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Complex Approach towards the Assessment of Waste-to-Energy Plants' Future Potential

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There is a fierce debate ongoing about future recycling targets for municipal solid waste (MSW) at the European level. The old linear concept of waste management is being changed into a circular economy. Since the separation yield and post-recycling MSW (later on residual solid waste, RSW) production have an opposite relationship, assuming the constant production of particular components (paper, plastics etc.), lower RSW rates are also expected. This is having a negative effect on Waste-to-energy (WtE); especially in terms of its future optimum capacity in particular countries.

A circular economy will rely on the enhanced utilization of secondary sources, which is only possible if a sufficient amount of recyclables are secured. Source separation – i.e. sorting by inhabitants – appears to be the most preferred option. In any case, a certain amount of non-recoverable waste is inevitable and this is concentrated into RSW. This stream is mainly produced by inhabitants and is preferred for energy recovery.

Regarding the effective utilization of waste, general goals are well-known. However, their introduction into practise will differ from country to country. We may distinguish three groups of countries within Europe. Their classification is based on their current recovery rates – both material and energy – as presented by the latest data from 2014, issued by Eurostat [3].

Group 1 – Moderate enhancement towards higher recovery rates. This group encompasses countries with well-developed waste management (WM), where landfilling has been nearly eradicated. The majority of MSW is recovered for material reuse. These successful countries focus on sophisticated and effective waste collection, which consists of dozens of parts. Landfilling untreated waste is forbidden. Residual waste is recovered for energy production within WtE plants. The amount of incinerated waste is high and ranges between 30 and 40 percent of the total waste generation. Incineration plants, therefore, play a significant role in these countries. The promotion of recycling is reinforced by incineration taxes. Waste prevention policies, combined with demographic development, may create overcapacities in the following years and there is an ongoing discussion whether intensive recycling is sustainable in the future.

Group 2 – Countries where changes towards more sustainable WM are in progress. Here, legislation is already in place and policies are implemented in waste management plans (WMP). Despite sufficient processing capacity, processing capacity commonly refers to landfill sites and a great share of biodegradable waste is still landfilled. These countries do not forbid waste landfilling, but they do impose landfill taxes. Material recovery is insufficient. Countries in this group are experienced in operating some WtE plants. More WtE projects are being prepared; new WtE plants are being built or have obtained building permission.

Group 3 – Countries awaiting transformation of WMPs. These have an insufficient capacity for processing waste, even concerning landfilling sites. Landfilling is not restricted, a low amount of waste is recycled and no WMPs are in place.

Each of these groups has its own specific challenges. On the other hand, they have something in common too; that the use of a sophisticated tool for decision-making in WM would be helpful to optimize future waste streams between producers and processors. A general optimization task covering the aforementioned issues was formulated by Giani et al. [5], who revised a network flow model where the logistics of waste plays an important role. Another recent work presented by Bing et al. [2] addressed research opportunities for modelling MSW recycling in Europe.

As a contribution to research with a high practical relevance in this field, a unique computational tool, *Neruda*, was introduced in our previous paper [6]. The latest achievements in the development of this tool are the concern of this contribution. The examples presented later on are motivated by real case studies featuring a specific region – the Czech Republic and its sub-regions. In terms of waste streams, they handle RSW. However, *Neruda* is an open tool and may be applied and adjusted to other countries and regions and other types of waste streams.

1. *Neruda* – a complex tool for decision-making in waste management

In general, the system represents an original approach for the early investment planning of any project in waste management and evaluating its reliability at various levels. This tool was first introduced by Šomplák et al. [7] and it is based on a comprehensive logistic mathematical problem which minimizes the total cost combined with an extensive techno-economic analysis.

Initially, it was mainly devoted to WtE plants and their competing technologies – landfill sites and mechanical-biological treatment plants producing refuse-derived fuel. In other words, for processing RSW. However, the approach is not limited to only this technology at present. In general, the outcomes are as follows:

- An allocation of capacities (where to build a new plant and of what capacity; economies of scale is included)
- The collection areas proposed for a particular plant and evaluating its stability
- An assessment of feasibility (determination of so called *survival function*, see [7])
- An assessment of waste availability (evaluation of newly formulated *waste availability factor*, for details see section 3.1)
- The selection of an appropriate transportation system, including transfer station locations, etc.

Neruda represents an integrated approach because tactical issues (future collection areas) are included in strategic decisions about capacities. Its practical relevance has been proven by several recent applications:

- In 2015, it was applied to determine the most advantageous structure of facilities for processing different types of waste – recyclables, biodegradable waste, and residual waste – in the Czech Republic. The work supported the fulfilment of the new Waste management plan of the Czech Republic for 2015 to 2024.
- In 2015, it was applied to support the development of waste management plans for the next decade in several regions (regional Waste management plans) of the country.
- In 2015, a small WtE plant (capacity up to 50 kt/y), integrated with existing combined heat and power plant, was studied.
- In 2013, it was applied to analyse the future demand for new WtE facilities in the Czech Republic. A ban on landfilling was considered and the potential of heat delivery within existing district heating systems was addressed.
- In 2013, a selection of localities and risk analyses were carried out for a large energy conglomerate operating in the Czech Republic.

As follows from the list of references, several subjects may profit from the application of the tool:

- Strategic decision makers at the country and/or regional level (government).
- Individual producers (municipalities).
- Potential investors interested in new WtE plants and other treatment facilities.
- Operators of existing plants.

In this paper, we focus our attention on two particular aspects; first, the pre-processing of waste related data and secondly, selected outcomes of the calculations will be introduced.

2. *Justine* – a tool for forecasting in incomplete spatially distributed data problems

Gathering waste production data and its reprocessing into a suitable form are crucial steps leading to the practical application of any optimization tool for modeling future improvements in WM. Regarding network flows modelling generally, the situation is complicated due to:

- Forecasting the future is inevitable, since the calculation focuses on future state modelling.
- Waste quantities have to be known for all nodes of an investigated region (depending on the level of detail, it may be hundreds of nodes).
- There are interactions between streams.

  MSW consists of several sub-streams and fractions such as paper, plastics, biowaste, mineral, etc. Some of them are recyclables and these are collected separately within various collection systems – containers, bring-in systems, kerb-side or a combination thereof. Efficiencies in the systems may differ; however, they are supposed to increase over time, resulting in higher rates of recyclables and a lower amount remaining in RSW.

First, a brief review of the state-of-the-art in the statistical analysis of waste production data is provided. Limitations of common methods are highlighted in terms of their use for forecasting. Then, an innovative approach for forecasting for hundreds of nodes, organized within a tree structure, is introduced.

2.1. Statistical analysis applied to waste quantities data – some general remarks

There were several works published on the topic of MSW quantities forecasting. They come from different countries and regions, and employ different statistical techniques. One common feature is that lots of manpower is spent on the investigation of local data. *Regression analysis* or *time series analysis* are often employed and sometimes both are combined. A comprehensive review of this topic was published e.g. by Beigl in 2008 [1].

The regression analysis used here aims to explain variations in production among producers. A wide range of independent (explaining) parameters are tested to find those with the most significant impact. These often are gross domestic product, income, share of different types of housing, type of heating, tourism rate, container distance, etc.

Regression analysis, if employed correctly from a mathematical point of view, requires strict conditions to be met before its application. Among others, data is supposed to be of normal distribution. Therefore, outliers and extreme values have to be removed in the data validation phase.

Regarding the outcomes of the analysis, even models evaluated as precise may still provide enormous variation in quantities, which hinders their practical use. In fact, these models describe an average production. Therefore, they are well accepted for WM planning at regional and/or country level, where positive and negative deviations reported by particular producers are compensated. The larger the territory, the better the fit usually is.

2.2. Limitations of statistical analysis-based forecasting

Regarding forecasting, knowledge of explanatory parameters opens new opportunities for indirectly altering the future course of the production. Initiatives for encouraging desired trends of explanatory parameters may be discussed. Alternatively, the explanatory parameters may be forecasted and results introduced into the regression models to forecast waste production.

In addition to the averages, regression analysis provides information about the distribution around this average. So, producers performing below, around, and above the average may be classified. In this respect, results may be used as benchmarks and future targets can be specified. For example, it is recommended that those below the average will reach the current average in the next decade.

The second method, time series analysis, employs time as the sole explanatory parameter. Waste amounts in previous years are investigated to develop a model, which describes the variation over time. Forecasts are then derived by extrapolating historical data.

From a mathematical point of view, preciseness is secured only for series with a large number of values. With respect to strategic decision-making, which this paper focuses on, the time series method for waste production – which are reported on an annual basis – are often too short because older data are not available. As a consequence, a precise trend analysis is nearly impossible and, therefore, this technique is preferred to model data gathered within a shorter time period – daily, hourly, etc. – to support tactical and operational decisions.

Regardless of the time interval, a consequence of introducing stipulating measures – new taxes and bans, change of current practice, etc. – would be a significant positive development in WM in the future. Logically, their impact cannot be addressed by analysing previous data. There is no evidence observed from historical data, since they have not occurred yet.

To sum up, forecasting based on time series analyses describes the business-as-usual scenario, where no significant changes in the system are expected. Here, rather than precise statistical analysis, we have to rely on expert models and utilize experience from other countries and regions where those particular measures have been implemented and their effect can be justified. Then, historical data from one country/region/municipality may outline the future in the other. The challenge here is the credibility of models, if geographically carried over to a different place.

2.3. A proposed solution for forecasting waste quantities

Regarding the aforementioned limits in statistical analysis methods, we developed a computational system for simulating and forecasting in uncertain and spatially distributed data problems. A region is divided into several sub-regions – and their parts again – and a hierarchical tree structure is taken into account. Forecasting is performed for all nodes and several streams simultaneously – e.g. components of MSW.

The computational system processes a variety of spatially distributed forecasts on production and composition at every point obtained by the aforementioned regression or trend analysis. These models are bound together through additional equations and constraints which refers to mass and energy balances and which must be kept to.

From a mathematical point of view, it follows the principle of regression analysis. We focus on first forecasting at the lowest territorial units. Trend analysis is applied to annual data, even though the basic requirements for its application are not met and less precise results are expected – due to uncertain data. In addition, this is done altogether with forecasts on a higher geographical level and larger administrative units.

Nevertheless, based on our extensive investigation of data available for the Czech Republic and its organizational units, we experienced a violation of the following basic assumption if extrapolation was used: The sum of forecasted values for all lower organizational units in the region must be equal to the result of the forecast performed on the aggregated data of the region. Further investigation revealed that the achievement of a full consistency is not guaranteed even from a mathematical point of view. This general conclusion has implications for the development of a new approach.

The approach assumes inaccuracies, so less precise models – e.g. extrapolation based on short time series – are not excluded. It performs corrections where distances between resulting values (an unknown parameter) and all available forecasts are minimized, taking into account each of the territorial units. Due to the fact that the input point estimates may differ and even frequently provide contradictory information, such a correction is only feasible if there are additional constrains to be met. Some of these additional constrains are obvious, since they describe the distribution of individual components of MSW – paper, plastic, biowaste, minerals etc. – into separated fractions (SEP), and their remaining amounts forming residual waste. Additional constrains secure mass conservation within the tree structure.

As a result of this elaborated system of expected inaccuracies and weights, the forecasted values are determined. The result is *balanced* taking into account all models and constraints.

2.4. Benefits and applications

The examples of outcomes from the calculations, if applied on MSW and it components, are as follows (available at a micro-regional level):

- waste production,
- composition of waste,
- lower heating value,
- separation rate for different fractions,
- separation efficiency for different fractions.

Data about the production of MSW components, and their distribution into separately collected streams and residual waste, are often missing. The provided estimates open several research opportunities:

- analysing rational recovery targets by reflecting the current situation in individual (micro) regions,
- investigating historical data from different regions and formulating general models on the production and composition of waste ,
- exploiting examples of good practice from regions with high recovery rates
- combining analogy with rigorous regression models (historical data from one region can serve as one scenario for another region),
- treatment capacity is necessary to be judged considering the broader context as well as local conditions,
- a proper transportation system has to be designed,
- a proper solution in the strategic planning phase needs detailed analysis (possible only when implementing robust optimization tools).

2.5. A case study

In this section, a particular result of complex calculation is provided which was carried out within the framework of a project for The Ministry of Environment of the Czech Republic in 2015.

A simultaneous calculation for 206 micro-regions, 14 regions and the country as whole was performed. Data were available on residual waste amounts and the yield of separately collected fractions in the years 2009 to 2013. Residual waste analysis from a few micro-regions represented additional information. Many statistical models were investigated, including extrapolation from current trends of separately collected fraction and RSW, regression models on recyclables yields etc. These were further balanced according to the aforementioned approach. There is not enough space to describe all the details so Figure 1 demonstrates only one particular result for a selected micro-region and selected fraction plastic. Figure 1b shows the constant projected production of plastic waste in MSW and ineffective plastic separation, as only 12 percent of its production was separated in 2013 (Figure 1a). This very low value is highlighted in Figure 1a), where a frequency diagram for all 206 micro-regions is provided. A future increase in yield is expected, resulting in lower amounts of plastic in residual waste (Figure 1b), and significantly increasing efficiency (Figure 1c). Similar outcomes were obtained for all territorial units.

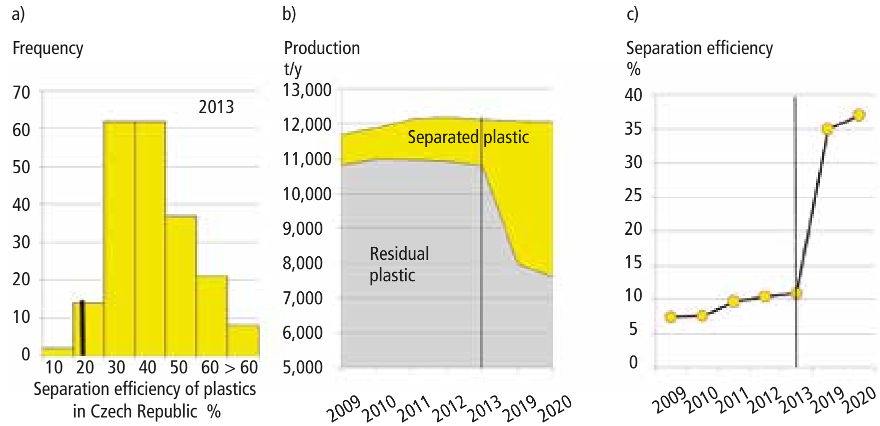

Figure 1: The production and separation efficiency of plastics in selected micro-regions, results of complex analysis

3. Examples of complex simulation results

In our previous contribution [6], we presented a few results derived from an early application of the tool *Neruda*. Here other examples of outcomes from real case studies are presented. An analysis related to waste availability for a particular new WtE project is demonstrated first. It reveals how potential investors may benefit from *Neruda*. Finally, an analysis for producers (municipalities) is briefly mentioned.

3.1. Waste availability

Waste availability, and related income from waste processing, represents key aspects for the sustainable operation of every WtE plant. Therefore, computation to determine prices at which waste is available in a sufficient amount to fulfil the intended plant's capacity represents another complex task, which can be effectively solved by *Neruda*.

Assuming a plant with the capacity C_{ref}, an expected collection area is simply drawn based on the projected future waste rates in the nearest locations to the site (Figure 2's solid line). A novel approach towards complex evaluation of waste collection area was proposed by Ferdan et. al. [4], where risks associated with limited waste delivery were taken into account. Here waste availability, precisely defined by mathematical formulas, is assessed based on a complex simulation of future competition between potential and existing plants in the waste market. The producer opts for the cheapest alternative and the waste is attracted only when it is the cheapest.

The outcome is comprehensively demonstrated for two particular scenarios (scenario 1 and scenario 2 in Figure 2). The two scenarios featured two different gate-fees. In the event of scenario 1 and 2, it corresponded to a return in investment of 11 percent and 9 percent, respectively. Plant capacity was considered unlimited to test the maximum amount of waste available at these gate-fee levels. In the event of a higher gate-fee (Scenario 1), the collection area is significantly reduced. Many micro-regions preferred the cheaper option. On the other hand, a slightly lower project profitability resulted in a lower gate-fee and a significantly higher waste amount attracted. In any case, an intuitively designed collection area was significantly corrected by the calculation in both cases.

The ratio of the amount in the collection area for a designed plant's capacity was titled *waste availability factor – WAF* in [4]. The total waste transported to the facility in scenario 1 was lower than the reference capacity; WAF was equal to 0.80. In the other scenario, the amount of waste exceeded the reference capacity and WAF was 1.28. WAF may be incorporated into a complex stochastic-based analysis, where various uncertainties embodied in the scenarios are taken into account.

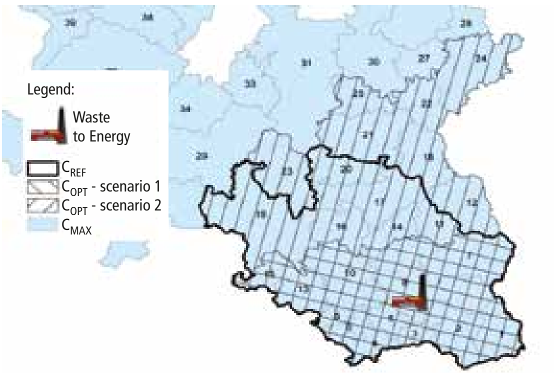

Figure 2:

A graphical illustration of two proposed collection areas for two different scenarios

after Ferdan, T.; Šomplák, R.; Zavíralová, L.; Pavlas, M.; Frýba, L.: A waste-to-energy project: A complex approach towards the assessment of investment risks, Applied Thermal Engineering, 89, 2015, pp. 1127-1136

3.2. Analysis for producers – increased future processing cost as a consequence of future legislation changes

The tool, and the same principle of calculation, is also helpful for producers. Generally, municipalities in countries where environmental taxation (a landfilling tax or ban) will come into force will definitely suffer from increased waste treatment costs in the future. Since landfilling is considered the cheapest option – not considering the future environmental cost, – any introduction of other technologies will result in a price hike.

The negative impact will be regionally dependent since specific aspects should be taken into account. For example, in the case of localities where existing district heating can easily absorb heat produced, WtE will be preferred and will lead to affordable gate fees. Similarly, the existence of a cement industry, where quantities of fossil fuels may be substituted with refuse-derived fuel, means a mechanical-biological treatment plant may be the favoured option. Since there is no general rule on how to proceed, producers should consider different options and evaluate their impacts when making decisions.

The aforementioned assertions were demonstrated through a complex study involving a specific region, the Czech Republic. In total, 206 micro-regions and their RSW produced were subjects of a comprehensive price investigation. The result of which is obvious from Figure 3. The average future processing cost was evaluated for a wide range of scenarios and the average value (Figure 3a) and deviation (Figure 3b) are presented.

Significant local dissimilarity was found where some producers would suffer from considerably increased treatment costs. For some producers, a limited number of preferred options could be identified where acceptable costs can be expected. Those municipalities which are have darker shading in Figure 3b) should start dealing with the issue of waste treatment as soon as possible since there is a risk that the allocated capacities of cheaper options will soon be taken by other municipalities.

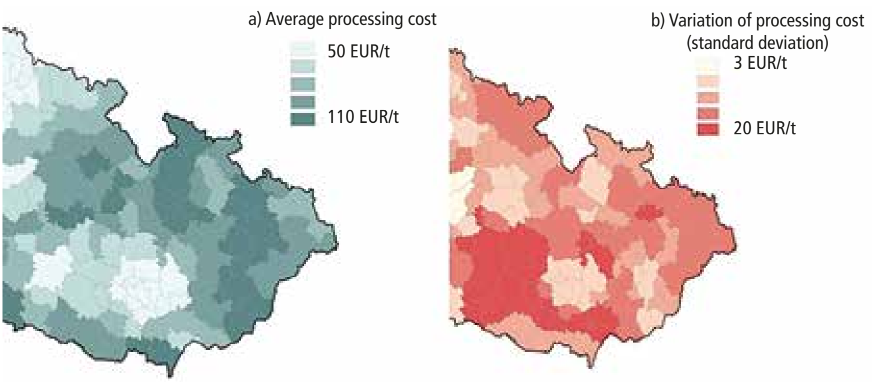

Figure 3: Future waste treatment cost in a large geographical area – The eastern part of the Czech Republic a) Average values, b) standard deviation of waste treatment cost

Taking a look at the variability of total costs for a particular micro-region, there are clearly several alternatives for this municipality as follows from Figure 4, which shows the frequencies of total costs. Due to the absence of a district heating system in the locality, there is no possibility to establish a feasible WtE or RDF plant here. Therefore, the waste produced will be exported from the region to other locations where a WtE or MBT plant is feasible (description of alternatives 1 to 4 in Figure 4). For each alternative, an average price and probability is evaluated – i.e. the number of positive scenarios over the total number of scenarios. Based on the results, the municipality should promote the establishment of a WtE plant in locality 2 (Alternative 1) to secure the cheapest solution. If the municipality is passive in the issue of waste treatment or if this project is not established, there is a relatively high risk of significantly higher costs in comparison with Alternative 1.

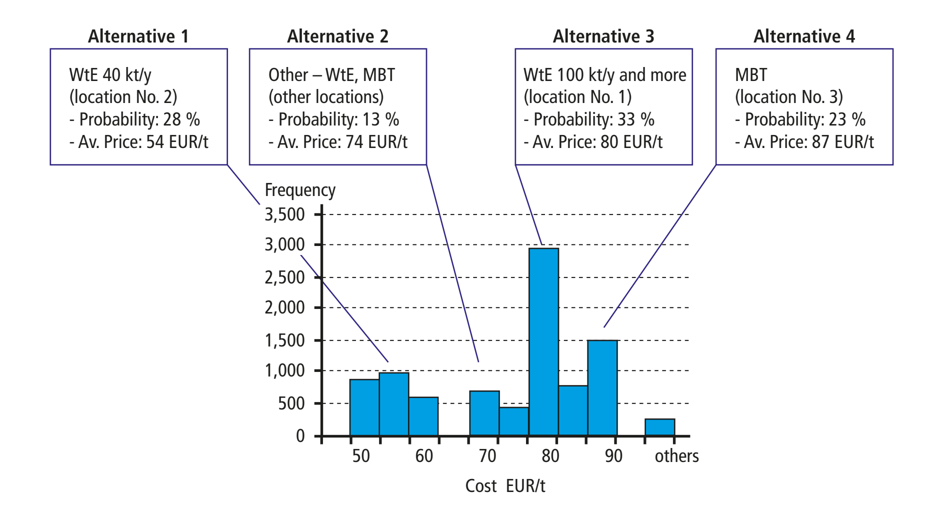

Figure 4: The resulting waste treatment options for a particular producer of waste

In some cases, producers are organized into alliances to secure more favourable contracts and prices. Basically, the assumption for a successful partnership within such structures is that all members should benefit. Very often there is an ongoing discussion about the rules of cost redistribution between individual members and the aforementioned cost analysis may be beneficial even for these issues.

4. Conclusion

This paper has reviewed recent progress in complex modelling in the field of waste management. Since logistics plays an important role in waste treatment, the modular and open system *Neruda* is introduced first. This network flow model consists of a core stochastic mathematical model and external modules supporting the core with input data and scenarios. Its practical relevance has been justified by several concrete applications. Some illustrative results related to one country – the Czech Republic in this case – were presented, however, this approach can also be generalized. The main objective was thermal treatment and issues such as risk-analyses, waste availability simulation and future treatment cost simulations. The results were carefully selected to cover a wide range of subjects who may benefit from its use, i.e. investors, producers.

Special attention was paid to forecasting the amount of waste simultaneously across different territorial units. In this respect, the novel tool, *Justine*, was introduced. *Justine* follows the principle of regression analysis, where a least squares approach is applied.

The sum of the squares of the distances between results and models is minimized on the future waste production available in each of the territorial units. The importance of additional constraints was highlighted. These constraints concern the mass conservation equation in the tree structure. Since data about the production of municipal solid waste and its components are often missing or inadequate, research opportunities accelerated by this tool were proposed.

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