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Legislation-induced planning of waste processing infrastructure: A case study of the Czech Republic

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ABSTRACT

Trends in the treatment of municipal solid waste are changing worldwide. In the European Union, one of the largest economies in the world, the waste treatment and management among the member states vary significantly. To support and promote environmentally friendly waste management, the European Union issued directives commonly called the Circular Economy Package. This legislative is designed to accelerate the transition to a cleaner future. It gives an obligation to member states to meet specific landfilling and recycling targets. To reach these ambitious goals will be a challenging task, especially for the member states with less developed waste management systems. An approach using multi-stage stochastic programming is suggested for solving such a problem. The developed model considers current material recovery rates and trends in municipal waste, while uncertain waste production is forecasted by possible scenarios. The model enables sequential decision-making and assessment of various strategies for different future scenarios with specific years, locations, technologies and capacities for the establishment of the waste processing infrastructure. The utilization of the model and its computational tractability is demonstrated in a case study of the Czech Republic.

1. Introduction

Sustainability of human activities is evaluated by three basic aspects: economical, environmental and social. Sustainable development is highly influenced by municipal solid waste (MSW) treatment [1]. In the European Union, the preferred ways of waste treatment are defined by *Waste hierarchy*, which is anchored in the directive [2]. Waste management is a very complex task, which encompasses the whole process of waste handling: waste collection, transportation, eventual adjustment and final treatment. Different phases of waste handling are linked with a great variety of technological options and waste management methods.

Population growth, urbanization, and the changing lifestyle of people in developing countries are connected with an increase in the production of waste worldwide [3]. If the waste cannot be recovered materially, the next preferred way of treatment is energy recovery [4]. Waste management sustainability can be supported by the utilization of hidden potential in waste, which is one of the most significant future renewable energy source [5]. It presents one of the alternatives for fossil fuels which still cover most of the global energy production [6]. Waste incineration is not available in many developing countries (except in countries with fast-growing economies such as China, Malaysia, etc.) for the following reasons [7]:

- high initial and operating costs,
- unfavorable waste composition,
- lack of technical knowledge,
- availability of easy landfilling.

In developed countries (EU, US and Japan), the waste incineration for energy production is one of the common waste treatment options [8]. The Waste-to-Energy (WtE) facilities have quite lower emissions compared to electricity production facilities from fossil fuels (except natural gas), and help to reduce further greenhouse gases emissions from landfills [9]. The increase in the utilization of WtE plants in the EU is expected in the view of strict limitations of waste landfilling that should follow from the passed legislation.

In order to reinforce interventions that change currently

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List of abbreviations, units and nomenclature

Abbreviation	*Definition*	*Notes/Case study values*
MSW	municipal solid waste	
EU	European Union	
US	United States	
WtE	waste-to-energy	
CEP	Circular Economy Package	
MBT	mechanical biological treatment	
BAU	business as usual	
EUR	Euro	
kt	kilotonne	
s, z	Indices for scenarios $s, z \in \{1, \dots, 27\}$	
i	Index for cities $i \in \{1, \dots, 206\}$	
j	Index for routes between the cities $j \in \{1, \dots, 1898\}$	
t	Index for periods $t \in \{1, \dots, 11\}$	
τ	Index for decision stages $\tau \in \{1, 6, 11\}$	
o^i_{WtE}	Set of possible options for WtE plants in city i; For every city i, there are 9 options (these can differ between cities). These options have different capacities and treatment costs, based on the analysis of the candidate locations in the individual cities	
o^i_{MBT}	Set of possible options for MBT plants in city i; For every city i, there are 9 options (as in the WtE case discussed above)	
$k^i_{o^i_{WtE}}$	The capacity of the options for the WtE plant in city i	
$k^i_{o^i_{MBT}}$	The capacity of the options for the MBT plant in city i	
${}^{WtE}c^i_{o^i_{WtE}}$	Treatment cost of the options for the WtE plant in city i	
${}^{MBT}c^i_{o^i_{MBT}}$	Treatment cost of the options for the MBT plant in city i	
c^i_L	Landfilling cost in city i; Assumed static (not developing in time), around 70 EUR/t	
c^j_R	Shipping cost on arc j; Assumed static, 0.12 EUR/(t·km). The cost of fuel did not show any significant trend in the past years. If it were the case, the augmentation of the model by adding time-dependent shipping costs would be quite straightforward.	
$\xi^i_{t,s}$	Amount of produced MSW that requires treatment in city i, the time period t, scenario s; The most important stochastic parameter that was considered in this study. The scenario branching considers possible demographic and societal changes that affect the MSW production in individual cities	
$\xi^i_{[t],s}$	Progression of MSW production up to time period t, city i, scenario s, i.e. $\xi^i_{[t],s} = (\xi^i_{1,s}, \xi^i_{2,s}, \dots, \xi^i_{t,s})$; “Dummy” parameters used in the nonanticipativity constraints	
$A^{i,j}$	Incidence matrix of the road network	
pen_{WtE}	The penalty for unused WtE capacity $pen_{WtE} = 0.8$; This rather high penalty value ensures that the installed waste treatment facilities are properly utilized	
pen_{MBT}	The penalty for unused MBT capacity $pen_{MBT} = 0.8$; Same as above	
κ	The ratio of MBT treated MSW that needs to be landfilled $\kappa = 0.4$; Assumed static (no significant technological breakthroughts during the planning period) and independent of the MBT option	
$MSW_{t,s}$	The total amount of MSW generated in the whole region/country in time period t, scenario s	
p_s	The probability of scenario s; In the case study, all the scenarios had the same probability	
g_1, g_2, g_3	Target values for the amount of landfilled MSW $g_1 = 0.3$, $g_2 = 0.2$, $g_3 = 0.1$	
$x^j_{t,s}$	Flow on the arc j, time period t, scenario s; Real nonnegative variable	
$w^{i,o^i_{WtE}}_{\tau,s}$	Building the WtE plant in city i, with option o^i_{WtE}, in decision stage τ, in scenario s; Binary variable	
$m^{i,o^i_{MBT}}_{\tau,s}$	Building the MBT plant in city i, with option o^i_{MBT}, in decision stage τ, in scenario s; Binary variable	
${}^{WtE}r^{i,o^i_{WtE}}_{t,s}$	Amount of MSW treated in WtE in city i, with option o^i_{WtE}, in time period t, in scenario s; Real nonnegative variable	
${}^{MBT}r^{i,o^i_{MBT}}_{t,s}$	Amount of MSW treated in MBT in city i, with option o^i_{MBT}, in time period t, in scenario s; Real nonnegative variable	
${}^{L}r^{i}_{t,s}$	Amount of MSW landfilled in city i, in time period t, in scenario s; Real nonnegative variable	
${}^{WtE}u^{i,o^i_{WtE}}_{t,s}$	Amount of unused capacity in WtE in city i, with option o^i_{WtE}, in time period t, in scenario s; Real nonnegative variable	
${}^{MBT}u^{i,o^i_{MBT}}_{t,s}$	Amount of unused capacity in MBT in city i, with option o^i_{MBT}, in time period t, in scenario s; Real nonnegative variable	
f	Index for waste fraction	
RR_f	recycling rate for waste fraction f	
MAT_f	amount of materially recovered waste fraction f	
SEP_f	amount of separated waste fraction f	

unsustainable practices, the existing policies and legislation need to be reformed [10]. The trend in developed countries leads from the linear economy system to a circular economy. The impact of these legislative changes is an essential factor in waste management models. For example, the legislation induced changes on the gate-fee of and WtE plant were investigated in the paper [11]. To ensure the smooth transition to the circular economy in waste management, it is necessary to solve the complex tasks taking into account the different ways of waste handling and production forecasts. This contribution presents a multi-stage stochastic model as a support tool for the decision-making process. The approach is presented on the real data from the Czech Republic, which represents the country in the transition process from linear to the circular economy.

2. Literature review and theory

Waste management is a dynamically developing area that is currently subject to several changes that were outlined above. Within waste management, it is necessary to address the strategy of waste collection, waste transport and finally its treatment. The sustainability is measured along the triple bottom line [12]: economic, environmental and social impact. The following text is devoted to the literature review, which is divided into thematic parts with the final evaluation of the research gap.

2.1. Circular economy

In recent years there has been an effort to move from a linear economy to a circular economy. These tendencies arise worldwide, mainly because of the limited capacities of primary sources and environmental pollution. The study [13] pointed out that current trends in the circular economy are built on research into resource efficiency [14]. The paper [15] formulated ten common circular economy strategies: recovery, recycling, repurpose, remanufacture, refurbish, repair, re-use,

Table 1
The targets anchored in the Directives within CEP.

Action	Source	Waste stream	2025	2030	2035
Recycling/reuse (minimum)	Directive (EU) 2018/851 [18];	Municipal solid waste	55%	60%	65%
	Directive (EU) 2018/852 [19];	Packaging waste	65%	70%	
		Packaging paper	75%	85%	
		Packaging plastics	50%	55%	
		Packaging glass	70%	75%	
		Packaging ferrous metals	70%	80%	
		Packaging aluminum	50%	60%	
		Packaging wood	25%	30%	
Landfill (maximum)	Directive (EU) 2018/850 [20];	Municipal solid waste			10%
Reduction (minimum)	Directive (EU) 2018/851 [18];	Food waste	30%	50%	

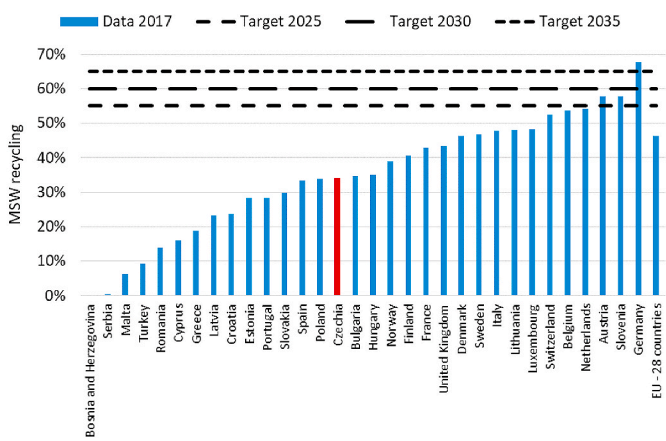


Fig. 1. Municipal waste recycling in the year 2017 and recycling targets (Eurostat, 2019 [21]).

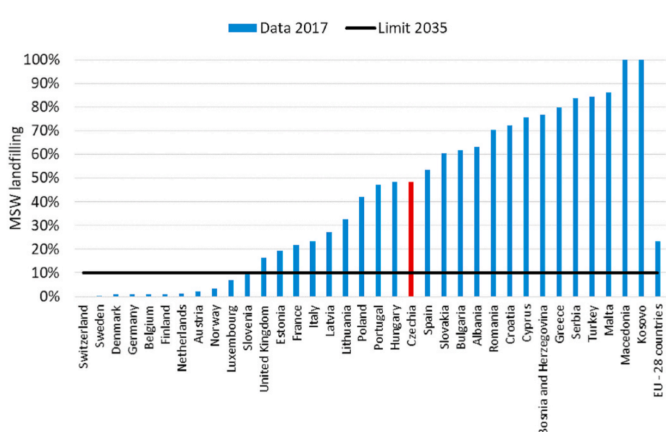


Fig. 2. Municipal waste landfilling in the year 2017 and the landfilling limit [21].

reduce, rethink, refuse. The aim is to maintain the value of the product for as long as possible to exploit its maximum utility. The principle is in the closing loops of products, product parts and materials. The transition from a linear to a circular economy brings with it a range of practical challenges for policies and companies. The paper [16] developed a framework of strategies to guide designers and business strategists in the move from a linear to a circular economy. The transition to a circular economy will be reflected throughout the production chain. Three basic principles characterize the circular business model: closing, slowing and narrowing resource loop. However, the measurement and assessment of circularity performances are not yet a common practice in companies.

The transition to a circular economy requires actions and legislative intervention. Turning waste into a resource is an essential part of increasing resource efficiency and closing the loop in a circular economy. In 2018, the European Commission accepted the Circular Economy Package (CEP) with the stated goal of "closing the cycle" of the product life cycle. It seeks to establish an action program with measures covering the whole cycle from production and consumption to waste management and the secondary raw materials market [17]. According to the CEP, the aim is to minimize waste so that once a product reaches the end of its life, its materials will be kept within the economy for as long as possible. What was previously considered as "waste" is therefore transformed into a valuable resource. The EU member states must incorporate directives included in the CEP into national legislation.

The targets included in the CEP are summarized in Table 1. The recycling targets set a minimum percentage of recycled or reused wasted, and they deal with both general municipal solid waste and particular packaging waste. The next important milestone is landfill restriction at maximal 10%, which will come into force in 2035. CEP also addresses the issue of prevention by means of food waste reduction.

The assessment of the current situation (in 2017) for European states is illustrated in Fig. 1 and Fig. 2. Fig. 1 shows the current waste recycling of 32 states in relation to the desired targets. On average, only 46.4% of MSW is recycled by the 28-EU Member States. The only country that currently meets the strictest target set for the year 2035 is Germany. Unfortunately, most countries are not very close to these recycling targets at present. The Czech Republic, as a representative of countries in the transition process from linear to the circular economy, recycles approximately 34% of MSW (red color in Fig. 1).

Alongside the recycling targets, the member states also have to react to the landfilling restrictions. A total of 11 countries already meet the landfilling limit, see Fig. 2. On average, EU-28 Member States landfill currently 23.4% of waste.

It is important to consider the different levels of development of individual EU member states and their starting position. In some cases, which are specified in the relevant Directives, a member state may request that the deadlines be postponed. The Czech Republic ranks in both the recycling and landfilling somewhere in the middle of the EU-28 countries. There has been a lack of financing in the Baltic countries to promote and operate waste incineration. Their first goal after joining the EU was to avoid dumping at uncontrolled sites and to meet the EU standards. Later on, Estonia has become the most advanced of these countries in terms of waste avoidance and recycling in the capitals, and it is ranking top even in the whole EU. The construction of WtE and MBT plants has shifted total landfilling drastically [22]. On the other hand, Poland, which is the neighbor of the Czech Republic, still has problems securing the real values of waste production. It is caused by existing gaps in landfill weighting or illegal dumping. Poland is also in the middle of the EU countries regarding landfilling, but its WtE sector has been evolving dynamically in the recent years in contrast to the Czech Republic, where new projects are waiting for greater legislative support.

Croatia, as the southern country from the EU, still landfills a significant amount of the MSW. Even though it has recently adopted the national Waste Management Plan 2017–2022, its implementation is delayed. Reaching the targets from the CEP will require substantial investment in waste infrastructure. So far, the investments and plans have not been efficient, causing the future overcapacity of MBT plants. The waste hierarchy has not been properly followed, and responsibilities among authorities were not in line with each other. One of the proposed changes is to focus on bio-waste, its composing and separation at source. Waste management centers in operation are costly and not the best option available since it only increases landfilling and produces low

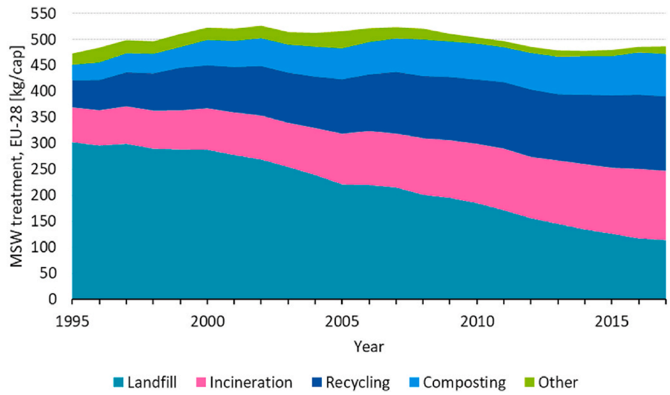


Fig. 3. Municipal waste treatment, EU-28, (kg/capita) (Eurostat, 2019 [21]).

quality refuse-derived fuel [23]. The performance of the EU-28 countries has been compared in detail [24]. The degree of transition to the circular economy is measured by defined indicators considering waste production, material reuse or recycling and their correlation with Growth Domestic Product has been proven.

In response to CEP, EU member states will make efforts to reduce the amount of landfilled MSW. Where possible, MSW is used for material or energy recovery. MSW treatment methods over the period 1995–2017 are illustrated in Fig. 3 for the EU-28 countries. Waste prevention is not reflected in historical data, although it is the most preferred method by *Waste management hierarchy* [2]. There is a clear trend in landfill reduction in the long-term. Despite the objectives of maximizing recycling, a direct transition from landfill is not possible without intermediate steps in the form of WtE, which plays a not negligible role in the circular economy [22]. Different WtE processes were clearly assigned to options in the waste hierarchy ladder [25]. However, there are concerns about undermining the waste hierarchy with respect to new incineration plants.

2.2. Waste management tasks

Waste management is concerned with adapting existing infrastructure to create a satisfactory and sustainable system. Most tasks from waste management can be classified into the following categories:

Waste collection and transport play an important role in the processing chain. Waste collection routes are the output of vehicle routing models. Because of the computational complexity, heuristic solutions are often used [26]. Most often, the minimum travel cost is the aim of optimization [27].

Location problems search for the optimum placement of new waste treatment facilities [28]. Also, the optimal location of transfer stations [29] and the deployment of waste collecting bins in the cities [30] fall into this category. There are several methods used to solve the location problems, among which are the overlay technique [28] and mixed-integer programming approaches [31].

Allocation problems deal with waste streams from producers to processing sites [32].

Facility design addresses all technological obstacles of individual subsystems. The aim is to dimension the facility so that it can process waste from the appropriate collection area [33].

The collection of MSW is highly dependent on the development level of the country in question [34]. While informal recycling and manual labor for collection and transportation of MSW are common practices in developing countries [35], in developed countries mechanical collection systems [36] of segregated MSW are more commonly practiced [37].

An extensive review of models for supply chain systems was presented by Ref. [38]. Collection and transportation represent a considerable part of the cost within the waste management system. For example, in India, which represents developing countries, the collection and transportation cost is estimated at 70–85% [39]. But collection and transportation costs are significant also for developed countries, e.g. in Sweden, they amount to 50–75% of waste management cost [40].

Transfer stations are often used to support waste transportation for long distances. Approaches for selection of appropriate transfer station locations include spatial multi-criteria analysis [41], interval optimization [42], multi-objective stochastic programming [43], and GIS-based

Table 2
Waste management tasks, data types and solution methods of the selected works.

	Task				Data type		Solution method
	Collection	Location	Allocation	Design	Deterministic	Uncertain	
Badran et al., 2006 [31];		✓			✓		MIP
Benjamin et al., 2010 [59];	✓				✓		Heuristic
Boonmee et al., 2018 [55];		✓	✓		✓		Heuristic
Cebi et al., 2016 [57];		✓				✓	Hybrid model
Chatzouridis et al., 2012 [45];	✓	✓			✓		MIP
Cheng et al., 2003 [32];		✓	✓			✓	MIP
Das et al., 2015 [27];	✓				✓		Heuristic
Gambella et al., 2019 [63];			✓			✓	MIP
Ghiani et al., 2012 [30];		✓	✓		✓		Heuristic
Ghose et al., 2006 [39];	✓				✓		Energy consumption
Hrabec et al., 2019 [65];		✓	✓			✓	MIP
Hu et al., 2017 [49];		✓				✓	MIP
Jin et al., 2019 [33];			✓	✓		✓	Fuzzy linear programming
Kim et al., 2005 [58];	✓				✓		Heuristic
Kudela et al., 2019 [43];		✓	✓			✓	MIP
Li et al., 2008 [66];			✓	✓		✓	Fuzzy MIP
Li et al., 2009 [67];			✓	✓		✓	Inexact fuzzy stoch.
Li et al., 2012 [64];			✓			✓	Fuzzy-stoch. Quadratic programming
López et al., 2008 [56];		✓			✓		Metaheuristic
Randazzo et al., 2018 [62];		✓			✓		GIS, multi-criteria analysis
Sonesson, 2000 [40];	✓				✓		Mechanistic approach
Tung et al., 2000 [26];	✓				✓		Heuristic
Yadav et al., 2016 [68];		✓			✓		MIP
Yadav et al., 2018 [29];		✓				✓	Interval programming
Yousefi et al., 2018 [28];		✓			✓		Index overlay method
Zhao et al., 2016 [53];	✓	✓			✓		MIP
this work		✓	✓			✓	MIP

Table 3
Optimization criteria and decision stages of the selected works.

	Criteria			Optimized part of the waste management chain	Objective function		Stage	
	Economical	Environmental	Social		Single	Multi	One	Multi
Badran et al., 2006 [31];	✓			Collection stations	✓		✓	
Benjamin et al., 2010 [59];	Number of vehicles			Collection	✓		✓	
Boonmee et al., 2018 [55];	✓	✓		Composting, recycling, land.		✓	✓	
Cebi et al., 2016 [57];	✓			MBT	✓		✓	
Chatzouridis et al., 2012 [45];	✓			Transfer station	✓		✓	
Cheng et al., 2003 [32];	✓	✓	✓	Landfill		✓		two
Das et al., 2015 [27];	✓			Transfer station, treatment facility, recycling, composting	✓		✓	
Gambella et al., 2019 [63];	✓			Treatment facility	✓			two
Ghiani et al., 2012 [30];	Number of collection sites			Bins	✓		✓	
Ghose et al., 2006 [39];	✓			Collection	✓		✓	
Hrabec et al., 2019 [65];	✓			Waste reduction	✓			two
Hu et al., 2017 [49];	✓	✓		WtE		✓		two
Jin et al., 2019 [33];	✓	✓		WtE, land.		✓	✓	
Kim et al., 2005 [58];	Traveling time, number of vehicles			Collection		✓	✓	
Kudela et al., 2019 [43];	✓	✓		Transfer station		✓		two
Li et al., 2008 [66];	✓			Unspecified ways of treatment	✓			two
Li et al., 2009 [67];	✓			Composting, recycling, land.	✓			✓
Li et al., 2012 [64];	✓	✓		Composting, recycling, land.		✓		✓
López et al., 2008 [56];	✓			Biomass power plant	✓		✓	
Randazzo et al., 2018 [62];	✓	✓	✓	Land.		✓	✓	
Sonesson, 2000 [40];	Energy consumption			Collection	✓		✓	
Tung et al., 2000 [26];	✓			Collection	✓		✓	
Yadav et al., 2016 [68];	✓			Transfer station	✓		✓	
Yadav et al., 2018 [29];	✓			Transfer station	✓		✓	
Yousefi et al., 2018 [28];		✓		Land.			✓	
Zhao et al., 2016 [53];	✓	✓		MBT		✓	✓	
this work	✓			WtE, MBT, land.	✓			✓

technologies [44], which can also be used together with binary optimization [1].

Based on the *Waste hierarchy*, landfilling is the least desirable way of waste treatment. Yet it still prevails in many countries, even in developed EU countries (as depicted in Fig. 2). However, current trends are gradually reducing landfilling and waste is largely used for material or energy recovery. A recent review of the WtE technologies can be found in the studies [46], which considered bio-waste, and [47], where the authors also consider the utilization of landfill gas for power production. The paper [48] reported that energy recovery from waste is an integral part of an environmentally sustainable waste management strategy. The contribution [49] developed the model for WtE location based on stochastic parameters considering economical and environmental criteria.

Recent studies [50] emphasized other advantages of incineration (apart from volume reduction and electricity generation) such as the utilization of bottom and fly ash of incineration plants in road construction and cement production, and recovery of ferrous and non-ferrous substances. This suggests that the technological development in metal recovery from dry bottom ash of incineration plants will enhance the acceptance of WtE facilities [13]. The study [51] reported on the average recoverable energy contents (in terms of electrical energy efficiency) of the different components of MSW using different WtE technologies. It was found that anaerobic digestion is the best-suited WtE option for food and yard wastes, while gasification is the best WtE option for treating plastic wastes. Incineration was found to be an attractive option amongst all the waste streams, as it can be used for energy recovery from all the reported waste streams. Other types of wastes, such as inert, metals, glass, etc., were not considered in the abovementioned study.

The study [52] focused on a Life cycle assessment of four waste management strategies in the municipality of Rome (Italy): landfill without biogas utilization; landfill with biogas combustion to generate electricity; sorting plant which splits the inorganic waste fraction from the organic waste fraction; and direct incineration of waste. Results, which they claim to be useful for most of the big European cities, show landfill systems as the worst waste management options and significant environmental savings at the global scale are achieved from undertaking energy recycling. Furthermore, waste treatments finalized to energy recovery provide an energy output that could meet 15% of Rome electricity consumption (in one of the considered case scenarios).

In the United States, for example, about 13% of power is generated from alternative electricity-production sources; of this fraction, approximately 11% of the alternative production is the contribution of biomass [53]. However, the high costs of biomass power generation, as well as the unreasonable distribution of biomass power plants [54] have led to an insufficient feedstock supply and some of the environmental issues hindering this industry from further development. Models can be targeted to exceptional situations such as in post-disaster waste management [55].

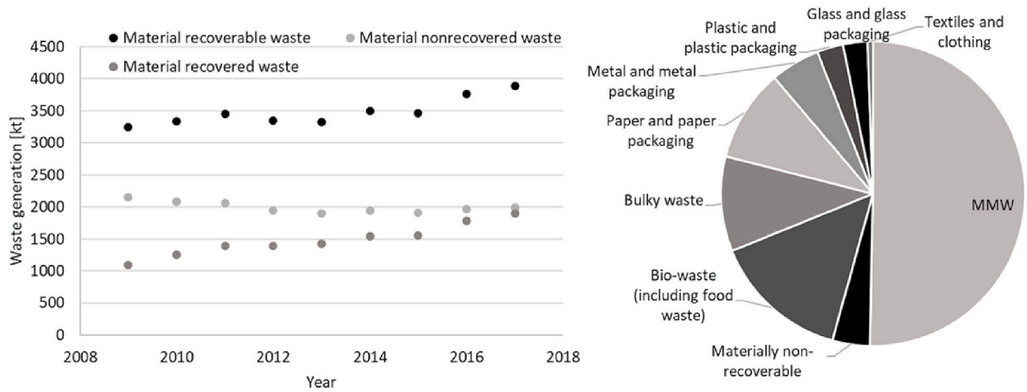
The types of waste management tasks for contributions mentioned in the literature review text are summarized in Table 2.

2.3. Optimization models

2.3.1. Single-criteria vs. multi-criteria models

When solving waste management tasks, models are often limited to just one criterion, in most cases total costs. The contribution [56] dealt with a suitable location for biomass power plant with minimum cost, where the model was solved using metaheuristic. Also [57] searched the location for a biomass power plant but with the fuzzy input information. The study [26] presented modified Solomon's insertion algorithm to solve the vehicular routing problem. The objective function sometimes minimizes other value, such as traveling time [58] or vehicles number [59].

The multi-criteria models consider not only the costs but also the environmental problems and social affairs that correspond to the different decisions [60]. The public acceptance of MSW treatment facilities can be largely driven by the social and cultural perception of the positive impact of resource recovery processes and facilities in the community. If they are perceived to foster climate change mitigation, and address local deficiencies or inefficiencies, such as employment, energy and fertilizer shortages, these are highly accepted by the community (especially in rural areas where jobs and energy supply are of greater concern) further enhancing socio-economic processes and



a) Material recoverable waste and its utilization 2009–2017, the Czech Republic

b) The MSW composition in 2017, the Czech Republic

Fig. 4. Material recoverable waste treatment in the Czech Republic.

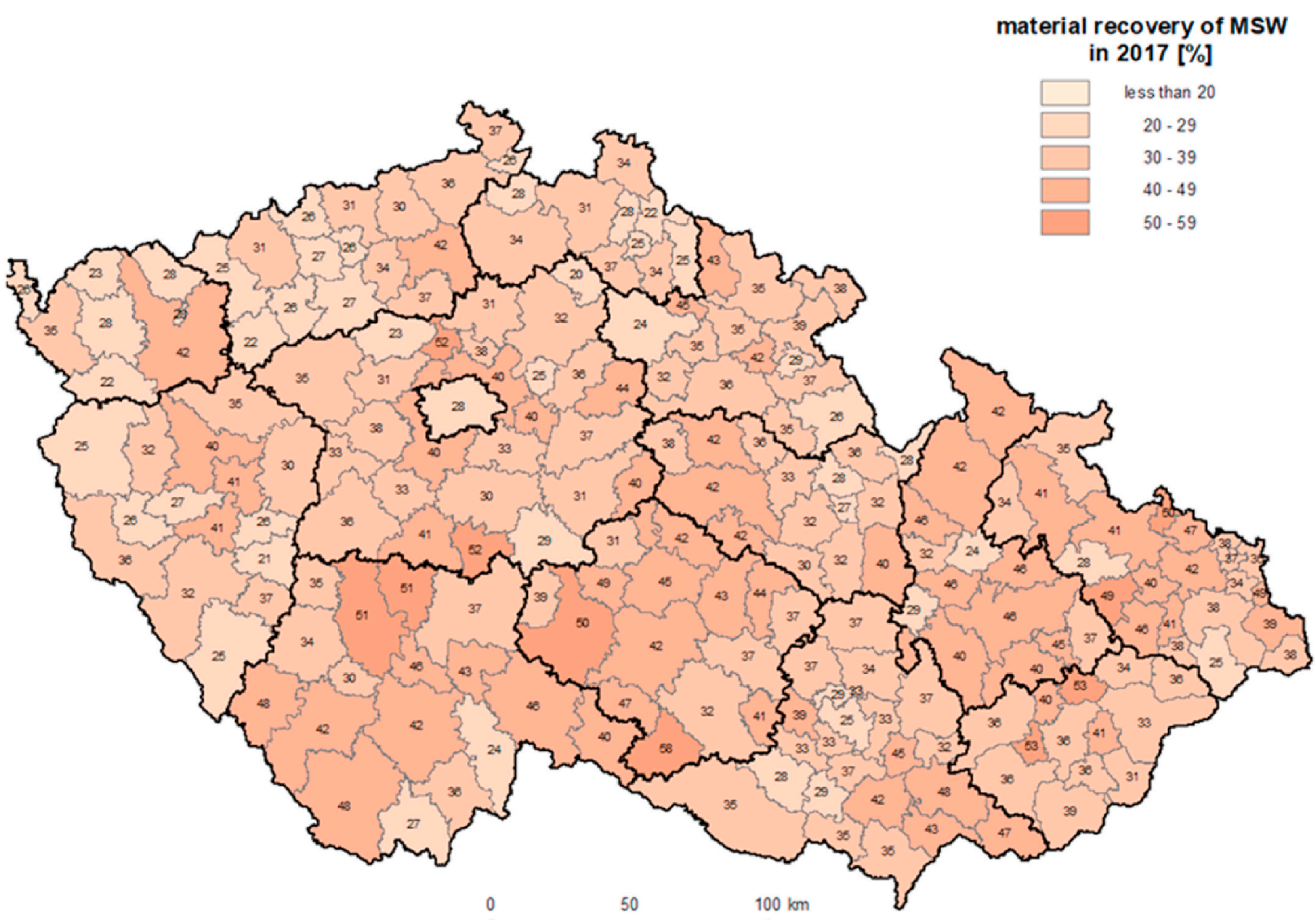


Fig. 5. Material recovery of MSW in the Czech Republic in 2017.

improving the human, social and cultural capital [61]. The operation research perspective on the strategic decision-making that takes place in designing sustainable systems was carried out [38]. The authors found that the economic and environmental aspect of the decision-making outweighed the social aspects in the majority of recent studies. One of the studies [32] that took into account economic, environmental and social impacts, where the authors created a comprehensive approach for landfill location and also dealt with waste stream allocation in the city of Regina (Canada). Similarly, the paper [62] developed an approach for landfill location in Sicily by multi-criteria analysis. The environmental assessment of the site of the landfill was discussed in the study [28] using an index overlay method.

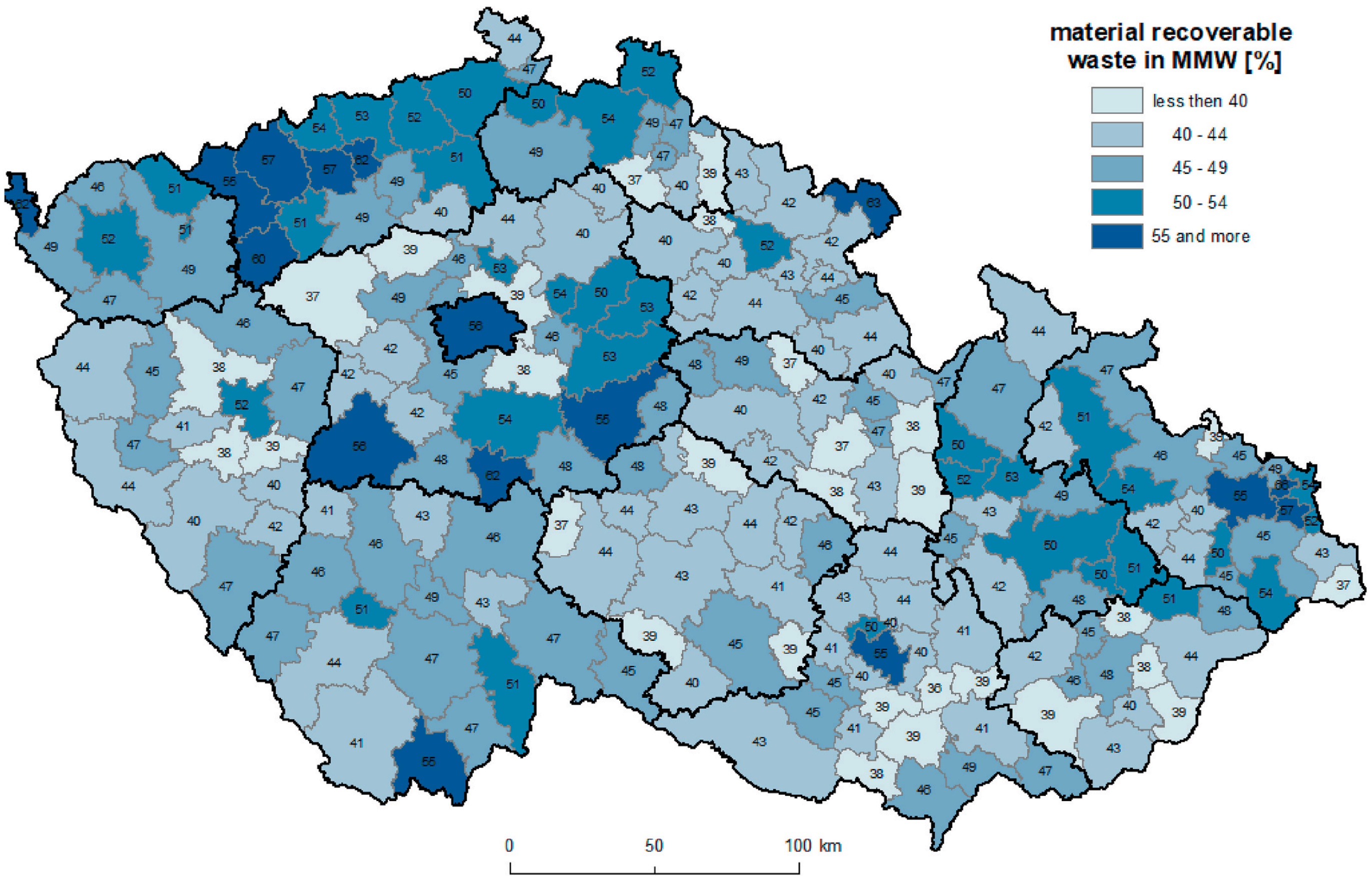


Fig. 6. Proportion of materially recoverable waste if MMW in the Czech Republic in 2017.

Table 4
Recycling rates for the different waste fractions in 2015.

Waste fraction f	RR_f
Bio-waste (including food waste)	0.91
Bulky Waste	0.17
Glass and glass packaging	0.90
Metal and metal packaging	0.87
Paper and paper packaging	0.90
Plastic and plastic packaging	0.89
Textiles and clothing	1.00

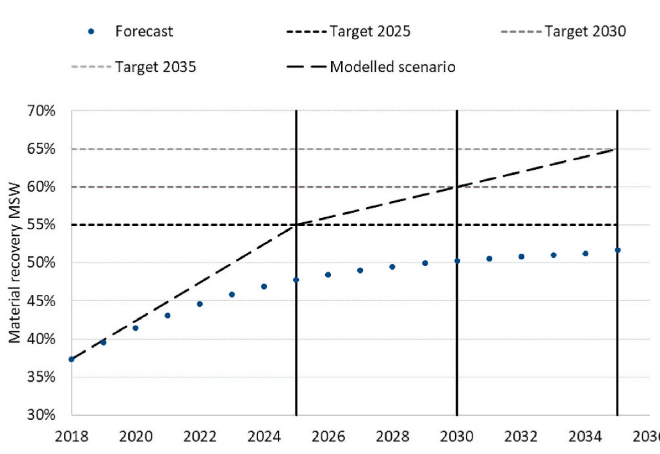


Fig. 7. Forecasting of material recovery in the Czech Republic under current conditions and scenario for targets fulfilling.

2.3.2. *Single-stage vs. multi-stage models*

The dynamic nature of the decision-making process is best captured in the use of models with several decision stages, that correspond to successive instances in time. Whereas single-stage models are best-suited to situations, where the corresponding model data are static (do not change over time), multi-stage models are more appropriate for dynamically changing environments. The difficulty with multi-stage approaches lies in an increase in computational and modelling complexity. As can be seen in Table 3, most of the relevant literature focuses on single-stage models. A sort of an intermediate step between the single-stage and multi-stage models is the two-stage model. In this setting, typically the "important decisions", such as facility locations and their design, are made in the first stage of the model. The second stage than serves to assess the impact that the "important decisions" will have in time. This approach was used in the study [63], where the authors describe a stochastic two-stage multi-period stochastic optimization model for the allocation of waste flows. Similarly, the two-stage model was used in a robust setting for a selection of WtE facilities [49] and in a stochastic setting for a design of a transfer station network [43]. The only work that presents a proper multi-stage model was the one [64] for bi-objective waste allocation in a fuzzy optimization setting.

2.3.3. *Deterministic vs. uncertain models*

A similar dichotomy, as the one between the single-stage and multi-stage models, exists in the approaches to the considered data of the model. When modelling a static situation with very little data variation, the deterministic approaches are the most sensible ones (and the ones most widely used). However, when the system that should be managed is dynamically changing and there are multiple possible paths of development, uncertain models are the most reasonable choice. This naturally means that there are very few contemporary works that are in

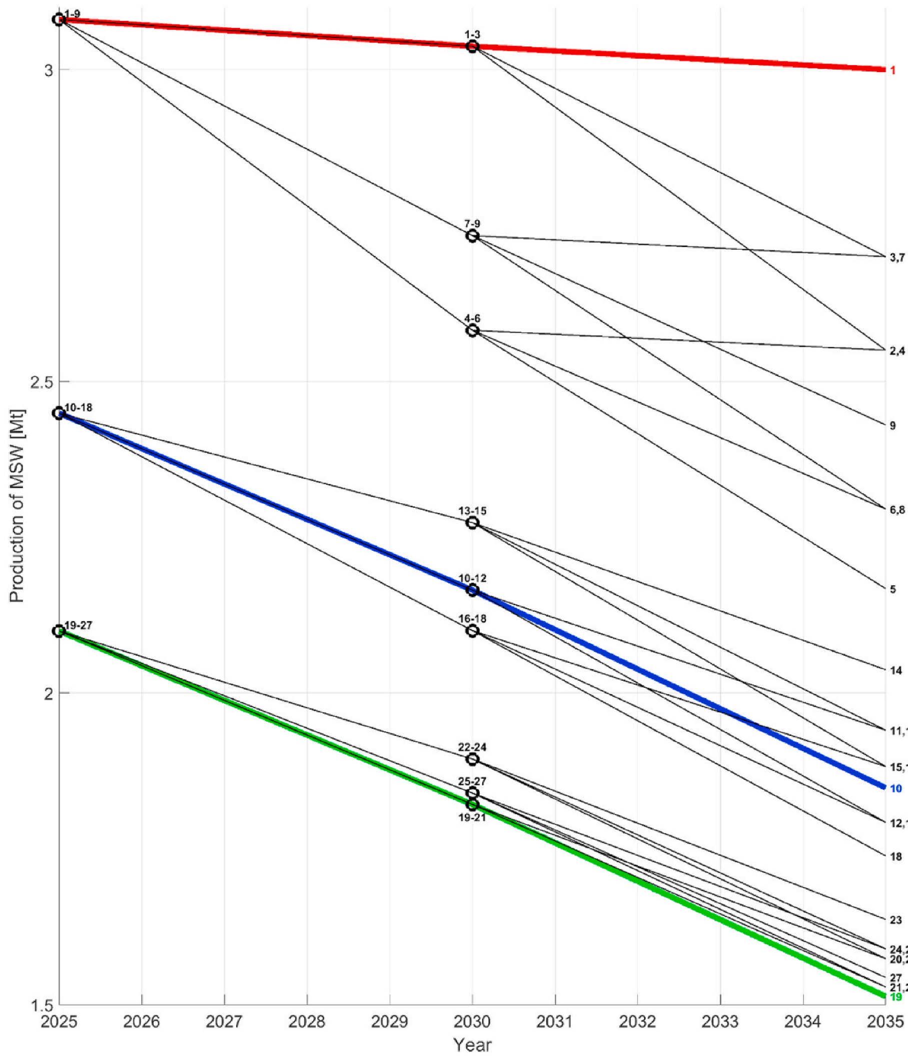


Fig. 8. Scenario branching. Red scenario (1) – BAU, blue scenario (10) – middle, green scenario (19) – on target. Aggregate data for the whole republic. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

a multi-stage setting with deterministic data. Three major approaches try to deal with uncertainty in the data: fuzzy programming, robust programming and stochastic programming. Fuzzy programming was used for waste allocation [33] and facility design [64]. Robust programming was used for waste reduction [65] and a bi-objective selection of WtE facilities [49]. Stochastic programming approaches were used in transfer station planning [43] and waste flow allocation models [63].

2.4. Research gap and novelty

Most contributions deal with setting up individual parts of the processing chain. There are also papers with a comprehensive approach to waste management, but the sequence of steps with regards to time is often disregarded. The dynamical decision-making process that is enabled by the multi-stage models increases the likelihood of a successful deployment of the system, compared to radical changes that correspond to the one-stage models. Since the legislation-induced changes that are coming into effect will significantly alter the production of MSW and its possible treatment options, this dynamic setting is well justified. This paper presents a stochastic multi-period and multi-stage model that captures the planning and decision-making process of selecting the locations and sizes of waste treatment plants, and the subsequent waste flow allocation. Sequential decision-making during the time horizon represents a significant benefit of the model. Despite the complexity of the model, it remains computationally tractable even for real-world instances, which is demonstrated in a case study of the Czech Republic. The approach represents a suitable supporting mathematical apparatus for the "smooth" transition from linear to the circular economy.

3. Multi-stage stochastic optimization model

The presented optimization model falls into the category of multi-stage multi-period stochastic mixed-integer optimization models. There are several monographs dedicated to stochastic programming, with [69] offering the standard more theoretical treatment, and [70] with a more hands-on modelling focus. The goal is to select the optimal locations and sizes of waste treatment facilities in selected cities. Two types of facilities are considered: WtE plants where the waste is incinerated to produce heat and electricity, and mechanical biological treatment (MBT) plants where the MSW is sorted and then either treated with anaerobic digestion or landfilled (the proportion of MBT that needs to be landfilled is denoted as κ). The relationship between the size and cost of treatment in a facility is not simply linear. To model it efficiently, the sizes of the facilities can be chosen only from a predefined set of values. In this way, the linearity of the model can be preserved, although at the cost of introducing new binary variables.

The objective function is purely economical and expresses the ex-

Table 5
The results of the computations. (PG – progressive goals).

	year 2025		year 2030		year 2035	
	with PG	without PG	with PG	without PG	with PG	without PG
max landfilling [%]	29.85	40.15	19.92	38.57	10	10
mean landfilling [%]	21.03	31.61	13.25	26.65	7.35	8.78
max # of new facilities	9	0	6	0	5	16
mean # of new facilities	9	0	2	0	1.89	10.66
mean installed WtE capacity [kt]	981	741	981	741	1099	1074
min used WtE capacity [%]	100	100	100	100	72.31	79.14
mean used WtE capacity [%]	100	100	100	100	97.14	96.69
mean installed MBT capacity [kt]	600	0	883	0	890	822
min used MBT capacity [%]	100	–	100	–	76.30	69.15
mean used MBT capacity [%]	100	–	100	–	96.33	96.80

pected costs of the whole waste treatment system over the considered time period (transportation costs, gate fees at the WtE and MBT plants, penalties for unused capacity, and landfilling fees):

$$\min \sum_s p_s \Bigg[\sum_{j,t} c_R^j \cdot x_{t,s}^j + \sum_{i,t} c_L^i \cdot {}^L r_{t,s}^i + \sum_{i,o^i_{WtE},t} {}^{WtE}c^i_{o^i_{WtE}} \left({}^{WtE} r_{t,s}^{i,o^i_{WtE}} + pen_{WtE} \cdot {}^{WtE}u_{t,s}^{i,o^i_{WtE}} \right) + \sum_{i,o^i_{MBT},t} {}^{MBT}c^i_{o^i_{MBT}} \left({}^{MBT} r_{t,s}^{i,o^i_{MBT}} + pen_{MBT} \cdot {}^{MBT}u_{t,s}^{i,o^i_{MBT}} \right) \Bigg] \tag{1}$$

The constraints can be grouped into a few categories. The first one comprises of the "conservation of mass" constraints, which enforce that the waste generated in or shipped into city i is either shipped away or disposed of (through one of the treatment options):

$$\sum_j A^{i,j} x^j_{t,s} - \sum_{o^i_{WtE}} {}^{WtE}r^{i,o^i_{WtE}}_{t,s} - \sum_{o^i_{MBT}} {}^{MBT}r^{i,o^i_{MBT}}_{t,s} - {}^L r^i_{t,s} + \xi^i_{t,s} = 0, \quad \forall i, \forall t, \forall s. \tag{2}$$

Another set of constraints restricts building new facilities. If there already is a facility of the given type (WtE or MBT), another one cannot be built:

$$\sum_{o^i_{WtE}} \sum_{\tau} w_{\tau,s}^{i,o^i_{WtE}} \leq 1, \quad \forall i, \forall s, \tag{3}$$

$$\sum_{o^i_{MBT}} \sum_{\tau} m_{\tau,s}^{i,o^i_{MBT}} \leq 1, \quad \forall i, \forall s. \tag{4}$$

Next are the constraints that compute the amount of used and unused capacity in the waste treatment facilities in different cities:

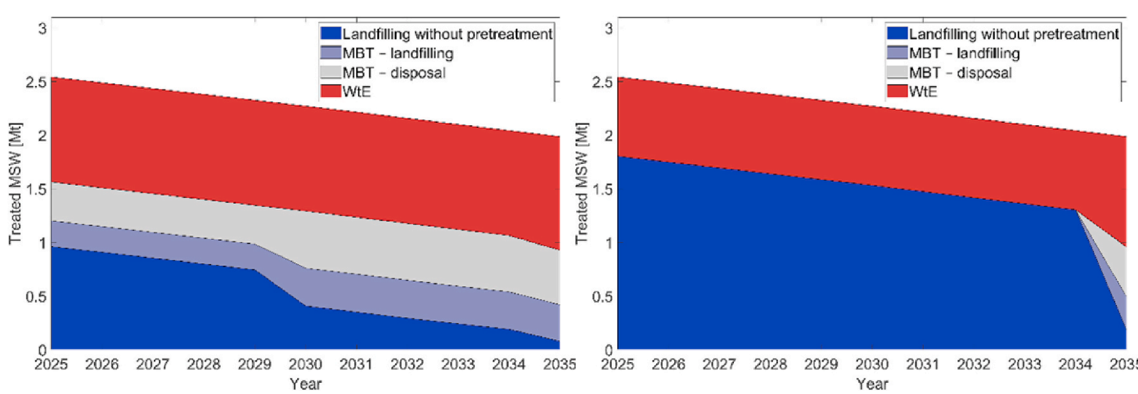


Fig. 9. The volume of MSW treated by the different options in 2025–2035. Solution with progressive goals on the left, the one without progressive goals on the right.

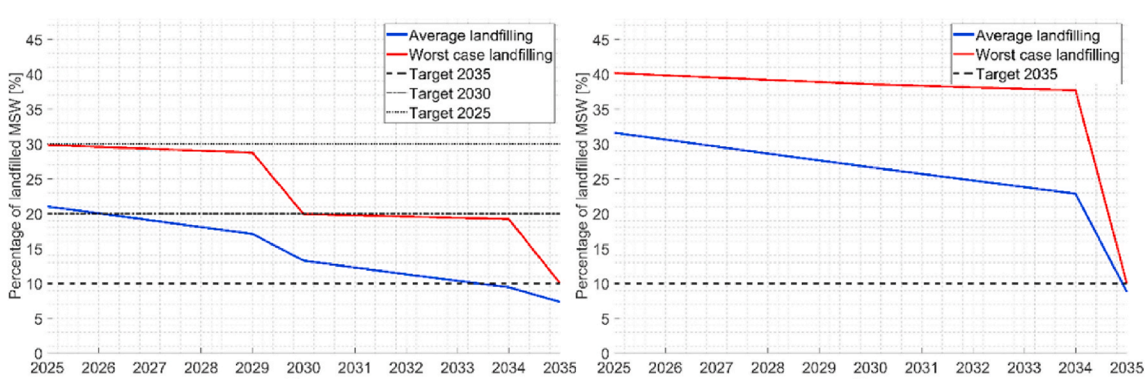


Fig. 10. Percentage of landfilled MSW in 2025–2035. Solution with progressive goals on the left, the one without progressive goals on the right.

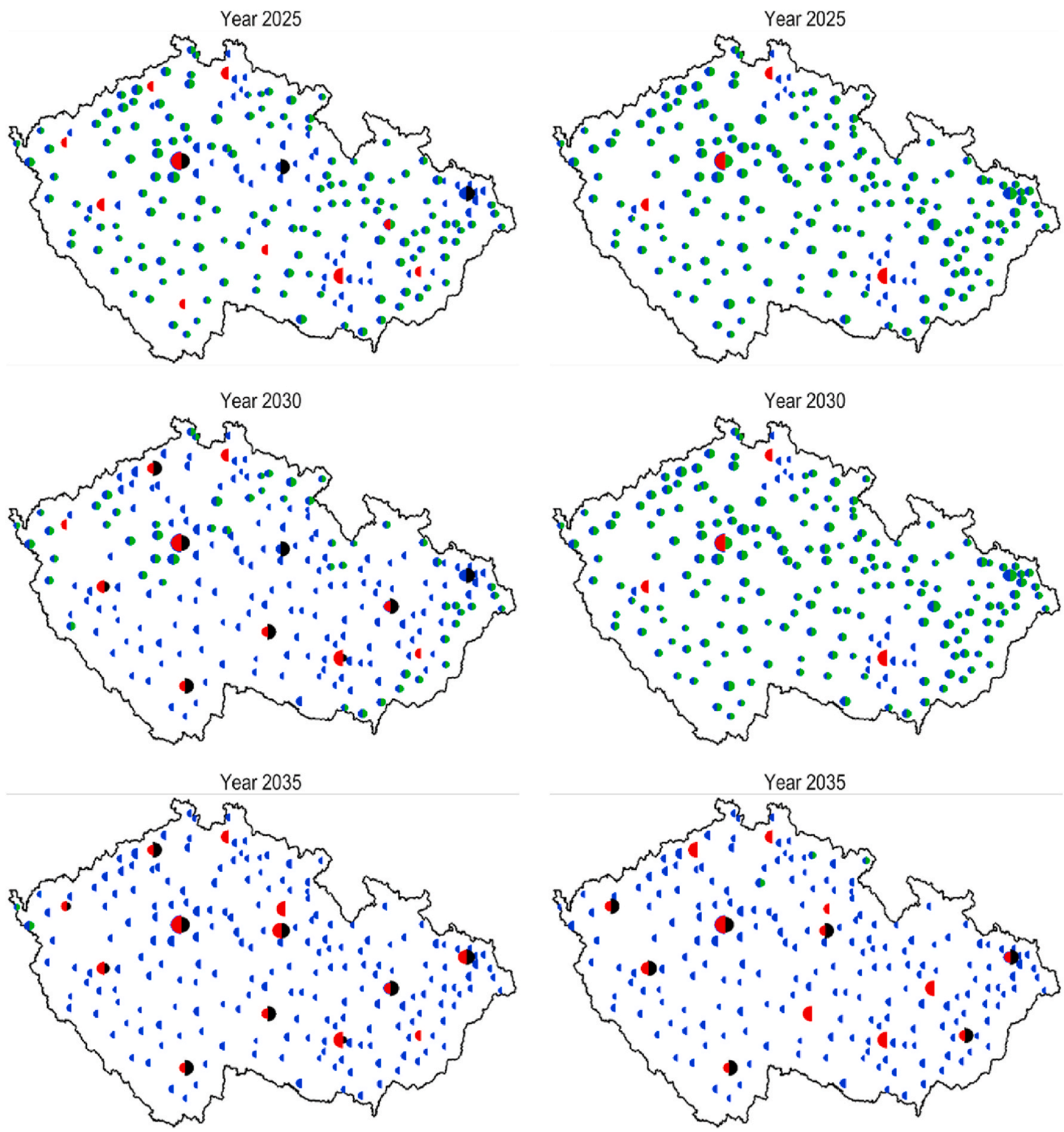


Fig. 11. Scenario 1. Solution with progressive goals on the left, the one without progressive goals on the right. The amount of generated MSW in blue, amount landfilled without pretreatment in green, amount treated in WtE plant in red, and the amount treated in MBT plant in black half-circles. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

$$ {}^{WtE}r_{t,s}^{i,o^i_{WtE}} + {}^{WtE}u_{t,s}^{i,o^i_{WtE}} = \sum_{\tau\le t} k^i_{o^i_{WtE}} \cdot w_{\tau,s}^{i,o^i_{WtE}}, \quad \forall i, \forall t, \forall s, \tag{5} $$

$$ {}^{MBT}r_{t,s}^{i,o^i_{MBT}} + {}^{MBT}u_{t,s}^{i,o^i_{MBT}} = \sum_{\tau\le t} k^i_{o^i_{MBT}} \cdot m_{\tau,s}^{i,o^i_{MBT}}, \forall i, \forall t, \forall s. \tag{6} $$

The penultimate set of constraints consists of the targets for the amount of landfilled MSW:

$$ \sum_j \left({}^{L}r^i_{t,s} + \kappa \cdot \sum_{o^i_{MBT}} {}^{MBT}r_{t,s}^{i,o^i_{MBT}} \right) \le g_1 \cdot \mathrm{MSW}_{t,s}, \quad \forall i, \forall s, t = 1, \dots, 5, \tag{7} $$

$$ \sum_j \left({}^{L}r^i_{t,s} + \kappa \cdot \sum_{o^i_{MBT}} {}^{MBT}r_{t,s}^{i,o^i_{MBT}} \right) \le g_2 \cdot \mathrm{MSW}_{t,s}, \quad \forall i, \forall s, t = 6, \dots, 10, \tag{8} $$

$$ \sum_j \left({}^{L}r^i_{t,s} + \kappa \cdot \sum_{o^i_{MBT}} {}^{MBT}r_{t,s}^{i,o^i_{MBT}} \right) \le g_3 \cdot \mathrm{MSW}_{t,s}, \quad \forall i, \forall s, t = 11, \dots, 16. \tag{9} $$

Lastly, there are the nonanticipativity constraints. These constraints guarantee that the decisions on building the facilities only depend on the information of realized uncertainties up to the present stage:

$$ w_{\tau,s}^{i,o^i_{WtE}} = w_{\tau,z}^{i,o^i_{WtE}}, \cdot \forall i, \forall \tau \text{ for which } \xi^i_{[\tau],s} = \xi^i_{[\tau],z} \tag{10} $$

$$ m_{\tau,s}^{i,o^i_{WtE}} = m_{\tau,z}^{i,o^i_{WtE}}, \cdot \forall i, \forall \tau \text{ for which } \xi^i_{[\tau],s} = \xi^i_{[\tau],z}. \tag{11} $$

It should be noted that the number of cities, scenarios, time periods, decision stages and target values that are present in Table 2 and Eq (1)–Eq (11) are the ones used in a forthcoming case study. These can be readily generalized to take any values depending on the situation at hand.

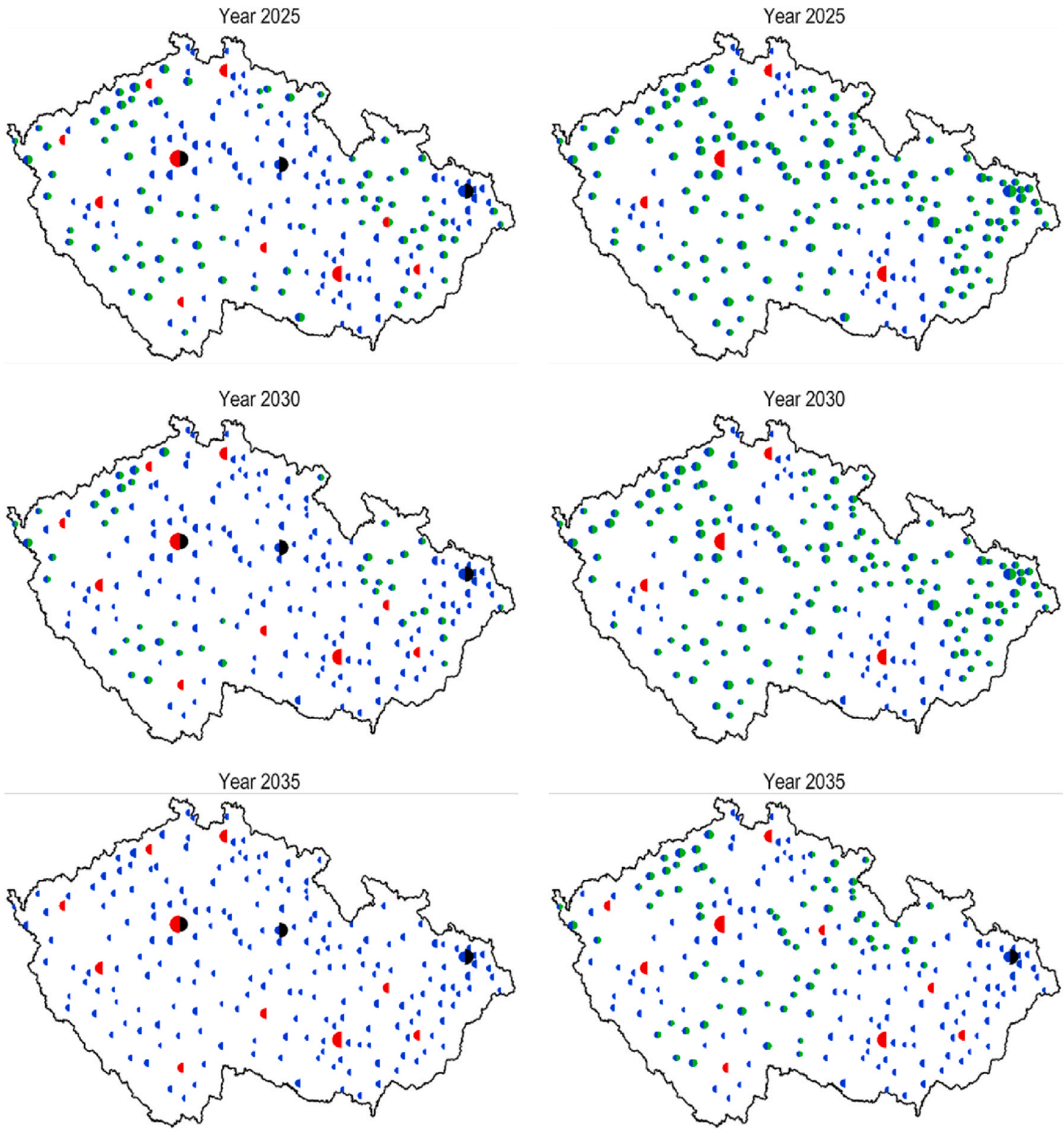


Fig. 12. Scenario 19. Solution with progressive goals on the left, the one without progressive goals on the right. The amount of generated MSW in blue, amount landfilled without pretreatment in green, amount treated in WtE plant in red, and the amount treated in MBT plant in black half-circles. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Case study

To demonstrate the strengths of the presented model, it is employed in the assessment of the waste treatment situation in the Czech Republic. The granularity of the case study is the following: 206 cities, connected by a road network with 1898 arcs are considered. Out of the 206 cities, 13 were selected as the most favorable locations for possible WtE and MBT plants. These are the largest cities in their respective regions, which can benefit the most from the electricity and heat generation by the waste treatment facilities and have the largest production of MSW. In 4 of the 13 cities, there already are existing WtE plants with a combined capacity of 741 kt. It is assumed that in these four cities, no additional WtE capacity can be built (although it is possible to build a new MBT facility). There are nine options for possible sizes of the WtE and MBT plants.

The considered planning period covers 11 years, from 2025 to 2035. The reason for the gap between the current year (2020) and the first period is the following – both the WtE and MBT facilities cannot be build overnight. It is assumed that for a facility to be fully operational in a given year, the decision for its construction must be made five years prior. This necessarily means that this decision will be based not so much on the current levels of the MSW production, but on an estimate of the possible levels of MSW production in the upcoming years. The reason for omitting the years 2020–2024 in the analysis is that there are no "substantial" decisions to be made (the model could only manage the system that is currently in place). The 5-year lag between the decision on building the facility and its operation will be achieved through the nonanticipativity constraints Eq (10)–Eq (11) and is discussed further in a forthcoming subsection. In order to make the model computationally tractable (to reduce the number of binary variables), the decisions about building the facilities will be considered only in three decision stages, that corresponds to having the facilities operational in years 2025, 2030, and 2035. Additionally, the costs associated with the year 2035 are multiplied by a factor of 6 to account for the costs that are likely to occur in the years 2036–2040. This should deter the decision that results in building too much infrastructure that will not be efficiently used.

4.1. Data collection and scenario generation

According to the *Waste hierarchy*, energy recovery should be treated if the waste cannot be recovered materially. The rate of waste recycling thus affects the amount of waste for energy recovery.

Waste fractions for material recovery were determined based on the *Waste management plan of the Czech Republic for the period 2015–2024,* which was developed by the Ministry of Environment of the Czech Republic. The following waste fractions were determined as the materially recoverable: glass and glass packaging, metal and metal packaging, paper and paper packaging, plastic and plastic packaging, textiles and clothing. The mandatory waste management records identified other fractions, which are materially recovered: bio-waste and bulky waste. Fig. 4a) depicts the production of MSW fractions, which is material recoverable and its real materially recovery from the year 2009 is still growing. The spatial distribution of the material recovery of the MSW in 2017 is illustrated in Fig. 5.

Mixed municipal waste (MMW) currently accounts for a significant proportion of MSW – about 50% in the year 2017 in the Czech Republic. It is a waste fraction that can be sorted and thus creates the potential for material recovery. Fig. 6 shows the materially recoverable waste in MMW in 2017, which should be separated in the future.

However, the separated waste does not correspond directly to the materially recovered waste. Material recovery of separated waste is mainly dependent on technological and cost conditions. The recycling rate RR_f for waste fraction f, where MAT_f is materially recovered and SEP_f is separated waste f is computed as $RR_f = MAT_f/SEP_f$. The latest available data make it possible to determine the recycling rate RR_f for 2015, these values are summarized in Table 4. The expected development of the material recovery municipal solid waste (if it continues in the current fashion) achieves approximately 47% in the year 2025, as indicated in Fig. 7. But the EU target in 2025, which lies at 55%, necessitates additional steps and effort in order to be reached. The situation for the targets in the years 2030 and 2035 is quite similar, if not more severe.

Material recovery constitutes an extremely important factor as it directly affects the amount of MSW that will be treated in the considered WtE and MBT plants. At present, it is not certain in which direction the production of waste with material recovery will be taken. Three base scenarios for the material recovery are constructed to model this uncertainty:

1. Scenario: BAU – business as usual, depicted as “Forecast” in Fig. 7.
2. Scenario: middle – the EU targets with a 5-year delay
3. Scenario: on target – the “Modelled scenario” in Fig. 7.

These three base scenarios were further “branched”, as depicted in Fig. 8, to more evenly capture the possible developments, resulting in 27 individual scenarios. Alongside the material recovery, other factors went into the construction of the scenarios for the production of MSW that can be treated in the WtE or MBT facilities (denoted as $\xi^i_{t,s}$) in individual cities in the successive time periods. Additionally, demographic changes, i.e. the expected continuation of the trend of higher immigration to bigger cities in the core of the republic (such as Prague or Brno) and the population decline and ageing of the periphery were considered.

With Fig. 8 in mind, the nonanticipativity constraints Eq (10)–Eq (11) that tie certain scenarios together and enforce decisions that can be based only on the current state of knowledge about the uncertain parameters work as follows. As there is currently (the year 2020) no way of knowing which of the 27 scenarios will be the one that comes true, the decision on building the facilities must be made with all 27 scenarios in mind. In other words, for all 27 scenarios, the decision on which facilities will be operational in the year 2025 must be the same. In the year 2025, the situation changes, as one will be able to pinpoint which of the three branches (1–9, 10–18, or 19–27) is the “true one”. This affects the decisions on which facilities to open in 2030, as they will be grouped based on this branching (i.e. one decision for scenarios 1–9, the second one for 10–18, and the third one for 19–27). A similar situation repeats in the year 2030, but with even more branching, as nine possibilities tie the scenarios together.

5. Results and discussion

The optimization model was programmed in the high-performance dynamic language JULIA [71] with the JuMP package for mathematical optimization [72]), that is very well suited for large-scale scientific computing. The solution was computed by the GUROBI 8.0 solver [73]. The optimality gap parameter was set to 1%, which was decided to be sufficiently low for this application. The computations were carried out on an ordinary computer (3.2 GHz i5-4460 CPU, 16 GB RAM) and took about an hour to finish. Two distinct models were considered. The first model has progressive goals ($g_1 = 0.3, g_2 = 0.2, g_3 = 0.1$, in the years 2025, 2030, and 2035, respectively) towards the landfilling target of 10% in the year 2035, to facilitate a “smoother” transition. The second model is without these progressive goals and has only the final goal ($g_3 = 0.1$, in the year 2035). The proportion of the MBT treated waste that still will be landfilled is assumed to be $\kappa = 0.4$. The results of the computations are best summarized in Table 5 and Fig. 9 to Fig. 12

In the model with progressive goals, in the year 2020, the WtE capacity amounted to 981 kt and the MBT capacity to 600 kt (the placements were identical in all scenarios due to the nonanticipativity constraints). In 2025, in the scenarios 1–9 (that stem from the BAU base scenario) additional 850 kt of MBT capacity were built. No other facilities were deemed as needed. In 2030, additional WtE capacity was needed in 15 scenarios (1–15), and additional MBT capacity was needed in 9 scenarios (1–3, 10–15). This leaves 12 scenarios (16–27) in which the initial capacity built in 2020 was all that was necessary to achieve the progressive goals. The differences are exemplified in Fig. 11 and Fig. 12. The optimal objective value was $2.50 \cdot 10^9$ EUR.

In the model without the progressive goal, the results suggest quite the opposite strategy. As there is no pressure to decrease the amount of landfilled waste immediately, the optimal decision is to “wait until the last moment” and act according to the particular scenario path. The optimal objective value in this setting was $2.44 \cdot 10^9$ EUR, which is about 2.4% cheaper than the model with progressive goals.

There is, however, an important issue with this approach, as it requires building a large number of new facilities in the time period between 2030 and 2034 (that can be operating in 2035), in order to reach the 10% landfilling target. For instance, in scenarios 1–9, there are 16 new facilities to be built in this time interval. This would likely put a strain on whatever agency which will be given the task of building these facilities. To find a compromise between the two approaches, one could look at the facilities that are built in both. There are 9 facilities that should be built in 2025 according to the strategy with progressive goals. For the strategy without progressive goals, out of these 9 there are 7 that are built in more than half of the scenarios in 2035, and 5 that are built in more than two-thirds of the scenarios in 2035.

One of the biggest strengths of the model is that it can be used for “rolling-horizon” planning. After analyzing the compromises between possible strategies and deciding on particular facilities to open in the current year (that will become operational in the future) it is expected that the model will be recomputed again after a few years, bringing updated data and trajectories of future development.

The suggested approach has limitations in many ways. The main shortcoming may seem to be the forced link to the material recovery of the waste. Its fair value depends on the capabilities of individual territorial units. Individual regions and micro-regions are different, so their specific potential should be considered. Options for energy recovery should then only be considered for remaining waste in all municipalities. The actual implementation of the new WtE plant is time-consuming and requires the fulfillment of many legislative conditions, including environmental analysis. From the implementer's point of view, the calculation can be applied repeatedly, taking into account new or more accurate information. However, these can only be obtained or changed after binding decisions. Ideally, the options should be analyzed at the lowest possible level of territorial division, i.e. at the level of municipalities (currently around 6250 in the Czech Republic). Calculations on such level are related to the need to make predictions for small areas. However, the results for these areas can be highly variable, and these inaccuracies could affect the credibility of the outputs. Regarding the predictions, it would be beneficial to encompass the demographic development in the population across the Czech Republic. Despite all of this, the feasibility of suggested projects is also highly dependent on the willingness of local authorities and residents to support implementation, where the result of the public referendum can play a significant role.

6. Conclusion

The presented paper reviewed the current state-of-the-art within the waste management of Europe and the possible strategies on how to handle the planning of sustainable processing infrastructure with regards to the circular economy targets. It consists of crucial landfilling and recycling goals that were anchored in legislation. At the same time, the current waste treatment and material recovery were analyzed to define rates and trends used as the baseline point. Scenarios of waste production were generated from forecasts and targets to simulate three scenario trees. These were – business as usual, middle scenario considering 5-year delay and scenario on target. All scenarios were further branched to more evenly capture the possible developments.

The approach was demonstrated within the Czech Republic. One of the main contributions lies in the comparison of models with and without progressive goals. In the model with progressive goals, in the year 2020, the WtE capacity amounted to 981 kt and the MBT capacity to 600 kt. The second model suggests quite the opposite strategy. Since there were no restrictions during the time horizon, the optimal decision suggests to wait until the last moment with changes in processing infrastructure. The strength of the model is that it can be used for "rolling-horizon" planning, which means that it can be recomputed again after a few years and update the upcoming decisions with newly available data.

The future research may incorporate the decision-making regarding material recovery to meet all goals. The current approach requires a steep change from the trend. Also, the detail of the territory level will be analyzed in order to obtain more precise results. The model will identify micro-regions, where there is a potential for more effective waste treatment and management.

Author contribution

Jakub Kůdela: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. Veronika Smejkalová: Investigation, Resources, Data curation, Writing - original draft, Visualization. Vlastimír Nevrlý: Investigation, Resources, Data curation, Writing - review & editing, Visualization. Radovan Šomplák: Conceptualization, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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