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Strategic Multi-Stage Planning of Waste Processing Infrastructure

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In the upcoming years, the member countries of the European Union (EU) are expected to reach certain milestones with regards to different waste management policies: reducing the amount of generated waste, maximizing recycling and the energy usage of the appropriate waste types, phasing out landfilling, etc. With the increasing demands on these criteria comes also the need for the planning of the construction and modernization of the required waste processing infrastructure. This paper summarizes the current state of affairs for selected member countries of the EU and describes the possible technologies that are suitable for reaching the specific milestones. A multi-stage multi-period stochastic mixed-integer programming model is developed, with the goal to minimize the overall costs associated with reaching the milestones. This model describes well the sequential nature of the decision-making process. The present-day decisions must regard the possible effects of the decisions on the future. The planning considers the possible modernization of infrastructure which gradually increases the efficiency in order to hit the time-respective milestones. The model is presented on a case study which examines the situation in the Czech Republic divided into 13 regions, considering 27 scenarios for future development.

1. Introduction

In recent years the European Union (EU) countries managed to reduce the amount of Municipal Solid Waste (MSW) that is being landfilled and increase the volume of MSW that is used in a material or energy recovery. However, there is no apparent long-term trend in the total amount of MSW produced, see Figure 1. The paper by Castillo-Giménez et al. (2019) assesses performance and convergence in the treatment of municipal waste by the members of the European Union-27 (EU-27) during the period 1995 – 2016. The analysis of suitable methods for the treatment of MSW was conducted in Maisarah et al. (2018), with the results that a mixed MSW is suitable for incineration process in Waste-to-Energy (WtE) plants, whereas segregated MSW (e.g. food waste which is rich in labile organic matter) is more suitable for mechanical biological treatment (MBT). The increased effectivity in the treatment of MSW is one of the main goals of the circular economy (Pieroni et al., 2019). The strategy is also to reduce the footprint from processing site processes (Varbanov et al., 2018). The Circular Economy Package (CEP) – an initiative for the circular economy adopted by the European Commission – set up a series of targets that are summarized in Table 1. Among the most important targets belongs the reduction of landfilled MSW, see Figure 2. It is important to note that the reported data regarding waste management (WM) can be burdened by errors (Šomplák et al., 2017). The inconsistency in the methodology of reporting the WM data across different countries can bring additional complications.
In recent history, there have been multiple works focusing on the optimal location of the waste treatment capacities with different technologies, often combining both the economic and the environmental aspects (Fan et al., 2019) of the decisions. A broad literature overview of planning in WM can be found in Barbosa-Póvoa et al. (2018). This review found that most papers (77 %) deal with static models, where the

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transportation/processing network, when defined, stays the same during the analyzed time horizon. Also, only 16 % of the papers have considered uncertainty aspects.

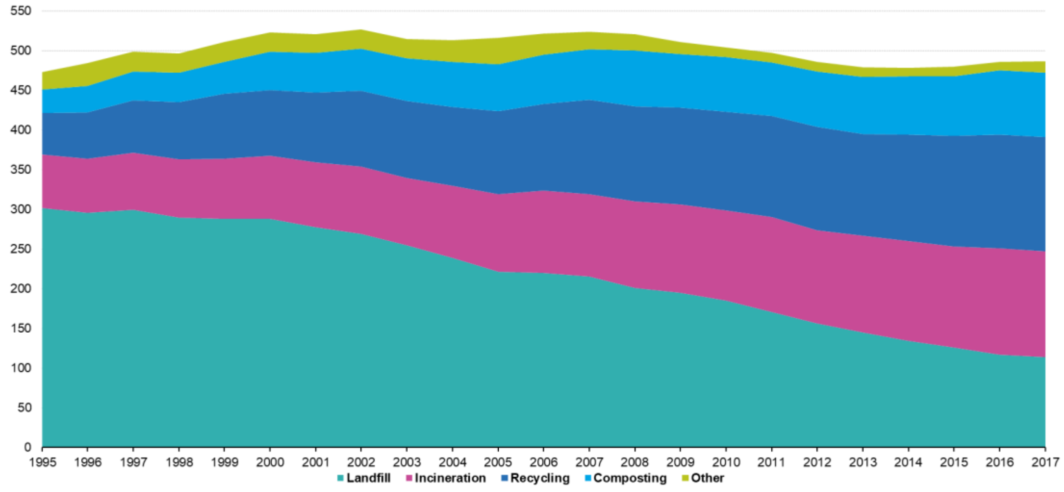


Figure 1: Municipal waste treatment, EU-28, (kg/capita), (Eurostat, 2019)

Because of the active development of legislation in WM, it is arguably more appropriate to use dynamic models, which can support decisions that have to deal with uncertainty (with respect to different parameters, e.g. the production of waste in the upcoming years). Models of this type fit into the category of multi-stage stochastic programming models which are quite broadly adapted in financial areas, such as portfolio selection (Dupačová and Kozmik, 2014). In the area of WM, the paper by Wu et al. (2015) used this type of a model for planning the development of an integrated biomass-MSW power plant and managing the power supply based on varied energy resources. A similar approach with regards to the MSW treatment was described by Li and Huang (2009). This paper presents a multi-state multi-period stochastic mixed-integer programming model, whose main aim is to serve as a support for strategic decisions in WM on a national scale. The multi-period (with regards to the time hierarchy) and multi-stage (with regards to the strategic decision) nature of the model provides an appropriate environment for the planning of the MSW treatment infrastructure. The model is dynamic, allowing the change of the infrastructure in the considered stages, which will enable the successful transition into the circular economy, while still focusing on the important economic aspects.

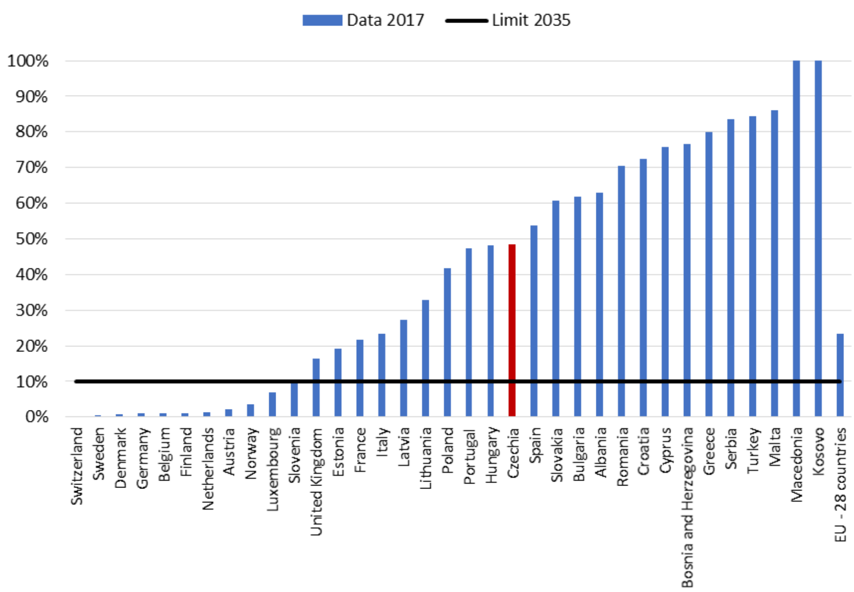


Figure 2: Current levels of landfilled MSW in selected European countries (Eurostat, 2019)

Table 1: The EU targets for the treatment of MSW included in CEP

Directive EU	Waste type	Intention	Target		
			2025	2030	2035
Directive 2018/850	MSW	landfill			10 %
Directive 2018/851	MSW	material recovery	55 %	60 %	65 %

2. Mathematical model

The problem at hand can be described as follows: To reach the target for the amount of landfilled MSW by 2035 an appropriate infrastructure needs to be built in order to facilitate the desired transition. The decision process is divided into several decision stages when new treatment facilities (WtE or MBT) can be built. These decision stages are a subset of the corresponding time periods (years in this case). This design choice is needed for the model to be tractable, as the increase in decision stages means an increase in the number of variables. The size and the cost for treatment of the facilities do not have a simple linear dependence and need to be modelled by additional integer variables. To account for the uncertainty in the amount of produced MSW in the upcoming years, a scenario-based approach is adopted. The notation for the model is summarized in Table 2.

Table 2: The notation

Type	Symbol	Description
Sets and indices	$s, z \in \{1, \dots, 27\}$	Set of scenarios
	$i \in \{1, \dots, 13\}$	Set of regions
	$j \in \{1, \dots, 46\}$	Set of routes between the regions
	$t \in \{1, \dots, 16\}$	Set of time periods
	$\tau \in \{1, 6, 11\}$	Set of decision stages
	o^i_{WtE}	Set of possible options for WtE plants in region i
	o^i_{MBT}	Set of possible options for MBT plants in region i
Parameters	$k^i_{o^i_{WtE}}$	The capacity of the options for the WtE plant in region i
	$k^i_{o^i_{MBT}}$	The capacity of the options for the MBT plant in region i
	${}^{WtE}c^i_{o^i_{WtE}}$	Treatment cost of the options for the WtE plant in region i
	${}^{MBT}c^i_{o^i_{MBT}}$	Treatment cost of the options for the MBT plant in region i
	c^i_L	Landfilling cost in region i
	c^j_R	Shipping cost on arc j
	$\xi^i_{t,s}$	Production of MSW in region i, the time period t, scenario s
	$\xi^i_{[t],s}$	Progression of MSW production up to time period t, region i, scenario s, i.e. $\xi^i_{[t],s} = (\xi^i_{1,s}, \xi^i_{2,s}, \dots, \xi^i_{t,s})$
	$A^{i,j}$	Incidence matrix of the road network
	pen_{WtE}	The penalty for unused WtE capacity
	pen_{MBT}	The penalty for unused MBT capacity
	κ	The ratio of MBT treated MSW that needs to be landfilled
	p_s	The probability of scenario s
	g_1, g_2, g_3	Target values for the amount of landfilled MSW
Variables	$x^j_{t,s}$	Flow on the arc j, time period t, scenario s; real nonnegative
	$m^{i,o^i_{WtE}}_{\tau,s}$	Building the MBT plant in region i, with option o^i_{WtE}, in decision stage τ, in scenario s; binary
	${}^{WtE}r^{i,o^i_{WtE}}_{t,s}$	Amount of MSW treated in WtE in region i, with option o^i_{WtE}, in time period t, in scenario s; real nonnegative
	${}^{MBT}r^{i,o^i_{MBT}}_{t,s}$	Amount of MSW treated in MBT in region i, with option o^i_{MBT}, in time period t, in scenario s; real nonnegative
	${}^{L}r^{i}_{t,s}$	Amount of MSW landfilled in region i, in time period t, in scenario s; real nonnegative
	${}^{WtE}u^{i,o^i_{WtE}}_{t,s}$	Amount of unused capacity in WtE in region i, with option o^i_{WtE}, in time period t, in scenario s; real nonnegative
	${}^{MBT}u^{i,o^i_{MBT}}_{t,s}$	Amount of unused capacity in MBT in region i, with option o^i_{MBT}, in time period t, in scenario s; real nonnegative

The developed multi-stage multi-period stochastic mixed-integer programming mathematical model has the following form:

$$\min \sum_s p_s \left[\sum_{j,t} c_R^j \cdot x_{t,s}^j + \sum_{i,t} c_L^i \cdot {}^L r_{t,s}^i \right. \tag{1}$$

$$+ \sum_{i,o_{WtE}^i,t} {}^{WtE}c_{o_{WtE}^i}^i \left({}^{WtE}r_{t,s}^{i,o_{WtE}^i} + pen_{WtE} \cdot {}^{WtE}u_{t,s}^{i,o_{WtE}^i} \right) \tag{2}$$

$$\left. + \sum_{i,o_{MBT}^i,t} {}^{MBT}c_{o_{MBT}^i}^i \left({}^{MBT}r_{t,s}^{i,o_{MBT}^i} + pen_{MBT} \cdot {}^{MBT}u_{t,s}^{i,o_{MBT}^i} \right) \right] \tag{3}$$

s.t. $$\sum_j A^{i,j} x_{t,s}^j - \sum_{o_{WtE}^i} {}^{WtE}r_{t,s}^{i,o_{WtE}^i} - \sum_{o_{MBT}^i} {}^{MBT}r_{t,s}^{i,o_{MBT}^i} - {}^L r_{t,s}^i + \xi_{t,s}^i = 0, \quad \forall i, \forall t, \forall s, \tag{4}$$

$$\sum_{o_{WtE}^i} \sum_\tau w_{\tau,s}^{i,o_{WtE}^i} \leq 1, \quad \forall i, \forall s, \tag{5}$$

$$\sum_{o_{MBT}^i} \sum_\tau m_{\tau,s}^{i,o_{MBT}^i} \leq 1, \quad \forall i, \forall s, \tag{6}$$

$${}^{WtE}r_{t,s}^{i,o_{WtE}^i} + {}^{WtE}u_{t,s}^{i,o_{WtE}^i} = \sum_{\tau \leq t} k_{o_{WtE}^i}^i \cdot w_{\tau,s}^{i,o_{WtE}^i}, \quad \forall i, \forall t, \forall s, \tag{7}$$

$${}^{MBT}r_{t,s}^{i,o_{MBT}^i} + {}^{MBT}u_{t,s}^{i,o_{MBT}^i} = \sum_{\tau \leq t} k_{o_{MBT}^i}^i \cdot m_{\tau,s}^{i,o_{MBT}^i}, \quad \forall i, \forall t, \forall s, \tag{8}$$

$${}^L r_{t,s}^i + \kappa \cdot \sum_{o_{MBT}^i} {}^{MBT}r_{t,s}^{i,o_{MBT}^i} \leq g_1 \cdot \xi_{t,s}^i,, \quad \forall i, \forall s, t = 6, \dots, 10, \tag{9}$$

$${}^L r_{t,s}^i + \kappa \cdot \sum_{o_{MBT}^i} {}^{MBT}r_{t,s}^{i,o_{MBT}^i} \leq g_2 \cdot \xi_{t,s}^i, \quad \forall i, \forall s, t = 11, \dots, 15, \tag{10}$$

$${}^L r_{t,s}^i + \kappa \cdot \sum_{o_{MBT}^i} {}^{MBT}r_{t,s}^{i,o_{MBT}^i} \leq g_3 \cdot \xi_{t,s}^i, \quad \forall i, \forall s, t = 16, \tag{11}$$

$$w_{\tau,s}^{i,o_{WtE}^i} = w_{\tau,z}^{i,o_{WtE}^i}, \quad \forall i, \forall \tau \text{ for which } \xi_{[\tau],s}^i = \xi_{[\tau],z}^i, \tag{12}$$

$$m_{\tau,s}^{i,o_{WtE}^i} = m_{\tau,z}^{i,o_{WtE}^i} \quad \forall i, \forall \tau \text{ for which } \xi_{[\tau],s}^i = \xi_{[\tau],z}^i. \tag{13}$$

The objective function Eq(1) - Eq(3) is composed of the landfilling and transportation costs Eq(1), and the cost of operating the WtE plants Eq(2) and the MBT plants Eq(3). The constraint Eq(4) is a conservation of mass – the MSW produced in a region must be either shipped elsewhere or treated (by WtE, MBT or landfilling). The constraints Eq(5) and Eq(6) guarantee that at most one of the possible options for WtE and MBT plants can be built within a region. The constraints Eq(7) and Eq(8) control the waste processing capacities in the given region – if there was no (WtE or MBT) plant build in the decision stages up to time t, both the processing and the unused capacity variables will be set to zero. The considered milestones for landfilling are encoded in the constraints Eq(9) - Eq(11). The constraints Eq(12) and Eq(13) are the nonanticipativity constraints – in scenarios following the same progression of MSW production up to decision stage τ the same strategic decisions must be made (again, up to the decision stage).

3. Case study and future research directions

To test the validity of the method, a case study was conducted – the chosen country was the Czech Republic. The level of detail was rather small with the Czech Republic divided into 13 regions, considering 27 scenarios (see Fig 3.) and 9 options for the MBT and WtE plants. Aerobic processing was considered in MBT with subsequent processing of the outputs (e.g. refused-derived fuel utilisation in combined heat and power plant, landfilling of residuals). In 4 regions, the already existing WtE plants are also taken into consideration. The resulting model had over 50,000 variables, of which almost 19,000 were binary, which is by no means a small problem. The methodology described in Smejkalová et al. (2018) was used for the forecast of the production of MSW. As is apparent from Figure 1, almost 50 % of MSW produced in the Czech Republic is landfilled today. To ensure a smoother transition into the 2035 target of landfilling only 10 % of MSW (see Table 1), a series of progressive milestones is considered. These were set to 35 % by 2025 and 15 % by 2030.

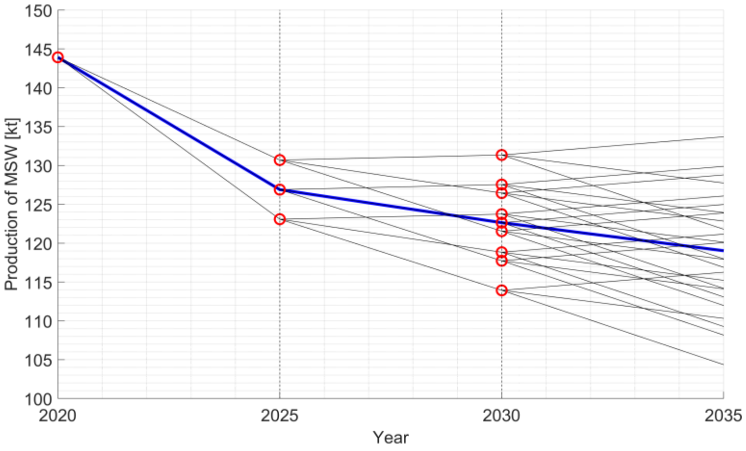
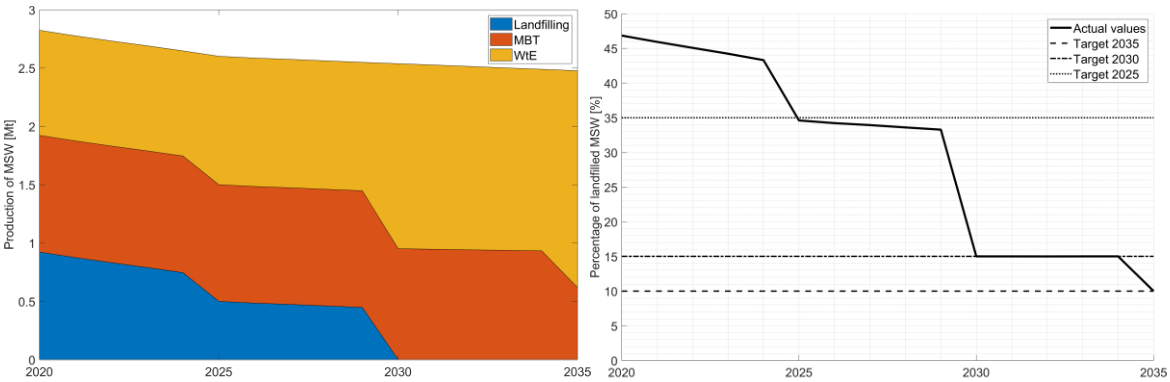


Figure 3: Scenario tree for one region. The forecasted production of MSW over the next 15 y is marked by a blue line. The red circles correspond to the strategic decision stages

The optimization problem was solved using the CPLEX 12.6.3 solver, with the optimality gap tolerance set to 1 %, which took about one hour of computations. The resulting strategic decisions were the following: In the first decision stage, 5 new MBT and 4 new WtE plants should be built – this decision was identical for all scenarios (enforced by the nonanticipativity constraints). In the second decision stage, one WtE plant should be built – the decision on placement/size of this facility is different for the three groups of scenarios with the same progression of MSW production (see Figure 3). In the third decision stage, 4 WtE plants (again, differing in location and size based on the scenarios) should be built. The optimal objective value (the treatment and transportation costs over the 15-y period) was $3.389 \cdot 10^9$ EUR. The resulting division of the MSW into different treatment options and the progression of the percentage of landfilled MSW over the 15-y period are summarized in Figure 4a and Figure 4b, showing the average values over the 27 scenarios. Direct landfilling as such is phased out by the year 2030 and the only material that needs to be landfilled is some percentage (κ) of the MBT treated MSW.

Future research will encompass further enrichment of the model by including a higher number of waste treatment options and the possibility of increasing the capacities of already existing waste processing plants. Another aspect that deserves a closer examination is the consideration of higher accuracy in the time domain (e.g. months instead of years). The incorporation of possible environmental and social aspects into the model will also be one of the primary considerations. A selection and implementation of a suitable solution algorithm for this type of optimization problem will enable us to analyze the situation on a much larger scale (in both the number of scenarios and the number of regions) – decomposition methods as in Málek et al. (2018) (progressive hedging algorithm) and Kůdela et al. (2018) (Benders decomposition), interval parameter programming as in Li and Huang (2009), and metaheuristics as in Marada et al. (2017) will be examined.



(a) (b)

Figure 4(a) MSW treatment over the 15-y period and (b) Percentage of landfilled MSW

4. Conclusion

In this paper, a multi-stage multi-period stochastic mixed-integer programming model was proposed for the strategic planning of waste processing infrastructure. The main concerns for establishing the MBT/WtE plants were the targets for the amount of landfilled waste, that are a part of the CEP initiative for the circular economy. The model was tested on a case study, considering the situation in the Czech Republic divided into 13 regions, considering 27 scenarios for future development. Through the presented approach, the direct landfilling was phased out by the year 2030. The only waste that is landfilled comes from MBT – residuals which are not suitable for material or energy recovery. The optimal objective value corresponding to the costs over the analyzed 15-year period was $3.389 \cdot 10^9$ EUR. Further improvements of the model in terms of the temporal/spatial granularity, the inclusion of social/environmental aspects, and the development of suitable algorithms are anticipated.

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