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The Potential for Future Material Recovery of Municipal Solid Waste: Inputs for Sustainable Infrastructure Planning

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The aim of the EU is to maximize material recovery from waste and minimize landfilling. For continuous development within the upcoming years, the circular economy package has been issued. It sets out gradually the goals of more efficient waste management. The waste production under the current conditions does not meet the EU targets in many states. The future waste management planning should take into account simultaneously both materially recoverable waste and the waste suitable for energy utilization. In this regard, the important aspect is their direct dependency and keeping the balance for a constant amount of produced waste for each year. The waste production can be forecasted, so it changes within the time horizon. Also, the interdependence of the targets changes other treatment ways, since landfilling significantly affects the residual amount of waste. However, approaches for assessing possible scenarios for the future development of waste production play a key role in transitions to cleaner treatment. Waste production scenarios are modeled to achieve recycling and landfilling targets. In order to integrate these connections into the infrastructure planning process, a penalty function for the potential of increase of material recovery is presented. Such a penalty differs among the regions within the analyzed area and is also waste type related. The approach is demonstrated using data from the EU member state – the Czech Republic is approximately average in the waste landfilling and recycling between EU member states. The results of this study define the potential of increase of material recovery for individual micro-regions of the Czech Republic. It represents a crucial input for multi-stage decision-making, which is usually modeled by mathematical programming. It can be integrated into the objective function, where it changes the cost of infrastructure modification. Systematic planning in waste management and infrastructure modification is highly required in the Czech Republic to meet the Circular Economy Package goals.

1. Introduction

Currently, the EU is in the process of a transition from the linear economy to the circular economy. The aim of this transition is to keep the value of a product or a material for as long as possible. An important aspect is the connection of the circular economy with the key areas of resource management and utility (Fan et al., 2019b). The principles of the circular economy are anchored by EU legislation in the Circular Economy Package (CEP). The CEP supports the Waste hierarchy (Directive 2008/98/EC), which defines the preferred ways of waste treatment because an appropriate waste treatment can significantly reduce emissions (Fan et al., 2019a). To ensure the smooth change based on the CEP and to build a sustainable system, it is necessary to plan in the long-term horizon. The inputs for the strategy planning come out of continuous development monitoring. In the case of undesirable development, which does not meet certain targets in the future, an intervention in the system is required with appropriate infrastructure modification.

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One of the suitable tools for effective planning in the waste management (WM) is mathematical programming, exemplified by the p-graph (Fan et al., 2020) and integer programming (Málek et al., 2018) approaches. The CEP recycling targets for years 2025, 2030, and 2035 are progressive (55, 60 and 65 %) (Directive 2018/851) and can be seen in Figure 1. In cases like this, it is possible to develop multi-stage decision-making models successfully, that can guide the strategic control of WM systems. On the other hand, these decision-making models are scarcely used because of their theoretical complexity and high computational requirements, which was confirmed in a wide-ranging literature review (Barbosa-Povoa et al., 2018). One of the first large-scale applications of the multi-stage models from circular economy problems was introduced by Kůdela et al. (2019). The developed model focused on the planning of the development of a new waste processing infrastructure with respect to the CEP targets. However, in the article (Kůdela et al., 2019) the decisions regarding different types of waste were not connected. In particular, with regard to the increase of material recovery (MR) of the municipal solid waste (MSW), only the current historical trend was used (Pavlas et al., 2020).

The CEP must be considered by all EU member states. The EU countries differ significantly in their current technologies for waste treatment, and also in meeting targets included in the CEP. The aim of the CEP is to support a smooth transition to a circular economy through recycling targets and landfilling prohibition (Directive 2018/850). The WM strategy for waste diversion from the landfill was assessed by pinch analysis in the study (Othman et al., 2018). Recycling and landfilling targets will also increase the energy recovery of waste. There are many types of Waste-to-Energy (WtE) technologies. The MSW can be divided into different categories, which can be linked with suitable WtE technology (Maisarah et al., 2018). The paper (Ahmad et al., 2019) developed an index for the selection of the most suitable WtE technology. It is possible to successfully meet the CEP targets with the responsible development of the required infrastructure in advance. The current state of the waste treatment in the EU countries is depicted in Figure 1.

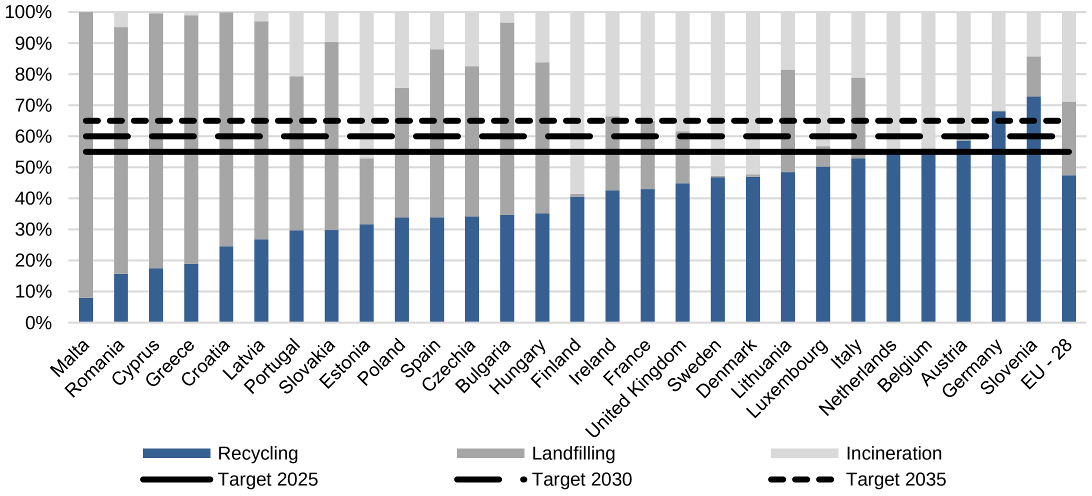

Figure 1: Municipal solid waste treatment in the EU, year 2018

The targets are usually defined for high regional units, such as on a country level (or a state level in case of a federal republic). However, it is desirable to search solution on the lower units, such as counties or municipalities. The change of the system on a regional or micro-regional level leads to a successful meeting of the targets for the whole country. It is essential for strategic planning to identify those micro-regions that are most suitable for improving the current situation. The aim of this study is to extend the model introduced in (Kůdela et al., 2019) by including the potential for MR of the MSW and a more accurate identification of the amount of MSW that is suitable for energy recovery (in WtE plants). This input is preprocessed in the form of penalty function for different fractions of waste. An important aspect in the potential MR of the MSW is the composition of the mixed municipal waste (MMW). The composition of the MMW is the best indicator for the possible increase of the MR of the separable fractions of the MSW. The novelty of the paper can be seen in the methodology for the computation of the potential, where a substantial increase of MR in micro-regions can be expected. Such a high increase of MR is assumed in locations, where there is currently a relatively low volume of the separated waste. At the same time, a relatively large volume of the possibly separable waste is still treated as the MMW. All decisions being made on the lower units must together meet the targets on the country level with regards to the composition of MMW.

2. Methods for determining the potential for increased material recovery

Most of the EU countries do not currently meet the CEP recycling targets for years 2025, 2030, and 2035 as shown in Figure 1. Nor does the current trend in the amount of separated waste indicate that the targets will be met, if the individual countries choose not to intervene. The targets are assessed on a country level, which can be put into a condition for an optimization model as follows

$$\frac{\sum_{i\in I}\sum_{f\in F} m_{i,f}^{MR}}{\sum_{i\in I}\sum_{f\in F} m_{i,f}^{SEP}+m_i^{MMW}} \geq target, \tag{1}$$

where $m_{i,f}^{SEP}$is the amount of MSW of waste fraction f that was produced and separated in the micro-region i. The parameter $m_{i,f}^{MR}$ describes the amount of materially recovered waste of the waste fraction f in the micro-region i. The parameter m_i^{MMW} describes the amount of MMW produced in the micro-region i. In Eq(1) the numerator is the total weight of all the recovered waste, and the denominator is the total amount of MSW, where some of the MSW is separated (into bins for plastic/paper/etc.) and some of it has a form of an MMW.

Unfortunately, it is not possible to recycle all separated waste. The efficiency of the recycling, the so-called recycling rate, differs for individual waste fractions and depends on the available technologies and the selling price of the materials. The recycling rate $RR_f \in \langle 0; 1\rangle$ for a given waste fraction f has the following form:

$$RR_f = \frac{m_{i,f}^{MR}}{m_{i,f}^{SEP}}. \tag{2}$$

The value of RR_f computed from Eq(2) is assumed to be constant for the given waste fraction f even for the not separated waste in the MMW. Although this is a very strong assumption, there are currently no sufficient data to model more accurate relationships.

Assuming a constant production of the MSW, there are two baseline ways to meet the CEP targets:

- increased recycling rate – limited by the available technology,
- increased separation rate – the transition of the MMW to separable fractions. This is the preferred method of increasing the MR of the MSW, but it requires changes to the current infrastructure.

If the WM plan aims to increase the separation rate (in order to increase the MR), it is necessary to evaluate the potential for MR of:

a) Waste fraction f: There are those waste fractions that are either not suitable for MR or their value of the recycling rate RR_f is too low. For the increase in separation rate, it is important to base the efforts on the composition of the MMW, from which the waste should be separated. To increase the MR, it is more efficient to focus on the waste fractions f, that are more efficiently recyclable (high values of RR_f) and at the same time have a relatively high share in the MMW.

b) Territorial units i: The division of a particular country into smaller regions uncovers important differences in the separation of waste between individual regions. The highest potential for the increase in MR can be identified in those regions, where a large portion of the separable waste is still treated as MMW.

The potential for the increase in MR of waste fraction f in region i according to points a) and b) is described in a criterion $k_{i,f}$:

$$\frac{m_{i,f}^{P,MMW}}{m_{i,f}^{SEP}+m_{i,f}^{MMW}} = k_{i,f}, \tag{3}$$

where $m_{i,f}^{P,MMW}$ is the amount of the waste fraction f in the MMW suitable for MR, $m_{i,f}^{SEP}$is the amount of separated waste fraction f, and $m_{i,f}^{MMW}$is the amount of waste fraction f in MMW without any regard to its recoverability. The assessment of the material recoverability of the waste will be one of the core inputs of the mathematical programming model for the planning the WM infrastructure that will help to meet the CEP targets. It is assumed that if there is low sorting level at the region, there is a great potential to increase and vice versa. This has to be addressed, and it can be incorporated into the objective function by appropriate penalties. The criterion $k_{i,f}$ is used to formulate the penalty function $v_{i,f}$:

$$v_{i,f} = 1 - k_{i,f}. \tag{4}$$

In some cases, for a modification of the current infrastructure, the specific waste fraction is not of major importance, but what matters is the region i. The penalization for the region i has the form:

$$w_i = \frac{\sum_{f\in F} m_{i,f}^{P,MMW}\, v_{i,f}}{\sum_{f\in F} m_{i,f}^{P,MMW}}, \tag{5}$$

which is a weighted average of the individual waste fraction on the given region. The territorial partition of the country $i \in I$ can also be assumed on a regional or other levels of the country.

3. Case study – the Czech Republic

In the year 2018, only around 38.6 % of the MSW in the Czech Republic was materially recovered. This means that an additional 21 % is needed to meet the first CEP target. The RR_f for the different waste fractions was computed based on data from the year 2015, which is the last year when this kind of data was completely available. It is assumed that the value of RR_f did not substantially change. The estimate of RR_f is depicted in Figure 2a, along with the estimate of the composition of the MMW in the year 2017. Clearly, bio-waste represents a very large component with around 29%, with a very high RR_f of 0.91. This corresponds to Figure 2b, which shows the material recoverable waste fractions of in the MMW, where the bio-waste contribution is nearly 50%. The MMW composition was estimated using the methodology described in (Šyc et al., 2018).

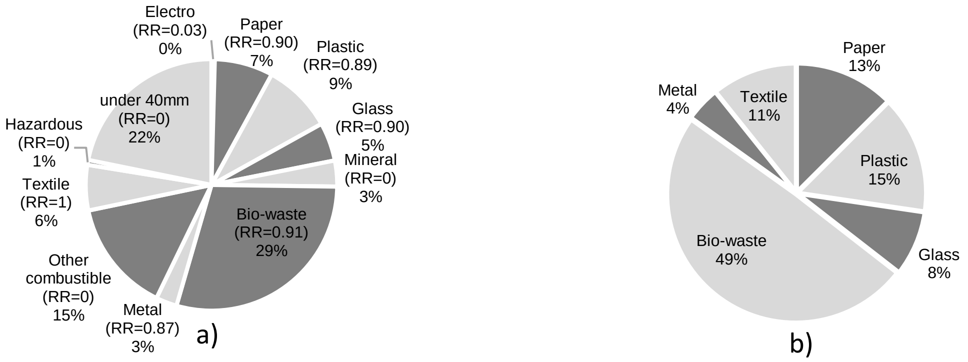

Figure 2: (a) The MMW composition and (b) material recoverable fractions in the MMW, the year 2017, the Czech Republic

The amount of the MMW and its composition differs significantly in the individual micro-regions in the Czech Republic, with some of the regions having high MR potential. Figure 3 depicts the MR potential for plastics in the micro-regions, using the penalty criterion $v_{i,f}$ defined in Eq(4). Higher values of this penalty criterion mean better effectivity in the MR of the MSW in the micro-region. On the other hand, for the interesting regions with high potential for the increase in MR, this value is smaller.

The summary of the values of the penalty function for the different waste fractions of the MMW can be found in Table 1. Based on this penalty, the most promising fraction seems to be textile, which is currently only scarcely separated and has almost a perfect recycling rate.

Table 1: Penalty $v_{i,f}$ for the different waste fractions

	$Q_{0.1}$	$Q_{0.25}$	Median	$Q_{0.75}$	$Q_{0.9}$
Paper	0.48	0.57	0.72	0.86	0.93
Plastic	0.33	0.40	0.49	0.61	0.67
Glass	0.40	0.51	0.64	0.78	0.89
Bio-waste	0.31	0.45	0.55	0.63	0.69
Metal	0.45	0.64	0.80	0.88	0.92
Textile	0.09	0.12	0.17	0.23	0.29

An aggregate potential for the MR of the MMW in the individual regions, which is computed using Eq(5), is displayed in Figure 4 and Table 2, which shows its quantiles.

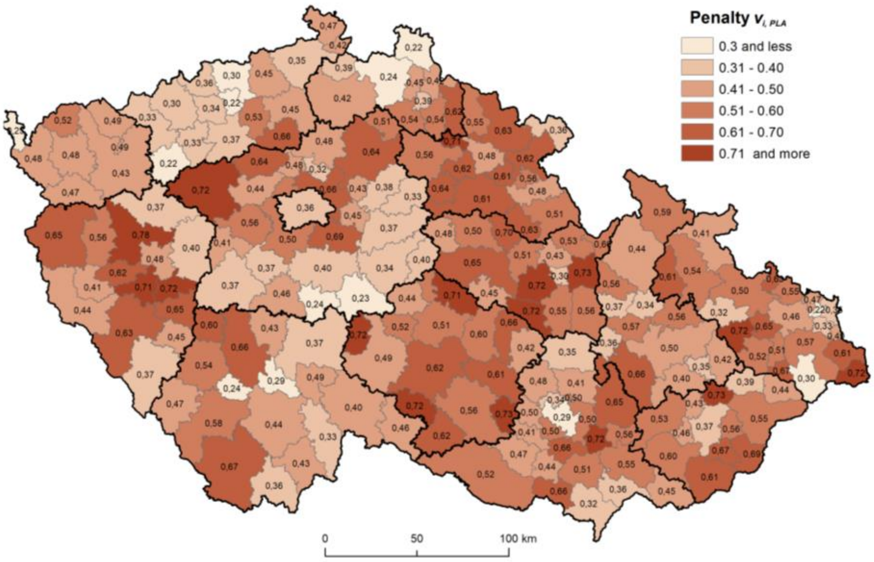

Figure 3: Penalty function $v_{i,PLA}$ for the potential for the increase in material recovery of plastics (PLA) from MMW in the micro-regions

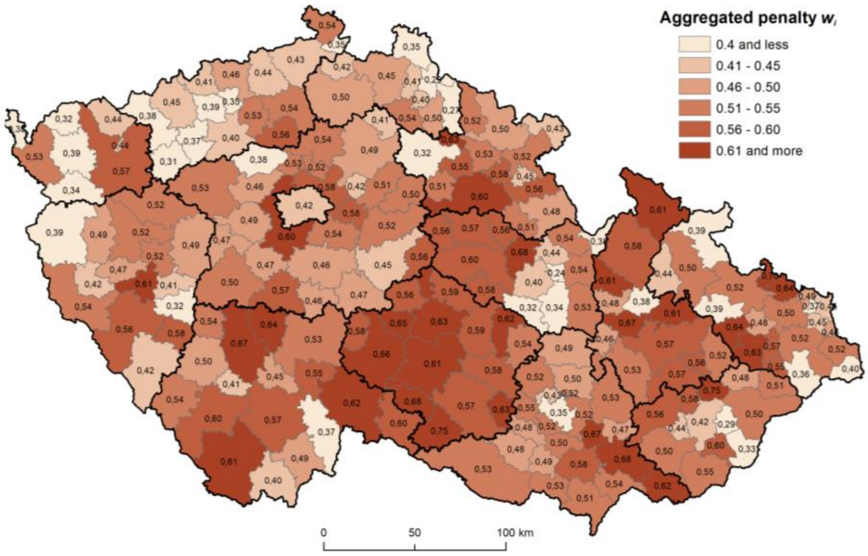

Figure 4: The aggregate penalty for the increase of the material recovery of the MMW in the micro-regions

Table 2: The quantiles of the aggregate penalty w_i

	$Q_{0,1}$	$Q_{0,25}$	Median	$Q_{0,75}$	$Q_{0,9}$
w_i	0.37	0.44	0.51	0.57	0.62

The results of this work will serve for the development of a multi-stage optimization model that will extend the previous work (Kůdela et al., 2019) with new measures and constraints. The new model will provide improved suggestions with respect to the WM planning under the CEP targets. Its novelty will be in the connection between the materially recoverable waste and the waste suitable for energy utilization. It will be important to include in this complex model also other MSW fractions, such as bulky waste, which has high energy and MR potential (Šomplák et al., 2019). The evaluation of economic and environmental process efficiency (Pintarič et al., 2015) could also be integrated into WM technologies and considered as net present value per unit footprint reduction in total investments.

4. Conclusions

CEP targets issued by the EU motivated countries to transition the current WM practices into more efficient and environmentally friendly ones. MSW generation, quantity, and composition represent crucial inputs for assessment of the whole system. This paper introduced a method for determining the potential for the increase in MR of MSW fractions with the connection to waste suitable for energy utilization. It is necessary to identify the potential increase in material recoverable waste at a micro-regional level. This was evaluated by the current rates of separation and recycling. Based on this data, the potential criterion was defined as one of the main outputs. The result should be used for the efficient planning of the infrastructure. The potential increase of MR was transformed into penalties suitable for integration into the objective function. Further research will use the output of this work for application on real data in WM. It will encompass the development of a multi-stage optimization model that will guide interventions to the WM infrastructure. This approach should ensure a smooth transition of the WM strategy and effective modernization of the WM infrastructure, while still considering the economic impacts on the waste producers.

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