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Implementation of Circular Economy through the Mathematical Programming for the Complex System Evaluation

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The current trends in the waste management field point to the circular economy. This system has been also projected in the EU directives and legislation, specifically Circular Economy Package, which gives the targets about recycling of different waste fractions. The obligation of member states is to put these goals into the local legislation. These regulations tend to the development of sustainability, but the industry implementation and how to reach the targets is not provided. The issue needs to be enhanced in a complex way and the suitable approach seems to be the mathematical programming. The ongoing necessity of sustainability evaluation must combine both the economic and environmental criterions through the usage of mixed integer linear programming. The task can be stated as multi-objective or constraint selective. The model includes costs related with operating the facilities, transportation costs, waste treatment costs and the cost and/or profit related to the handling of the separated waste (sale prices, separation technology, donations or support from the government). The environmental part covers the production of greenhouse gases respecting all processes in the system (savings related to the replacement of fossil fuels included). Constraints include all necessary balances and flows, separation and recycling rate targets as well as the total production of individual waste types and their distribution among fractions. Non-linear functions are substituted by piecewise linear approximations to reduce the computational time and ensure the solvability of the whole task. The presented approach is applied on a small testing instance. Future research can include new targets from the real-operated sorting lines in the form of more accurate costs.

1. Introduction

Depletion of some limited primary resources and relevant negative impact on the environment have become a worldwide problem (Hofmann et al., 2018). The situation has worsened with inefficient secondary material recovery from waste (Zhang and Xu, 2018). The response of the EU and other developed countries lies in their efforts to transfer to the so-called circular economy (Kalmykova et al., 2018). The core of the EU circular economy is in municipal solid waste (MSW) treatment which has been supplemented with so-called Circular Economy Package (CEP). Most of the CEP focuses on restrictions of MSW landfilling (Directive (EU) 2018/850) and increase in MSW separation efficiency (SE) (Directive (EU) 2018/851). A large number of specialized publications focuses on mixed municipal waste (MMW) processing with a potential of MMW energy recovery (Walmsley et al., 2017) without interactions with other MSW fractions (Ziegler-Rodriguez et al., 2018). Several papers have provided a more in-depth and complex analysis of the problem, that is the authors of these papers work with both MMW and other separated MSW fractions (paper (PAP), plastics (PLA) and glass (GLA), mostly), see (Rizwan et al., 2018). This type of task concerns Waste-to-Energy (WtE) plants as well as sorting lines, transfer stations and landfills. However, reverse waste flows are not usually included, or they are incorporated in the model only theoretically without any functional dependence related to separate fractions composition

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(Asefi and Lim, 2017). A typical example of reverse flow is a residual waste after plastic sorting (Brouwer et al., 2018). The composition of the separated fractions is given by SE and results in recycling efficiency (RE) of the separated MSW (Van Eygen et al., 2018). The presented comprehensive model combines several aspects which were previously dealt with separately. Interactions between waste fractions are considered also including reverse flow, which provides an overall view of waste handling. Links involved in the system are displayed in Figure 1.

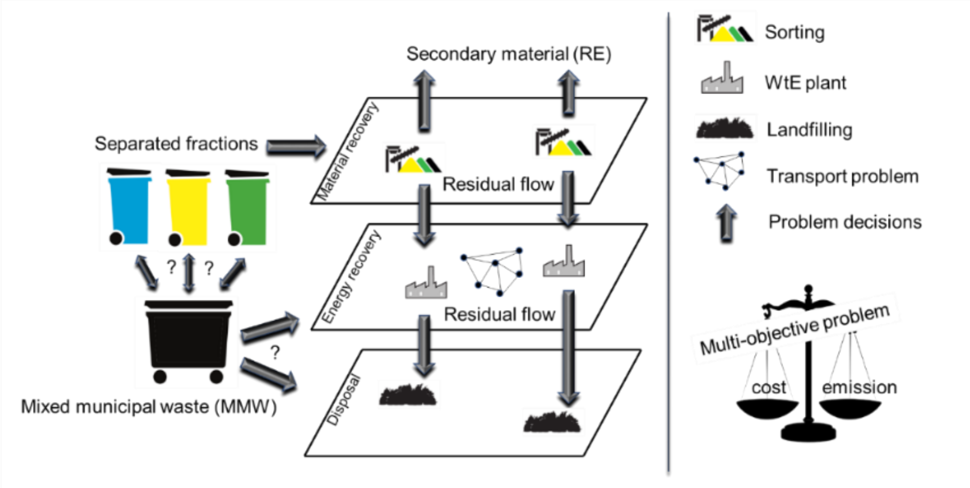

Figure 1: Concepts of the waste flow through the whole system

This paper presents a novel approach which accounts for economic and environmental factors of MSW treatment with an actual link to MSW recycling (not a mere separation) as well as the integration of novel technologies for WtE plants into current co-generation systems. Environmental factors are quantified using a method based on Global Warming Potential for the upcoming 100 years (Bong et al., 2017). Economic costs and benefits of Greenhouse Gases (GHG) have been analysed for all elements of the system in the next section. In (Van Fan et al., 2019), the GHG emissions of incineration were studied. Various aspects of waste transportation, both in terms of GHG (Van Fan et al., 2018) and its economic profitability (Gregor et al., 2017), have been considered, too. The approach is formulated through a mixed integer programming. The mathematical model is introduced in section 3 and demonstrated on a small instance in section 4. Results are discussed in the conclusion, and potential development of the novel approach is outlined for a specific case study with real data.

2. Technology and waste flows

This paper addresses the main fractions of MSW that are collected separately – MMW, PAP, PLA and GLA. Amount of separable waste fractions is predisposed by the total waste amount, which is represented by separated waste fractions and unseparated MMW (see Figure 1). The amount of separated fractions has a direct impact on collection costs and the amount of residuals from sorting lines. The higher the SE, the more unrecyclable waste there is in the separated waste. This effect may be commonly observed in plastics separation, not so much with glass and paper.
Costs related to the collection of separated fractions vary. It reflects the properties of transport infrastructure such as density of collection containers, waste production, separation method (smashed PET bottles, for example) and so on. In order to realistically estimate changes in collection costs, it is necessary to work with sophisticated methods based on the so-called Vehicle Routing Problem or Arc Routing Problem. These methods must be further accompanied by high-quality technical and economic data. Authors of this paper have adequately suggested functional dependence of waste collection costs on SE. General functional dependence is given in Eq(1) and Eq(2). The independent variable in Eq(1) is overall separation efficiency, given by the formula in brackets. In the case of Eq(2), the SEP should be replaced by particular separated fraction (PAP, PLA and GLA).

MMW: $$y_{SE,MMW} = a_{SE,MMW} - b_{SE,MMW}\left(\frac{PAP+PLA+GLA}{PAP+PLA+GLA+MMW}\right)^{c_{SE,MMW}}, \quad (1)$$

PAP, PLA and GLA: $$y_{SE,SEP} = a_{SE,SEP} + b_{SE,SEP}\left(SE_{SE,SEP}\right)^{c_{SE,SEP}}, \quad (2)$$

where $y_{SE,MMW}$ and $y_{SE,SEP}$ designate waste collection costs of MMW and separated fractions $a_{SE,MMW}$, $b_{SE,MMW}$, $c_{SE,MMW}$ resp. $a_{SE,SEP}$, $b_{SE,SEP}$, $c_{SE,SEP}$ denote regression coefficients. With respect to these equations, coefficient $c_{SE,MMW}$ resp. $c_{SE,SEP}$ is crucial since it determines the rate of waste collection costs increase in relation to SE (and differs for PAP, PLA, GLA). Parameters $c_{SE,MMW}$ and $c_{SE,SEP}$ are expected to reach ca. 1, which corresponds to the linear model. Initial price for the vehicle use is constant ($a_{SE,MMW}$ resp. $a_{SE,SEP}$) and next cost is directly proportional to the SE. In-depth analysis of input data and functional relations is to be extended in future when the approach and its application on a case study with real data are anticipated. Similar approach is used for estimation of residuals from sorting lines (with respect to SE). Functional dependence according to Eq(2) is applied also for RE modelling ($y_{RE,SEP}$), $c_{RE,SEP} > 1$ is expected. Transfer stations for more efficient waste transportation, WtE plants, sorting lines and landfills are all incorporated in the waste processing network. Residual waste streams in WtE plants, where the slag is amounting up to 25 percent of input MMW weight, are also considered. This amount of slag is considered completely for landfilling. Mentioned technologies and dependencies are incorporated in the mathematical model.

3. Mathematical model

The method is divided into two follow-up steps since the nonlinear links in the system are time demanding. Particularly, the relationships between SE and RE (respectively the amount of residuals from sorting) are described by nonlinear dependency. In order to optimally design capacity of sorting lines, it is necessary to know average SE for waste which flows to the sorting line from more producers. This weighted average consists of uncertainty amount of separated fraction and unknown SE, both of them are variables. As a result, the nonlinear relationships appear in the model which often complicate the solvability of the problem in the sense of searching global extreme.

The iterative procedure consists of the following parts:

1) The appropriate SE is selected and that indicates the amount of separated PAP, PLA, GLA and MMW. As a result, the capacity and location of transfer stations, WtE plants and landfill are suggested. The sorting lines capacity and placement are not involved in this step (it is considered in all production nodes with the adequate capacity corresponding to the separated fractions of MSW).
2) The optimal location and capacity of sorting lines are designed with the already known amount of the separated waste and ratio suitable for recycling (respectively the amount of residuals from sorting). The primary design of processing grid is recalculated with regards to given production amounts.

Due to the scope of the task, the whole mathematical model is not to be described in detail. Only the objective function in the context of economic and environmental criteria is stated and described. The notation of used sets, parameters, and variables is defined in the following.

Sets

$i \in I$ set of nodes $j \in J$ set of waste types $h \in H$ set of arcs

$p \in P$, $q \in Q$ points for linearization using SOS2 (special order set of type 2), see (Williams, 2009)

Parameters

d_h length of arc h
f_h^D cost for waste transportation
e_i^S emission contribution of landfilling in the node i
e_j^V emission contribution due to waste collection
e_i^R emission contribution of waste transshipment
e_h^D emission contribution of waste transportation
f_j^O cost for separated waste
f_i^S cost for waste landfilling
e_j^O emission savings of separated waste processing
$M_{h,i}^S$ matrix for transportation to waste landfill
$M_{h,i}^R$ matrix for MMW from the transfer station
$L_{i,p}^Z$ transshipment cost
$S_{i,p}^Z$ WtE cost
$S_{i,p}^E$ WtE emission production
$T_{i,j,p,q}^Z$ separation cost
$T_{i,j,p,q}^E$ emission production from separation
$V_{i,j,p,q}^Z$ transportation cost
w_F weight of economic criterion
w_E weight of environmental criterion

Variables

o_j total amount of separated waste j
$r_{i,j}^U$ total amount of waste j in the node i
$x_{h,j}$ amount of waste j transported through arc h
z_F economic criterion in the objective function
z_E environmental criterion of objective function

SOS2 variables - linearization

$\alpha_{i,p}$ waste transshipment cost – amount of transported waste
$\beta_{i,j,p,q}^Z$ separation emission – emission production
$\theta_{i,p}$ waste incineration – amount of waste
$\lambda_{i,j,p,q}^Z$ separation cost – results of cost
$\xi_{i,j,p,q}^Z$ transportation cost – results of cost

Objective function

Multi-objective function Eq(3) combines the economic Eq(4) and environmental Eq(5) aspects. The weights w_F and w_E set the priority of cost and emission minimization. They are suggested as an inversion of results for the optimization of individual parts. The computation is organized in the two iterations (see above), therefore each of them includes three optimization processes. Particularly, two calculations do not taken into account the weights and the only one aspect (economic or environmental) is minimized for weights setting and the third part combines both of criteria supplemented by weights (Eq(3)).

$$\min w_F z_F + w_E z_E \tag{3}$$

The economic part of the objective function minimizes the total cost, so it includes the financial requirements of each part of complex infrastructure, the summation in a row: the waste collection cost in the production nodes, the transportation cost, operation costs of sorting lines and transfer stations, the cost of waste treatment in the WtE plants and landfills, the last summation represents the rewards for waste separation and profit from the sale of secondary raw materials. Some dependencies are considered in the linearized form using SOS2 variables, see (Hrabec et al., 2017).

$$\begin{aligned} z_F = {} & \sum_{i\in I}\sum_{j\in J}\sum_{p\in P}\sum_{q\in Q} V^Z_{i,j,p,q}\xi^Z_{i,j,p,q} + \sum_{h\in H}\sum_{j\in J} f^D_h x_{h,j} d_h + \sum_{i\in I}\sum_{j\in J}\sum_{p\in P}\sum_{q\in Q} T^Z_{i,j,p,q}\lambda^Z_{i,j,p,q} + \sum_{i\in I}\sum_{p\in P} L^Z_{i,p}\alpha_{i,p} \\ & + \sum_{i\in I}\sum_{p\in P} S^Z_{i,p}\theta_{i,p} + \sum_{h\in H}\sum_{i\in I}\sum_{j\in J} f^S_i x_{h,j} M^S_{h,i} - \sum_{j\in J} f^O_j o_j \end{aligned} \tag{4}$$

Production of emissions is taken into account by conversion to the equivalent of carbon dioxide (CO_2eq) produced in each partial process. The order of the individual parts of equation Eq(10) corresponds to the meaning of the previous equation in this case with regard to the environmental impact.

$$\begin{aligned} z_E = {} & \sum_{i\in I}\sum_{j\in J} e^V_j r^U_{i,j} + \sum_{h\in H}\sum_{j\in J} e^D_h x_{h,j} d_h + \sum_{i\in I}\sum_{j\in J}\sum_{p\in P}\sum_{q\in Q} T^E_{i,j,p,q}\beta^Z_{i,j,p,q} + \sum_{h\in H}\sum_{i\in I}\sum_{j\in J} e^R_i x_{h,j} M^R_{h,i} \\ & + \sum_{i\in I}\sum_{p\in P} S^E_{i,p}\theta_{i,p} + \sum_{h\in H}\sum_{i\in I}\sum_{j\in J} e^S_i x_{h,j} M^S_{h,i} - \sum_{j\in J} e^O_j o_j \end{aligned} \tag{5}$$

For the functionality of the model, it is also necessary to supplement the constraints of the mathematical model, which ensures the mass balance in the nodes, the capacitive constraints, the relationships connected with the SOS2 variables, the properties of the variables (non-negativity, binaries) etc.

4. Testing instance

The testing instance consists of 5 nodes and 8 edges with the respective distance depicted in the Figure 2. There is also noted the potential waste production for 3 fractions (PLA, PAP, GLA) and Other waste.

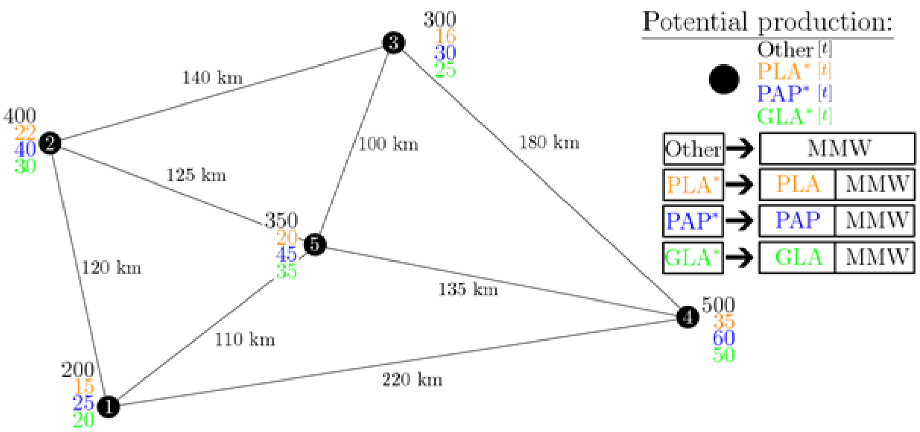

Figure 2: Schematic graph of infrastructure and its properties

The calculation was performed according to the presented scheme and equations, the results of the first iteration are depicted in Figure 3. The aim of the first iteration is the estimation of SE for individual fractions, in addition initial values for the second iteration are set. Simultaneously, the flow of MMW and treatment facility placement is suggested (transfer stations, WtE plants and landfills). The location of sorting lines is unknown in this part, for computational reasons it is solved within second iteration. The results of the first iteration are shown in the Figure 3 including the waste flow. The estimation of SE for analysed fractions is: PAP 75.0 %, PLA 56.5 % and GLA 63.1 %.

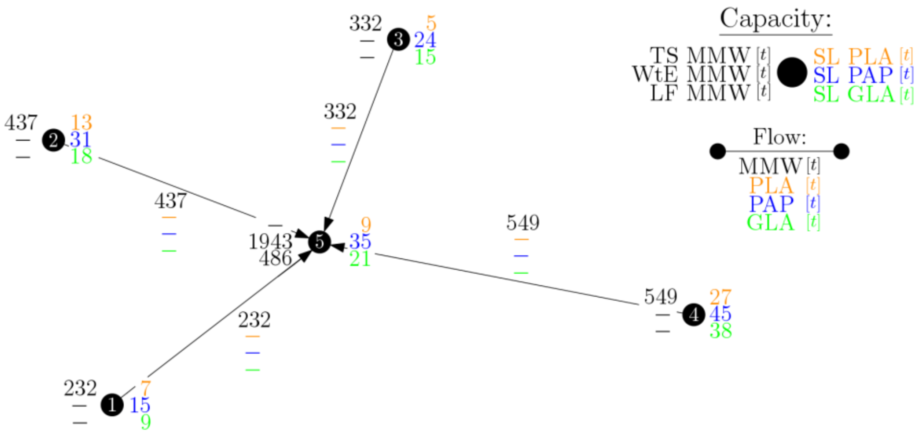

Figure 3: The resulting network flow, designed capacities and identified separation efficiency

The second iteration utilizes the results from the first iteration and the output of the first iteration is verified. The output of the second iteration is depicted in the Figure 4. The location and capacities of treatment facilities are edited within the second iteration due to inclusion sorting lines to the system, so the residual flow is also included in the system. The SE of fractions of MSW from the first iteration is maintained. The final decision suggested concentrating almost all waste at node 5. The rest of the nodes might save costs by establishing transfer stations with respective capacities. It applies for pressed MMW, which is afterwards incinerated in the WtE plant. The residuals from the WtE plant (slag) is assumed to be landfilled. Fractions of PLA, PAP and GLA are collected at sorting lines at node 5. There were also suggested sorting lines for PAP and GLA at node 4, which is caused by sufficient production in this area for the realization of a sustainable facility.

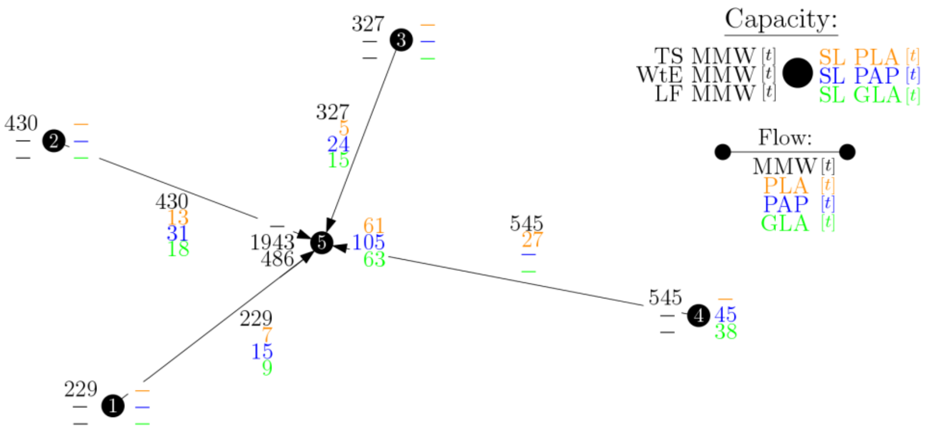

Figure 4: The resulting network flow and designed capacities for all potential fractions

The calculation was made using software GAMS (The General Algebraic Modelling System). As was mentioned above, the approach consists of two iterations and each of them includes both integer and continuous variables. The computation properties inclusive of computing time for testing instance:

1. Iteration: 1,740 integer variables, 248 continuous variables, 9 s computing time,
2. Iteration: 780 integer variables, 228 continuous variables, 4 s computing time.

5. Conclusions

The paper presented a comprehensive approach to support decision making in the transition of current waste management to a circular economy based strategy. The main benefit is the incorporation of reverse waste streams, which play an essential role in capacity planning and facility location. The approach takes into account the sustainability of the solution in relation to the environment and the economic burden on waste producers. The model assumes two criterions, where the environmental component was described by GHG contribution. With regard to the nonlinear system connections (see reverse waste flows), SOS2 variables were used for linearization. Because of the solvability, two important outputs of the task (SE vs. RE and the allocation of processing capacities) were solved iteratively in two steps. The approach was demonstrated on the small testing instance. The functionality of the approach has been verified with sufficient accuracy of results. Subsequent development will be focused on the tuning of the mathematical model and input data pre-processing. Functional dependencies have to be discussed as well with regard to the solvability of large-scale tasks comprising real data. The goal is to apply the modified model in the case study for the large geographical area.

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