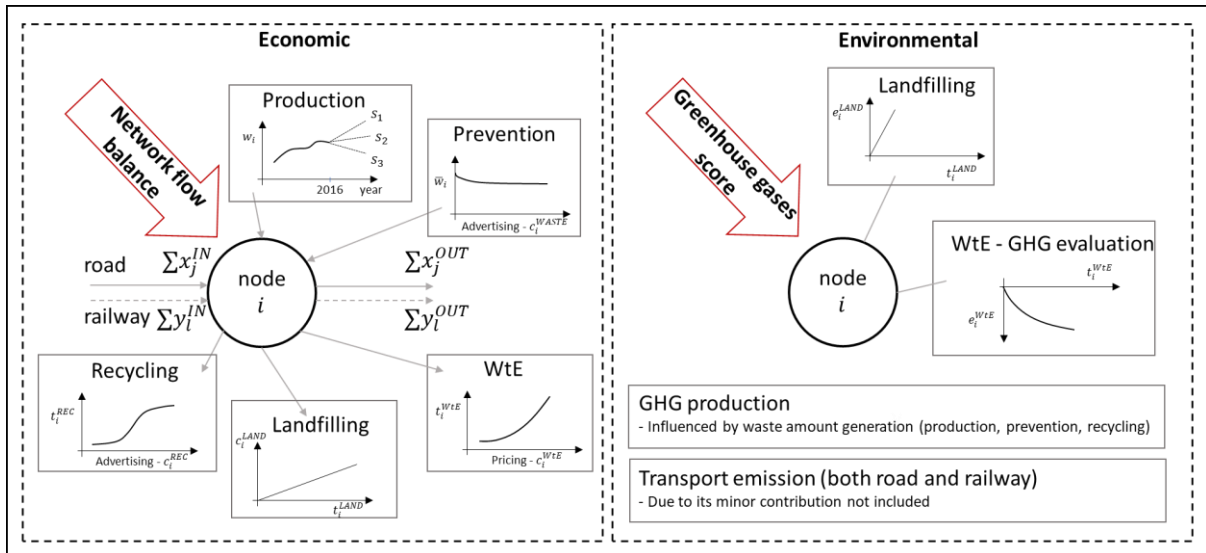


135
 136 *Figure 1: Scheme of the MSW processing system includes economic and environmental*
 137 *criteria*
 138

139 Basic layer analysed in this paper is related to RES and relevant optimization of processing
 140 infrastructure. Pricing and advertising methods are used to describe relationships between this
 141 RES layer and its surroundings, incl. layers focused on prevention of waste production, material
 142 recovery, and waste disposal. Figure 2 shows a complex view of the balance for one node of
 143 the network. The method combines economic and environmental criteria, a detailed description

144 is in Section 3. The aim is to design an effective plan for waste transport and subsequent waste
 145 processing, provided that the total waste production (reduced thanks to prevention) and
 146 recycling rate (material recovery) may be affected by targeted investments.

147



148

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

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

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

161 **2. Description of economic and environmental relationships in the system**

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

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

173 • **Waste prevention**

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

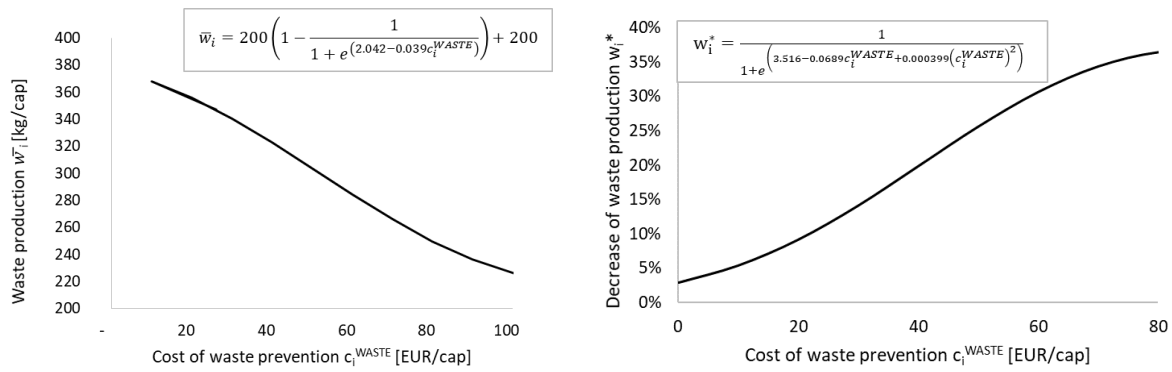
180 S-curves are usually used in waste management for modelling by regression (Ghinea et al.,
181 2016) and forecasting of waste generation (Lu et al., 2016). Waste production is in obvious
182 relation with the waste prevention. Amount of waste production as a dependent variable is
183 described by a regression model in the form of logistic function (S-shaped curve) Eq(1):

184

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

185 where \bar{w}_i is the estimation of waste production based on the independent variable c_i^{WASTE} which
186 indicates the investment in the waste prevention at node i and a, b are regression parameters.
187 The parameters w_{min} and w_{max} sets the minimum and maximum possible waste generation.
188 Estimate of minimum and maximum MSW* production (MSW* is a sum of particular MSW
189 fractions: paper, plastics, glass, RES) in the Czech regions is set to 200 kg/cap respectively 400
190 kg/cap, which corresponds to the best and worst regions in applying a prevention strategy.
191 Similar situation was also observed in Austria, see (Lebersorger and Beigl, 2011). Waste
192 processing price has a major impact on the amount of produced waste (MSW*). S-curve (see
193 Eq(1)) was selected due to nature of modelled prevention on the basis of waste management
194 experts. Data from Czech regions in 2015 were used to estimate regression parameters a and b
195 (see supplementary materials and Figure 3a). In general, it is assumed that higher costs spent
196 on public awareness raising are included in total costs (one of the aspects of higher unit costs).
197 Figure 3 illustrates the regression model of the dependence between waste prevention cost and
198 percentage decline of waste production (see supplementary materials). The model stems from
199 dependence illustrated at Figure 3a. It is assumed that if additional costs (additional to current
200 costs) are spent on waste prevention, the final effect will be at least the same as in Figure 3a.
201 The goal of further analysis is to improve the prevention cost definition and calculation. The S-
202 shaped curve in Figure 3b should lead through the point of 0% decrease of waste production in
203 the case of no waste prevention investment. The w_i^* corresponds to MSW* production decrease
204 for a specific node, which is further used in the model. This regression function leads to poor
205 approximation around the point $c_i^{WASTE} = 0$ (see Figure 3b). This inaccuracy will be reduced
206 in a mathematical model using the special order set of type 2 (SOS2) variables, see Section 3.
207 The mean absolute percentage error of function from Figure 3b equals to ca 6.5 % (against ca
208 9.7 % for linear function).

209



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

210

211 *Figure 3: Impact of waste prevention investments on waste production*

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

218 • **Recycling**

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

226 • **Quantitative**

227 ○ Producer of products – Adequate size packaging with regard to the product;
228 Aggregation of products into a smaller number of packages.

229 ○ Consumer – Denser net of containers.

230 ○ Operator – Separation of larger amounts of fractions.

231 • Qualitative

232 ○ Producer of products – Eco-design and utilization of recyclable materials.

233 ○ Consumer – Changes in the collection system; Fees related to production: PAYT –
234 pay as you throw (Elia et al., 2015); Separation of larger amounts of fractions.

235 ○ Operator – The technological level of the facility.

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

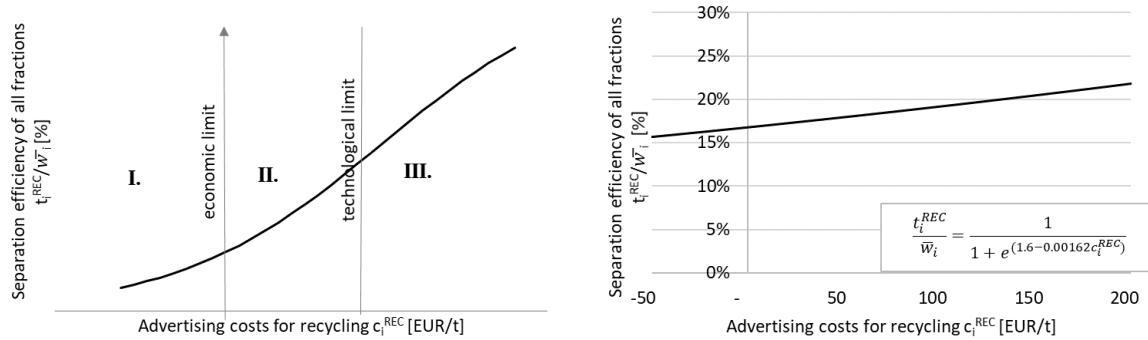
241 The dependence of the separation efficiency on investment is characterized according to Figure
242 4a by three phases:

243 I. Phase, when it is advantageous to recycle. Such waste constitutes an income
244 (material recovery).

245 II. Phase, when it is advantageous to support recycling, i.e., it is possible to increase
246 the ratio of separated fractions and residual waste by investments in infrastructure
247 and promotion for a general awareness of recycling benefits to the environment.

248 III. Phase presents an area of technological constraint for further increases of the
249 recycling ratio, alternatively, it presents a depleted potential of separable
250 components of the RES.

251 Figure 4b shows the S-shaped regression model of the relationship between recycling ratio
 252 and advertising costs based on real data. Curve at Figure 4b models efficiency of separation of
 253 consumer's part. Increase in separation depending on investments is very slow, which reflects
 254 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)

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

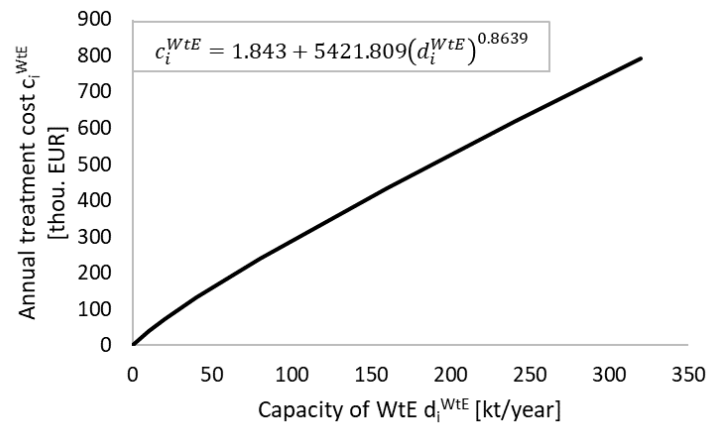
257 As the separation efficiency increase, the composition of the residual RES changes which is
 258 processed in WtE, see (Ferdan et al., 2017). Waste composition, which is treated in the WtE, is
 259 at the same time linked with high impact on GHG contribution. As stated by Chen (2018)
 260 incinerating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

266

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

277 • **Treatment**

278 The treatment cost is determined as dependent on WtE facility capacity, see (Hrabec et al.,
279 2018). In the case of landfills, the processing cost is assumed constant. The treatment cost is
280 based on the so-called gate fee, which is given as a cost per unit of processed waste. In this
281 paper, the annual treatment cost is considered and it has to be assessed for each locality
282 separately due to dependence on the local heat demand and on attributes of WtE facility, see
283 (Putna et al., 2018b). The following figures describe the annual treatment cost depending on
284 the capacity of WtE plant for a particular territory. The area covers ca. 40,000 inhabitants and
285 advanced industrial production with total heat supply of ca. 1,900 TJ/year. Figure 5 illustrates
286 treatment cost as a function of WtE capacity in particular locality. Both the investment and
287 operating costs are included. These costs are different for each (see supplementary material).
288 Construction is expected in the premises of existing heating plants (see supplementary material
289 for potential sites), where it is possible to ensure the sales of heat produced. In addition, some
290 old boilers are expected to be shut down.



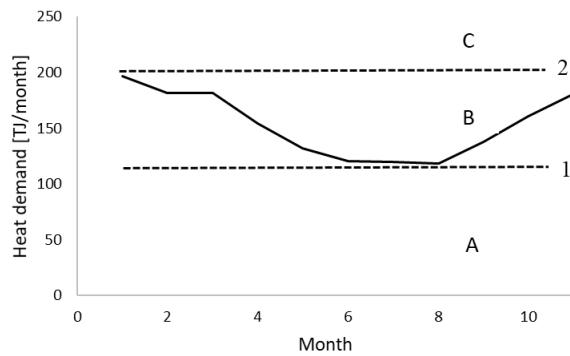
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292 *Figure 5: Annual treatment cost as a function of WtE facility capacity*

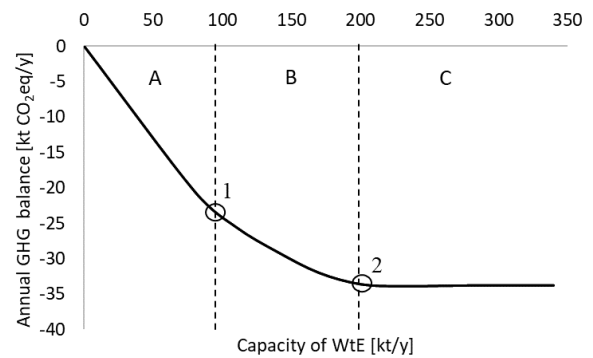
293 (Fan et al., 2018b) further examined the efficiency of the process and its integration in the plant
 294 for cleaner production. In the waste processing as well as in other businesses, there is an
 295 emphasis on emissions as GHG. The amount of GHG is given by a function of waste amount
 296 processed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

298 Figure 6a illustrates the heat demand during a year for the same area as in Figure 5 with an
 299 obvious decrease in summer months, marked by line 1. The increased heat demand, when
 300 covered by WtE, has the positive effect on the GHG contribution, see Figure 6b, which
 301 describes the reduction of GHG contribution when replacing fossil fuels (gas, coal) for heating.

302 In addition, several heat supply levels from WtE are displayed by horizontal lines in Figure 6a.
 303 Two break points 1 and 2 are highlighted and indicate three parts of graph A, B and C. In part
 304 A, the all heat produced in the WtE is absorbed. WtE covers the base, whereas peaks are
 305 supplied by additional heat sources. In some months, the demand is lower than WtE maximum
 306 capacity. As a result, some heat cannot be utilized. In part C, the heat demand is completely
 307 covered by WtE. Since that point, heat delivery reached its maximum. Annual GHG production
 308 does not change with increased WtE capacity considering power production is GHG neutral,
 309 see (Ferdan et al., 2018). The electricity production does not change and balance is
 310 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

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

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

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

324 • **Transportation**

325 Waste transport is planned using both roads and railways, while rail transport is preferred for
 326 the transportation of large quantities of waste over long distances. The economic aspect of these
 327 modes of transport is taken into account by the transportation costs (Gregor et al., 2017). Traffic

328 emissions are neglected in the model due to its minor production compared to a processing
329 facility. A respective air emission analysis has been proposed by (Fan et al., 2018a).

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

$$c_t^{RAIL} = 0.005 + 6.26h^{-1}, \quad (2)$$

334 **where parameter h represents the distance in km and c_t^{RAIL} defines the unit cost in EUR/t.**

335 **The relationships** are set according to information from company ČD Cargo, a.s. The unit cost
336 decreases with distance, which is due to the lower weight of the total cost for cargo handling.
337 Furthermore, it is possible to optimize the use of the rail more effectively, making transport
338 more efficient and reducing unit prices. Compared to disposal methods, transport also plays a
339 minor role in terms of GHG production for WM strategy planning (Ferdan et al., 2017). The
340 reason is that GHGs from transport are the same for every kind of waste processing.

341 **3. Modelling approach**

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

346 **3.1 Notation used**

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

352 **Sets**

353 $i \in I$ nodes in the network

354 $l \in L$ edges which connect nodes i by railway

355 $j \in J$ edges which connect nodes i by road

356 $s \in S$ scenarios representing the amount of waste production

357 $k \in K$ points for linearization – for each k the value on axis x and axis y is defined

358 **Decision variables**

359 f weighted multi-objective function

360 f_1, f_2, f_3, f_4 individual parts of objective function

361 y_l^s amount of flow on rail edge l in the scenario s

362 x_j^s amount of flow on road edge j in the scenario s

363 $t_i^{WtE;s}$ amount of processed waste in the WtE plant in the node i in the scenario s

364 t_i^{REC} amount of recycled waste in the node i

365 $t_i^{LAND;s}$ amount of landfilled waste in the node i in the scenario s

366 w_i^s waste production in the node i in the scenario s

367 d_i^{WtE} planned capacity of WtE plant in the node i

368 \bar{w}_i average waste production in the node i

369 $\omega_i^{WtE;s}$ non-utilised capacity in the WtE plant in the node i and scenario s

370 δ_l activation of rail edge l , a binary variable

371 **Parameters**

372 M big constant

373 $a_{i,j}$ incidence matrix for road transportation

374 $b_{i,l}$ incidence matrix for rail transportation

375 c_i^{LAND} cost of landfilling in the node i

376	$c_i^{WtE,PEN}$	cost of loss within electricity and heat generation in the node i in WtE plant
377	c_l^{RAIL}	cost of transportation on edge l
378	c_j^{ROAD}	cost of transportation on edge j
379	$c_l^{RAIL,PEN}$	penalization cost for railways
380	d_i^{LAND}	existing capacity of landfill in the node i
381	A_l	minimal amount of waste transported through rail edge l
382	ϵ_i^s	random value generated for scenario s in the node i
383	p^s	probability of scenario s
384	λ	weight of the objective functions
385	w_i^C	current production in the reference year in the node i
386	$f_{i,k}^{WtE}$	potential capacities of each linearization point k for WtE plant in node i
387	$f_{i,k}^{REC}$	possible advertising investments k for recycling in node i
388	$f_{i,k}^{WASTE}$	possible advertising investments k for waste production reduction in node i
389	$c_{i,k}^{WtE}$	cost for processing in the WtE plant in node i
390	$c_{i,k}^{REC}$	cost for recycled waste in the node i, b
391	$c_{i,k}^{WASTE}$	cost for waste reduction in the node i
392	$e_{i,k}^{WtE}$	GHG contribution in the WtE plant in the node i
393	e_i^{LAND}	GHG contribution for landfilling in the node i
394	SOS2 variables	
395	$\alpha_{i,k}^{WtE}$	the variable of special order set 2 type; indicates the activation of specific
396		capacity k of WtE for all nodes i
397	$\alpha_{i,k}^{REC}$	the variable of special order set 2 type; indicates the use of specific
398		advertising investment k for recycling in all nodes i

399 $\alpha_{i,k}^{WASTE}$ the variable of special order set 2 type; indicates the use of specific
 400 advertising investment for prevention of waste production k in all nodes i

401 3.2 Model formulation

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

404 Objective function

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

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

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

414

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

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

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

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

$$f = \sum_{s \in S} p_s [\lambda(f_1 + f_2 + f_3) + (1 - \lambda)f_4] \quad (7)$$

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

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

433

434 Constraints

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

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

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

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

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

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

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

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

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

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

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

448 road Eq(14) and for the rail Eq(15). The amount of processed waste, production, average
 449 production, and non-utilised capacity have to be non-negative as stated in Eq(16). Activation
 450 of rail edge l is performed by binary variable δ_l Eq(17).

451 **Additional constraints for SOS2**

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

$$d_i^{WtE} = \sum_{k \in K} \alpha_{i,k}^{WtE} f_{i,k}^{WtE} \quad \forall i \in I, \quad (18)$$

$$t_i^{REC} = \sum_{k \in K} \alpha_{i,k}^{REC} f_{i,k}^{REC} \quad \forall i \in I, \quad (19)$$

$$\bar{w}_i = \sum_{k \in K} \alpha_{i,k}^{WASTE} f_{i,k}^{WASTE} \quad \forall i \in I, \quad (20)$$

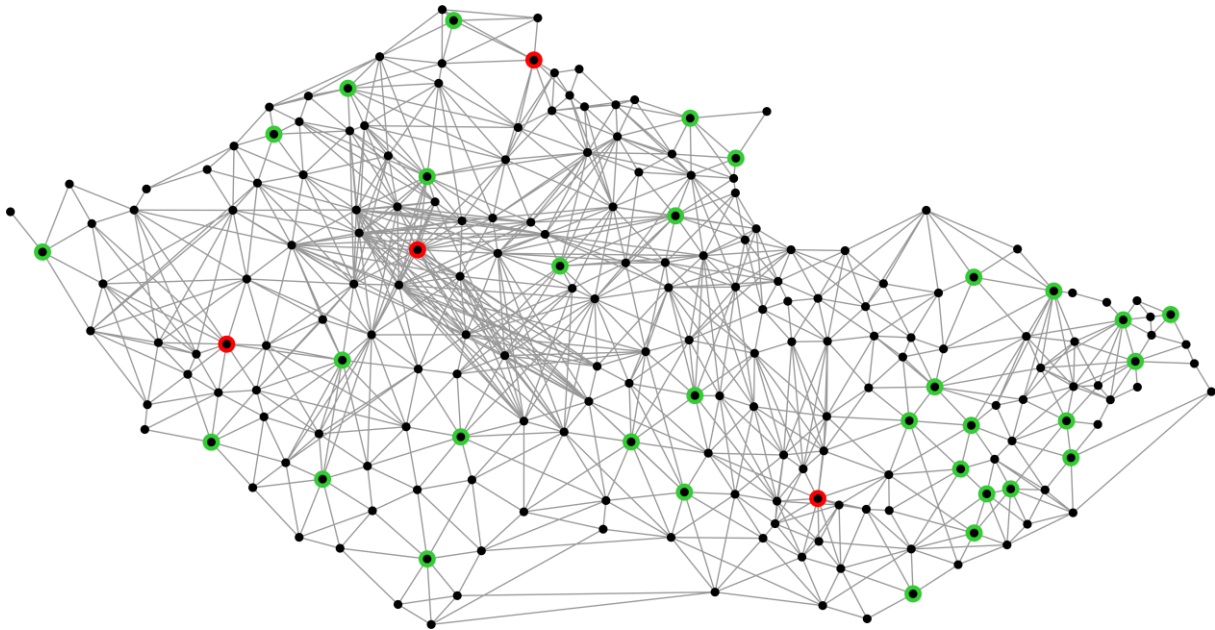
$$\sum_{k \in K} \alpha_{i,k}^{WtE} = 1, \sum_{k \in K} \alpha_{i,k}^{REC} = 1, \sum_{k \in K} \alpha_{i,k}^{WASTE} = 1 \quad \forall i \in I. \quad (21)$$

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

458 **4. Case study**

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

465 for new WtE plants in 32 different nodes (in some of the nodes, it is possible to build more WtE
466 plants). The details regarding the input data are provided in the supplementary materials.



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

471 The model considered 500 different waste production scenarios to adequately capture the
472 uncertainty involved. The uncertain values ϵ_i^s are drawn from a uniform distribution on the
473 interval $[0.9, 1.1]$. The probability of a scenario is the same for all scenarios $p^s = \frac{1}{|S|}$. The
474 problem was solved for varying values of λ (cf. the numerical results) to identify the trade-off
475 between the overall optimal costs and the amount of produced GHG emissions. The algorithm
476 that was used to solve the problem was the Benders decomposition scheme, thoroughly
477 reviewed in (Rahmaniani et al., 2017), utilizing the warm-start cuts developed in (Kúdela and
478 Popela, 2017). The optimization model and the decomposition algorithm were programmed in
479 the high-performance dynamic language JULIA (Bezanson et al., 2017) with the JuMP package
480 for mathematical optimization (Dunning et al., 2017), that is well suited for large-scale
481 scientific computing. The solver CPLEX 12.6.3 (CPLEX, 2019) was used to compute the
482 consecutive mixed-integer problems (in the Benders decomposition scheme). The optimality
483

484 gap was set to 1.5% and the computations took around 8 hours to complete (for each value of
485 λ) on an ordinary machine (3.2 GHz i5-4460 CPU, 16 GB RAM). The resulting optimal
486 decisions were subsequently tested on a separate set of 10,000 different scenarios and the
487 average costs, the amount of produced emissions are reported in Table 1, whereas the average
488 amount of waste prevented, recycled, treated and landfilled are reported in Table 2 (the
489 reference average waste production is a constant value 2,661 kt). The tests took around 1.5
490 hours to compute (for each value of λ).

491 *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

492

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

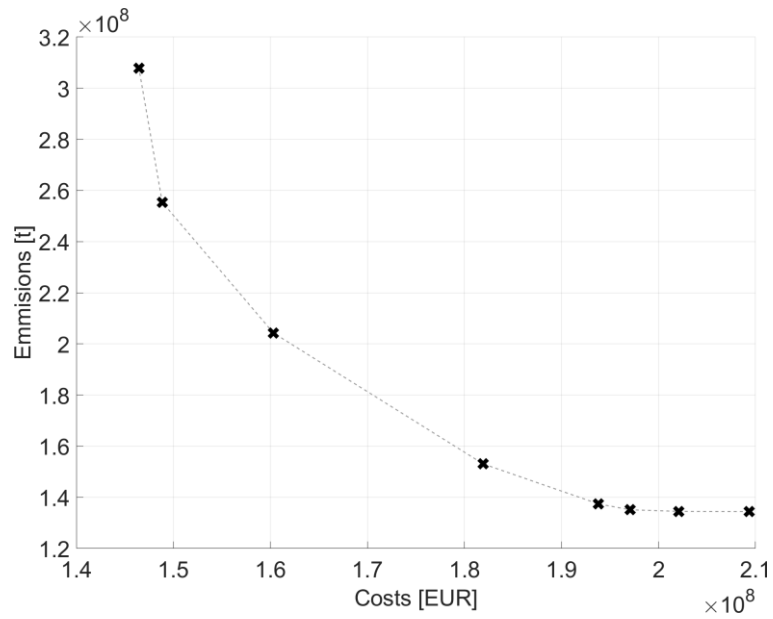
λ	Prevention [kt]	Prevention [%]	Recycling [kt]	Recyclin g [%]	Energy recovery [kt]	Energy recovery [%]	Landfilling [kt]	Landfillin g [%]
0	89.98	3.38	604.57	22.72	1,966.61	73.90	<0.01	<0.01
0.001	87.55	3.29	602.57	22.64	1,971.03	74.07	<0.01	<0.01
0.25	71.59	2.69	602.57	22.64	1,986.99	74.66	<0.01	<0.01
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

494

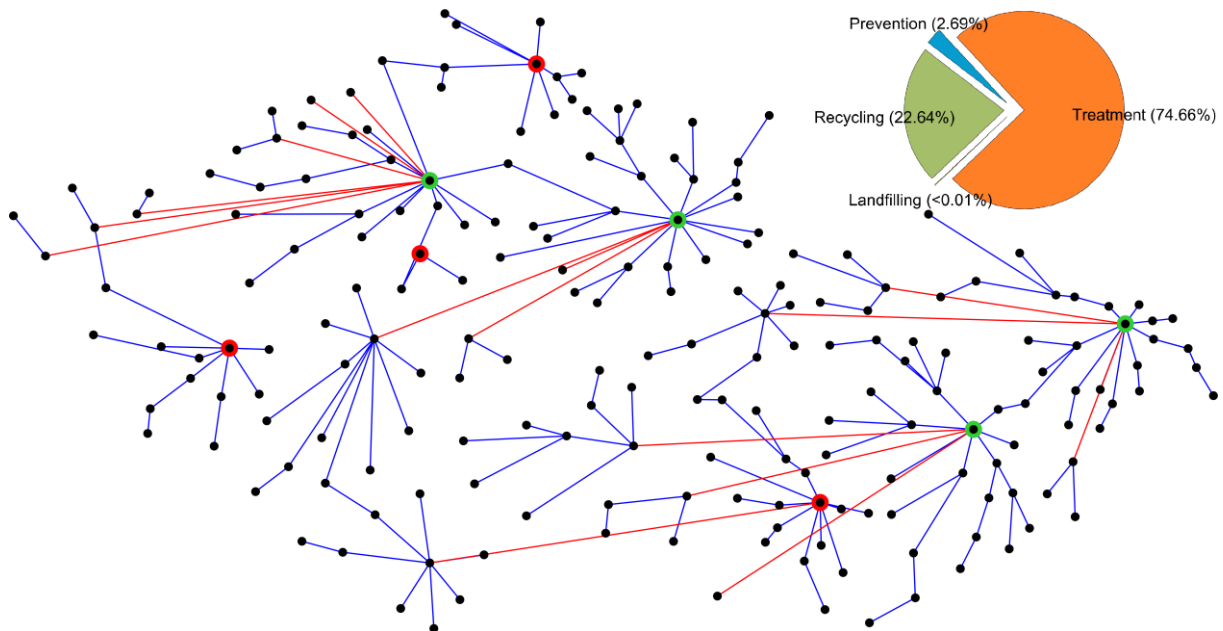
495 The results of the computations are summarized in Table 1 and 2. Although the optimal
496 decisions depend quite profoundly on the chosen value of λ , they have one thing in common –
497 in all the cases (and all the considered scenarios) the amount of installed WtE capacity is robust
498 enough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

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

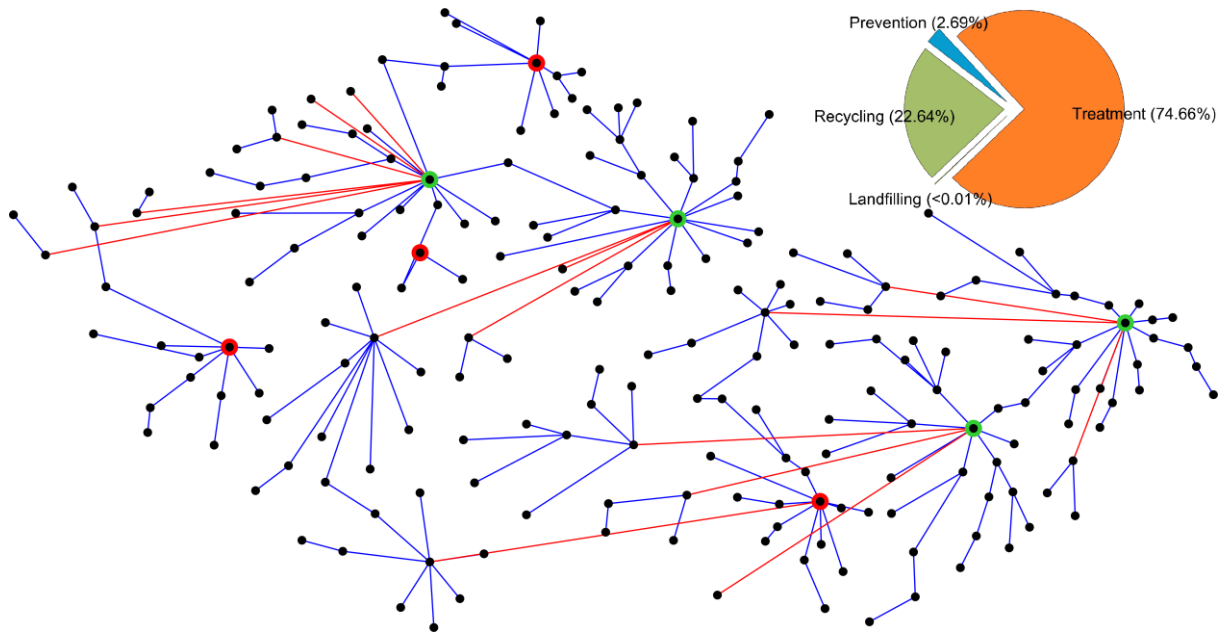


516
 517 *Figure 8: The Pareto frontier describing the trade-off between the optimal costs and the amount*
 518 *of produced emissions. The dashed line has only a visual purpose.*
 519

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



524
 525 Figure 9 and Figure 10. What can also be seen (especially in



526

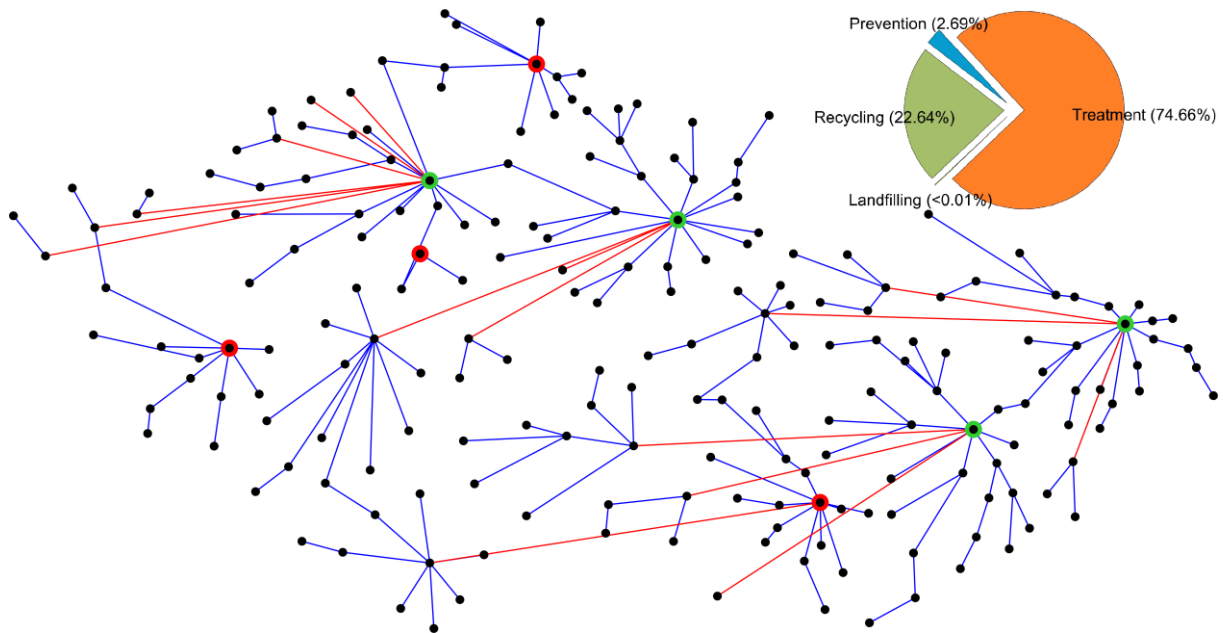
527 Figure 9) is that some of the nodes serve as a “transfer hubs” where the waste is being
 528 concentrated from nearby nodes by the road transport and subsequently loaded on a train and
 529 shipped to a node with a WtE plant.

530

531

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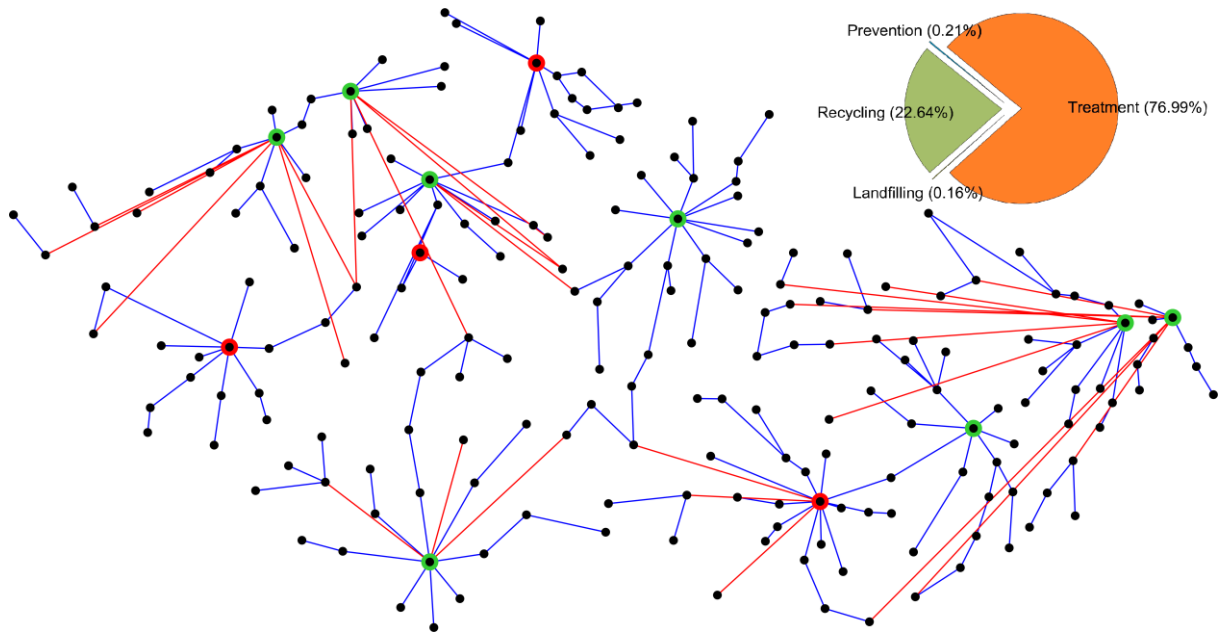
533



534

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

538



539
540 *Figure 10: The optimal solution for $\lambda=0.875$ (one scenario).*

541
542 The usage of different advertising investments varies greatly. The recycling investments (at
543 least in the presented form) are too expensive to be used and, therefore, are advised only when
544 costs are completely neglected. On the other hand, the waste-prevention investments are utilized
545 to a greater extent, mainly in places with high per capita waste production, as the investment in
546 waste prevention in these places has a higher impact compared to places with already low per
547 capita waste production (see Figure 3a). What can be seen from the results in Table 1 is that the
548 waste-prevention investments are being used to decrease the need for landfilling, without the
549 need to increase the WtE capacity. These investments are most prominent for lower values of
550 λ as they help to decrease the amount of GHG emissions while being rather costly.

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

566 **5. Conclusion**

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

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

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

579

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588

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