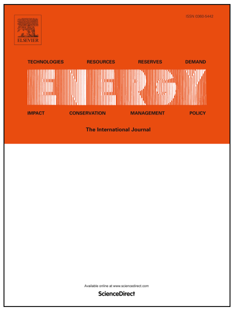

Sustainable waste-to-energy facility location: Influence of demand on energy sales

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Author contribution statements

Dušan Hrabec is a corresponding author. He is responsible for literature review, mathematical models and computations in GAMS.

Radovan Šomplák is responsible for mathematical models development and GAMS implementation.

Vlastimír Nevrlý is resposnible for data preparation and helped with the development of mathematical models and implementation in GAMS software.

Adam Viktorin is author of the meta-heuristic algorithm and for the other heuristic computations.

Michal Pluháček served as supervisor when developing the heuristic approaches.

Pavel Popela served as supervisor of most of the work. He is responsible for overal quality of the manuscript and he is author of some original ideas such as model I motivation, some mathematical functions, etc.

Sustainable waste-to-energy facility location: Influence of demand on energy sales

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Abstract

Waste-to-Energy facility location with practical insights into its economic sustainability is assessed by two mathematical models. The first model minimising transportation and investment costs leads to a mixed-integer linear problem, for which commercial solvers perform very well. However, economic performance, which is needed for long-term projects requiring large investments, is not met when the capacity of the plant is not fully utilised. This can be resolved by a revenue model defining gate fees for potential plant capacities. Therefore, a second model including penalty cost functions associated with reduced energy sales and unutilised capacity of plants is developed. This leads to a non-linear model where solvers perform well for small and medium-size instances and so a modified meta-heuristic algorithm is proposed. Both models are applied to data from the Czech Republic. Insights into performance of the models and their economical sustainability using demand influence on the energy sales are provided. While the solution of the linear model proposes a higher number of facilities with less total capacity repletion, the non-linear model suggests a smaller number of facilities with higher total repletion presenting a reasonable sustainable solution. The strategy supports the decision-making of authorities for the sustainable planning of new projects.

Keywords: Waste-to-Energy facility location, economic sustainability, energy recovery, heat demand, energy sales, meta-heuristic

Highlights

- Mathematical programming used to suggest an optimal site for Waste-to-Energy plants.
- Two models were developed and their results compared to evaluate sustainability.
- Energy utilisation included through its real sales to enhance economic performance.

1. Introduction

Economic and population growth is linked to the increasing amount of municipal solid waste (MSW) and change of its composition [1]. The MSW generated each year makes waste management (WM) one of modern society's most relevant and challenging issues [2]. The problem spans both industrialised as well as countries that are developing quickly; therefore, the current state requires new conceptual solutions [3]. Energy recovery from residual products and wastes is long established as a widely and successfully applied waste recovery alternative [4]. The countries of the European Union are not excluded [5]. While developed countries in Western Europe try to recycle the maximum amount of waste and use non-recyclable waste for energy generation, Central and Eastern European countries store a huge amount of mixed municipal waste in landfill sites [6]. However, landfills that accept MSW disregard environmental risks and so their usage is to be reduced [7]. The focus is moving towards green and clean energy technologies for the environmental

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Nomenclature

Superscripts and sets

I	a set of nodes (municipalities), $i \in I$
J	a set of treatment nodes (facilities), $j \in J$
K	a set of considered facility capacities, $k \in K$

Variables

p_j	penalty function depending on variables y_j and z_j [EUR]
t_j	the amount of waste treated in facility j [t]
$x_{i,j}$	the amount of waste transported from i to j [t]
y_j	auxiliary variable stating the rate of unused capacity (to penalise) [-]
z_j	auxiliary variable stating capacity of the facility [t]
$\alpha_{j,k}$	a binary variable stating facility location as well as its capacity decision [-]
$\delta_{i,j}$	a binary variable assigning of waste producer i to facility j [-]

Parameters

a_j	penalty function parameters (regression coefficients for all plants) [EUR^{-1}]
b_j	penalty function parameters (regression coefficients for all plants) [t·EUR^{-1}]
c_j	penalty function parameters (regression coefficients for all plants) [EUR^{-1}]
$c_{j,k}^{treat}$	the cost of waste treatment at node j with regards to considered capacity k [EUR]
c^{trans}	the unit (usually tonnes) cost for transportation [EUR/(km·t)]
$C_{j,k}$	a set of parameters presenting the considered capacities k at each point j [t]
$C_{j,max}$	maximum possible capacity of facility j [t]
$d_{i,j}$	distance from i to j [km]
D	dimensionality of the problem (number of possible facilities) [-]
H	historical memory size [-]
m_1	an auxiliary low positive number (to avoid division by zero) [t]
m_2	an auxiliary low positive number (to avoid division by zero) [-]
M	a large number [t]
$MAXFES$	maximum number of function evaluations [-]
N	number of random sequences of waste producers [-]
NP_f	final population size [-]
NP_{init}	initial population size [-]
$runs$	number of runs (by DR_DISH) [-]
w_i	the waste production amount at node i [t]

Abbreviations

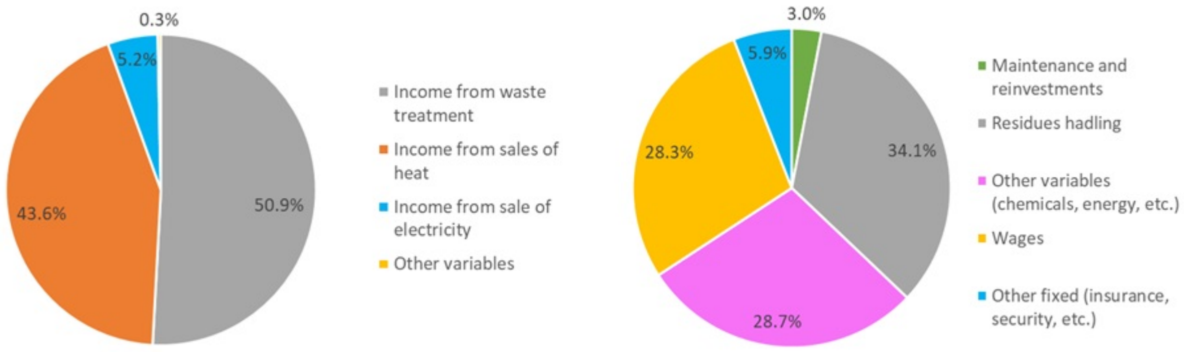
DISH	distance based parameter adaptation for success-history based differential evolution
DR_DISH	distance random distance based parameter adaptation for success-history based differential evolution
IRR	internal rate of return
MILP	mixed-integer linear program
MINLP	mixed-integer non-linear program
MSW	municipal solid waste
WM	waste management
WtE	waste-to-energy

protection and sustainable development [8], especially in producing power, transportation fuels and chemicals [9]. The Waste-to-Energy (WtE) technologies have been indicated by the European Commission as suitable to play a prominent role in the recovery of energy from waste in the near future [10]. Recently, a number of Central European countries have undertaken steps to improve their WM approaches in order to come into line with the more advanced countries in the west and follow the WM hierarchy options [11].

A typical example is the Czech Republic, where three WtE facilities have been in operation for several years, one new has recently been fully commissioned and others are planned [12]. In 2018, the production of mixed municipal waste was ca. 2.8 Mt while the overall waste production that is suitable for energy recovery (together with some other fractions of MSW) was ca. 3.2 Mt. However, the recent capacity for energy recovery waste is only about 0.75 Mt. Mixed municipal waste which is suitable for energy recovery but is not energetically recovered is mostly disposed at landfills. Similar conditions appear in other Central European countries [6]. Therefore, the need for new WtE capacities is necessary [13].

Very important aspects when deciding on location and size of WtE facilities are analysis and optimisation of facility utilisation since energy and economy efficiency require high utilisation [14]. What should also be emphasized is the potential waste heat demand [15] as it can increase the energy efficiency of the system [16]. While in the Southern Europe electrical energy recovery is the most common practice, in Central and Northern Europe the heat or combined heat and power recovery is diffused [17]. Incorrect dimensioning of the plant may result in loss of energy production while installation and operation cost would not be coped with [14]. WtE projects (such as incinerators locating) are expensive to build and operate that may place a huge financial burden on the government [18]. Although, the WtE projects are usually encouraged by the government, private investors that are more experienced and flexible in terms of financing have recently begun to get involved [19]. The potential income is represented by selling recovered energy as power [20], heat or combination of them in WtE facilities [21]. The incomes and costs of the WtE facility with combined heat and power generation are depicted in Fig. 1. An example is provided for the area with extensive central heating system, where the majority of produced energy is used for heat distribution. The incomes from waste treatment are usually incorporated in the objective function [22]. However, uncertainty related with the potential lack of waste in relation to the planned capacity impose a large financial risk on both the involved parties, the private investors and government [23]. It follows that the WtE capacity which is not utilised should also be reflected in the facility revenue. The varying energy supply has not been used in the context of the WM, but energy-based income is being used in other various models and areas (see review on the WM issues [24]), however, there are always multiple simplifications. There were not papers where the income from energy sales is directly incorporated in the objective function. Energy sales differ during the year and it is location dependent at the same time (the fuel used for energy production differs from gas to coal and the heat demand varies as well). The revenue decrease caused by lower sales of heat may significantly affect the sustainability of the project planning, see Fig. 1a. Therefore, two models are proposed and compared herein: one that minimises transportation and operating costs (gate fee oriented) and one that, additionally penalise the unused capacity of the facility and simultaneously reflects undelivered energy/demand.

This paper approaches the problem via the so-called facility location problem and attempts to derive a decision-making tool on the optimal WtE facility location reflecting its economic sustainability. It is well known, that optimal solutions lead to locate WtE facilities close to the waste generation points, in order to reduce the emissions and costs due to transportation [26]. General mathematical formulation of locating MSW facilities can be formulated by a mixed-integer programming model with a cost minimization objective. A whole range of studies have been conducted into the problems of effective MSW facility (incinerator, composting and recycling plants, transfer stations, landfill sites, etc.) location and the potential optimisation of waste collection; see, e.g., [27]. Refer to [28] for a survey of strategic and tactical issues in solid WM and to [29] for an extensive review of existing articles on MSW facilities location modeling. The existing models usually differ in various attributes such as number of objectives, number of potential/allowed locations, types of facilities to be located and knowledge of waste generation [19]. Most of the models share a common objective that is total cost minimisation. However, many recent approaches consider other additional objectives such as environmental (pollution, greenhouse gas emission, etc.) or social (Not In My Back Yard - NIMBY or Build Absolutely Nothing Anywhere Near Anything - BANANA phenomena [29], etc.) [30]. See also [31] for review of the usually used criteria. The main advantage of multi-objective



(a) Example of incomes (b) Example of expenses

Figure 1: An example of structure of incomes and costs [25]

approaches is the consideration of various criteria that cannot normally be compared. In the case of a combination of emissions and costs, it is then possible to construct a pareto curve from which a suitable point for compromise can be selected [32]. The disadvantage of these approaches is their dependence on the subjective decision of the evaluator. When more than two criteria are combined, the set of pareto optimal solutions is also too large. The number of candidate locations and methods of waste treatment significantly affect the computational complexity of the resulting model. The number of integer variables is growing here, which in combination with the existence of non-linear functions can lead to no solution being found at all. Another critical area is the way of thinking about waste production. This parameter is often not available for historical data depending on the size of the research area. In addition, there are expected trends over time, which can be a big problem for processing plants designed for twenty years of operation.

The main novelty of this paper lies in the analysis of location and capacity of WtE projects through economic sustainability that is made via a comparison of two different WtE facility location cost-minimising approaches: 1. one that minimises total cost, which is composed of waste treatment cost including investments for facility location and waste transportation cost; 2. second that, in addition, captures penalty for unused WtE facility capacity (penalty function capturing lack of waste corresponding to loss in energy sales). The first model presenting a common approach used in above-mentioned studies leads to a mixed-integer linear program (MILP), where conventional/commercial algorithms such as CPLEX perform very well. The second model, which additionally includes penalty costs in the objective function, leads to a mixed-integer non-linear program (MINLP) because the financial loss in energy sales is not linear due to varying heat demand during the year. Commercial algorithms such as DICOPT are reasonable to implement for relatively small instances, they do not provide sufficient results for larger (real-world) instances. In some papers, authors also define a penalty for unused facility capacity (see, e.g., [33]), but no one considers financial losses as a result of lower energy production: electricity and heat (see Fig. 1a). The huge number of combinations which is needed to be assessed meant that the computational problem would become extremely time-consuming; a problem that would only become worse with the increasing size of the analysed area. Therefore, the developed MINLP is also approached using a meta-heuristic algorithm, which does not guarantee the global optima, but provides a good solution which meets practical requirements. The authors follow up from previous work [12], where a similar algorithm was tested however only on relatively small instances. Herein, a specific meta-heuristic algorithm is developed in order to test results for large instances as the Czech Republic definitely is the latter. For both of the models, computational approaches are proposed, tested and compared for a real data-based case study. The complete flow chart of the study is depicted in Fig. 2. It illustrates all implemented models and approaches, and describes the links between individual stages. The reasoning for application of specific approaches is also highlighted.

The remainder of the paper is organized as follows. Chapter 2 gradually presents two mathematical models. First, a basic facility location model that leads to a MILP model I is introduced (Section 2.1). Section 2.2 follows with economical background description of WtE projects (subsection 2.2.1) and a MINLP

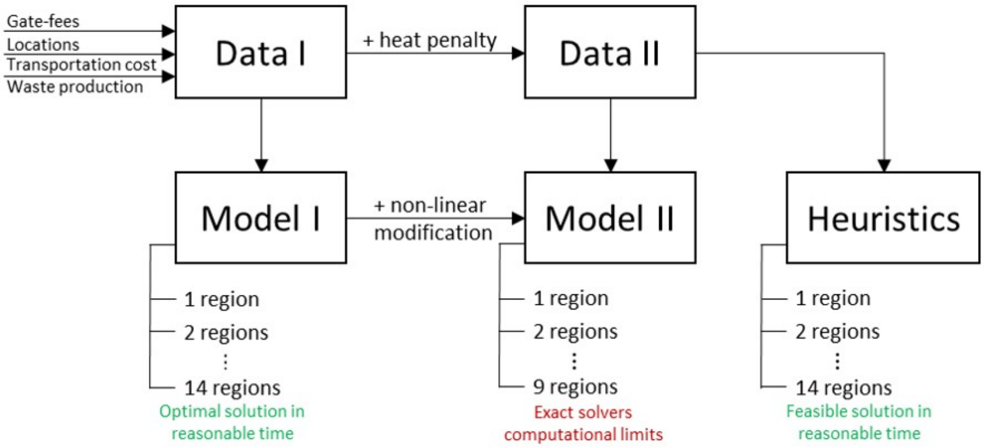


Figure 2: A complete flow chart of the presented models and approaches

model II involving penalisation of unused capacity and undelivered heat is provided (subsection 2.2.2). The models are applied in a case study in Chapter 3. First, results of the GAMS solvers are provided (model I in Section 3.1 and model II in Section 3.2). Then, an algorithm which is a combination of a meta-heuristic and a clustering method is developed (Section 3.3) and its results are presented (Section 3.4). This is briefly compared with some other heuristic approaches (Section 3.5). Finally, the paper concludes with Chapter 4.

2. WtE facility location: Mathematical models

In this section, two models supporting strategical WM decisions are developed, namely decisions on WtE facility location. First, mathematical formulation of a single-objective cost-minimising WtE facility location and its capacity allocation, which is based on assigning of waste producers, is provided. Based on this, another model providing insights into sustainability of the WtE project is provided in Section 2.2.

2.1. Basic model description

Consider a region, where government plans to launch as many WtE facilities as needed in order to have enough treatment capacity for a given production of waste that is suitable for energy recovery. The project usually has two phases [19]: the planning phase, where government makes strategic decisions about the location and capacity of the WtE facilities, and construction phase, where private investors spend money constructing the facilities based on the decisions of the government. It is commonplace that regions follow their own WM policies which are, more often than not, incompatible with the WM plan of the whole country. In most of the studies, the problem of territorial structures is ignored. However, this paper attempts to optimise the location of the WtE facilities for a country (group of regions, respectively) with regard to some other realistic conditions. The most relevant is the possibility of producers to select only one treatment facility to dispose of their waste. The relation between the producer and the particular facility is essential for a realistic description that respects the contracts signed usually for the period of 10 years or longer.

The description of the problem is simple: each municipality i (customer, producer) generate estimated amounts of waste w_i which is to be transported to a WtE facility j for transportation costs $c^{trans} d_{i,j}$ and treated for treatment costs $c^{treat}_{j,k}$. The facilities can be located at stated locations which are given by existing district heating systems (a key factor for project economics, see Fig. 1). Each facility can have various capacities $C_{j,k}$; herein, the cost for locating the WtE facility and its capacity/size is reflected in the treatment cost. We therefore define two sets of binary variables: location-capacity variable $\alpha_{j,k}$ and variable $\delta_{i,j}$ assigning each producer (municipality) to the WtE facility. Additionally, two sets of continuous variables are given: the total amount of waste t_j that is treated in the WtE facility and waste transported from producer to specific WtE facility, $x_{i,j}$. The developed MILP is defined as follows:

$$
\begin{aligned}
\min \quad & \sum_{j\in J}\sum_{k\in K}\alpha_{j,k}c^{treat}_{j,k} + \sum_{i\in I}\sum_{j\in J}x_{i,j}d_{i,j}c^{trans} && && (1)\\
\text{s.t.} \quad & w_i = \sum_{j\in J}x_{i,j}, && \forall i\in I, && (2)\\
& t_j = \sum_{i\in I}x_{i,j}, && \forall j\in J, && (3)\\
& t_j \le \sum_{k\in K}\alpha_{j,k}C_{j,k}, && \forall j\in J, && (4)\\
& \sum_{k\in K}\alpha_{j,k} = 1, && \forall j\in J, && (5)\\
& x_{i,j} \le \delta_{i,j}M, && \forall i\in I, \forall j\in J, && (6)\\
& \sum_{j\in J}\delta_{i,j} \le 1, && \forall i\in I, && (7)\\
& t_j, x_{i,j} \ge 0, && \forall i\in I, \forall j\in J, \forall k\in K, && (8)\\
& \alpha_{j,k}, \delta_{i,j} \in \{0,1\}, && \forall i\in I, \forall j\in J, \forall k\in K. && (9)
\end{aligned}
$$

The objective function (1) minimises the total costs, which is the sum of the waste treatment costs (that, in our setting, also includes investment costs for the new facility) and waste transportation costs. Equations (2) and (3) form a balance constraint, i.e. all produced waste is collected, transported, and processed. Constraints (4) guarantee that the volume of treated waste cannot be higher than the treatment capacity of the facility. Constraints (5) ensure that exactly one capacity k decision is made at each potential location j (the decision includes zero capacity with no cost $c^{treat}_{j,k}$). Constraints (6) serve as the indicator for variables $\delta_{i,j}$ (particular edge in use). Together with (7), these constraints state that one waste producer can be assigned to no more than one waste facility. Finally, constraints (8) – (9) state domains and properties for the decision variables.

2.2. Sustainable WtE facility location: Problem formulation

Regarding the location problem, where the goal is to situate new facilities with proper capacity with respect to existing demand, it is necessary to take into account economic sustainability. It is very difficult to motivate investors without ensuring viable operation. A high-quality techno-economic model is required to specify investment attractiveness of a project [34]. This must include the investment and the main components of revenue and costs. A key aspect also consists of a realistic estimate of price movements and necessary reinvestments. In the case of a WtE facility, some model attributes are related to capacity choice (e.g. investments, wages, maintenance). Besides that, other attributes depend on the specific operation and are affected by capacity utilisation (e.g. heat yield and related costs of residuals).

2.2.1. Economic sustainability of WtE facilities

When assessing a particular project, some inputs are fixed and some can be defined with respect to the technical possibilities and competitive environment. A typical example is the cost of waste processing, which is the only optional part of the income [20]. Other components are firmly established by the market or local conditions – the price of heat depends on the prices of the existing heat sources in the specified area (heating plants), the price of electricity is listed on the stock exchange (in the case of Europe, on the Frankfurt Stock Exchange), and the price of metal separated from slag is determined by the current commodity price. Cost items are also determined by the current market environment. Therefore, the attractiveness of a potential project is given by the specified cost for waste treatment. The quality of the investment is very often assessed on the basis of the internal rate of return (IRR) criterion, see [35] for IRR application in the green supply chain; in the case of cheap debt financing, the attractiveness of the investment increases – the weighted average cost of capital (WACC) criterion [36]. An example of an IRR change with respect to the set value of the waste treatment cost is shown in Fig. 3. To obtain realistic results of the facility location optimization tasks, the lower bound of IRR threshold is set for each project, which defines the minimum gate fee.

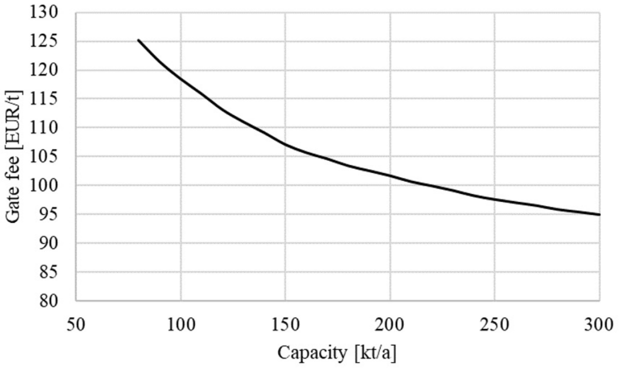
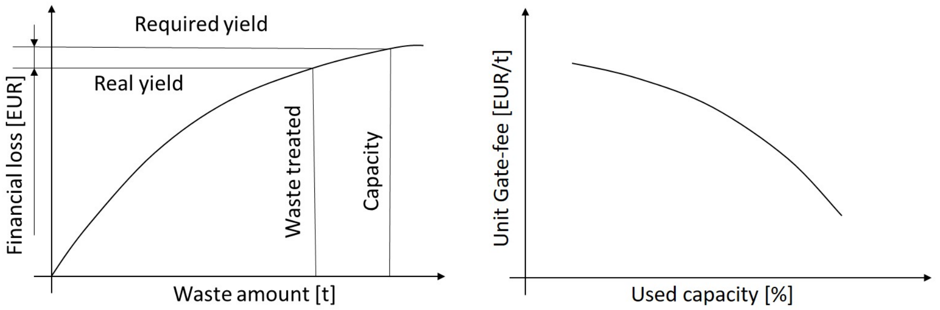


Figure 3: Gate fee of one particular city based on capacity and chosen economic criterion; city of ca. 94,000 of inhabitants (České Budějovice), heat demand: 1,958,874 GJ/year, basic heat source: brown coal, IRR: 10%, lower heating value 9.3 GJ/t

Note: The turbine with a rotary reduction is considered (low-pressure turbine with low efficiency), where all the steam always passes through before it is eventually used to heat the water entering the central heating system. Therefore, the electrical output does not depend on the heat demand. Thus, from technological reasons, 56 kWh and 7.2 GJ can be produced from the tonne of waste for small capacities. The large capacities can produce 118 kWh and 6.2 GJ. These values are based on the assumed lower heating value of input waste at the level of 9.3 MJ/kg and the boiler efficiency of 87%. The output power of low capacities results from the use of a back-pressure turbine with an internal thermodynamic efficiency of 50%. At higher capacities, a condensing extraction turbine with an efficiency of 78% is used. It is considered that the minimum steam flow through the condensing part of 10% must be be maintained [37].

In the case of an insufficient amount of waste with respect to the facility capacity, the revenues from waste treatment and energy sales are significantly reduced. Minor savings will arise in the costs (e.g., chemicals for the flue gas cleaning system). However, the overall balance is negative. The reduction in income can be resolved by the approach presented further in subsection 2.2.2. The idea of fixed income, which corresponds to the investment costs given by the choice of processing capacity, is illustrated in Fig. 4.



(a) Financial loss scheme (b) Gate fee dependent on the waste supply

Figure 4: Illustration of the expected financial loss

Fig. 4a shows a reduction in planned revenue in case of an insufficient waste supply compared to established capacity. If the IRR condition is required, it will be necessary to increase the gate fee for such project. The dependence of such a unit increase on the capacity utilisation is shown in Fig. 4b. This dependency is hidden in the constant value of the objective function, which is independent of the amount of waste processed (only capacity-dependent). Such a situation can occur when considering several waste production scenarios where the capacity needs to be decided in the first stage of a multistage stochastic task [19]. In such case, the capacity decision is based on scenarios with the largest increase in production, resulting in lower incomes for other scenarios. Thus, with constant cost per treatment, it is necessary to increase the gate fee for these scenarios, see Fig. 4a. Note that multi-stage programming represents the basic pillar of optimisation tasks with uncertainty.

The revenue problem of waste treatment is thus resolved, but the change also occurs in the case of the sale of heat and electricity (the revenue from the sale of metals plays a negligible role in the total) and the reduction of some cost attributes (see above). To gather this, it is necessary to introduce appropriate penalties following Fig. 1. The penalty function depends on the processing capacity and the utilisation of this capacity. In the case of an unlimited heat demand, it could be described by a linear function, which is easy to implement in a mathematical model. However, the heat demand and thus potential supply varies among localities. The typical heat demand and supply throughout the year is shown in Fig. 5 [38] for fully utilised capacity and partially unfulfilled capacity. Therefore, a suitable trade-off between heat demand and processing capacity needs to be chosen. This results in frequent changing of operations modes (winter months – heat oriented operation, summer months – electricity generation).

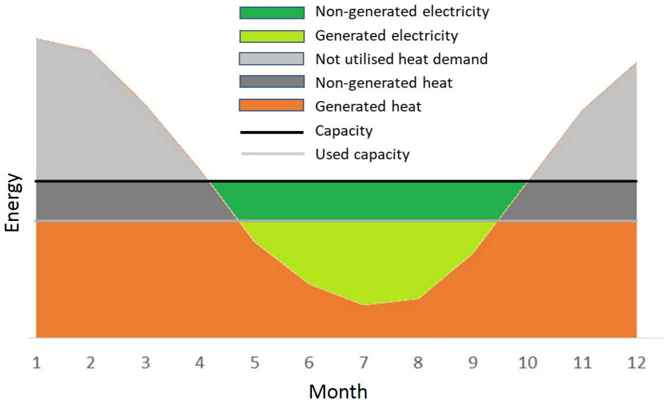


Figure 5: The basis of heat and electricity features for the formulation of the penalisation function

When the capacity utilisation is reduced (increasing the difference between the available waste and selected capacity), the impact of the penalty will be increased (heat revenue is an important income component of a WtE facility). On the other hand, the effect of the lower capacity will operate in the opposite direction. The dependency can be described by equation (10), which is used in the objective function in subsection 2.2.2:

$$p = \left(a + \frac{b}{z} + \frac{c}{y}\right)^{-1}. \tag{10}$$

The penalty function (10) was created on the basis of non-generated electricity and non-generated heat according to principle in Fig. 5. The penalty function is locality dependent, due to the heat demand. Furthermore, for each WtE facility the function comprises the chosen capacity z (in tonnes) and the rate of its utilisation y (from range $(0, 1\rangle$) while a, b, and c are the regression coefficients. For all of the locations, the coefficient of determination was above 0.95 with the chosen function. It also properly describes the behaviour of WtE facilities without fulfilled capacity. This function contains a saddle point, which further deteriorate the following optimisation. Thus, the penalisation function is non-linear and also non-convex. The regression was performed for all possible WtE facility locations. The penalty function is further implemented in model II. These non-linear relations result in a reversal point between the convex and concave surfaces describing this dependence, see Fig. 6.

In order to prove the impact of considerations of this penalty, second model is further formulated based on the MILP model I and penalty function (10).

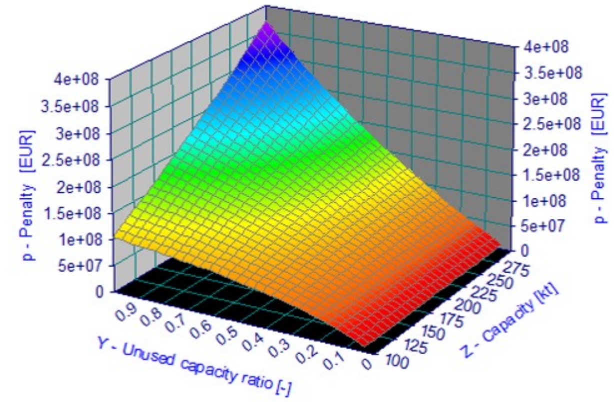


Figure 6: A graph of the penalty function for Přerov (a=-4.52E-09, b=1.03E-06, c=3.79E-09)

2.2.2. Model II description: Sustainable WtE facility location

This section proposes an improved model I, which contains additional costs as well as constraints based on the penalisation function defined in subsection 2.2.1, thus better reflecting the real situation. The model I assumes only the revenue loss from the waste treatment income, not from energy supply. However, heat supply is more crucial since it defines the sustainable economy of the plant. This feature supposes to be reflected in the project economy. The main income of the plant is due to waste processing and heat and electricity generation, see Fig. 1. The income from waste processing has already been incorporated in the objective function (1); however, the income from heat and electricity generation is not included. An illustration of the formulation approach of the penalty function is shown in Fig. 5.

Model II proceeds from model I. Therefore, the penalty function value p_j (depending on variables y_j and z_j) is subtracted in the objective function for each facility j, where a_j, b_j, c_j are parameters of the penalty function (regression coefficients for all the plants), m_1 and m_2 are auxiliary low positive numbers (to avoid division by zero); y_j is an auxiliary variable stating the rate of unused capacity (to penalise)and z_j is an auxiliary variable stating capacity of the facility. Then, the MINLP is as follows:

$$\min \quad \sum_{j\in J}\sum_{k\in K}\alpha_{j,k}c_{j,k}^{treat} + \sum_{i\in I}\sum_{j\in J}x_{i,j}d_{i,j}c^{trans} + \sum_{j\in J}p_j \tag{11}$$

$$\text{s.t.} \quad p_j = \left(a_j + \frac{b_j}{z_j+m_1} + \frac{c_j}{y_j+m_2}\right)^{-1}, \qquad \forall j \in J, \tag{12}$$

$$z_j = \sum_{k\in K}\alpha_{j,k}C_{j,k}, \qquad \forall j \in J, \tag{13}$$

$$y_j z_j = z_j - t_j, \qquad \forall j \in J, \tag{14}$$

$$z_j, y_j, p_j \geq 0, \qquad \forall j \in J, \tag{15}$$

$$\text{all together with: } (2),(3),(4),(5),(6),(7),(8),(9).$$

Obviously, model II consists of the new/modified objective function (11), new constraints (12)-(15), as well as constraints (2)-(9) that remain from model I. Similarly as in model I, the objective function (11) sums up all of the considered costs, i.e. waste treatment costs, waste transportation costs, and the cost/penalty for the redundant (unemployed, underused) capacity. Constraints (12) define the penalty function p_j. Equations (13) and (14) are auxiliary equations for the penalty value p_j computation. In equations (13), the selected capacity is defined for all candidate locations, while equations (14) calculate the rate of their unused capacity. Finally, (15) state the domains of the new variables z_j, y_j and p_j.

3. Case study

In this section, both above-developed models are applied in a case study. The overall task of the section is to provide computational results and to provide insights into differences between the various approaches. Both models are compiled and insights into applying the penalty function are provided – describing the effect of using the processing capacities to reduce the revenue from the sale of energy and the change of variable costs. Both models also cover the loss of incomes caused by lesser amount of treated waste. The issue of non-linear bindings involving penalisation results in the reduced solvability of the mathematical model. The large task at the level of the state, where the problem with the exact solution is identified, is faced. For these reasons, a meta-heuristic algorithm is also presented and compared with other heuristics to discuss the quality of its solution and the comparison with exact methods in the smaller problems.

The data from the Czech Republic are used. It includes 206 municipalities (with extended responsibility), 4 existing WtE facilities, and 36 potential WtE facility locations. Furthermore, the enlargement of 2 existing facilities with an additional capacity is considered. The input data of waste treatment cost [39] and waste transportation cost [40] are considered from the previous studies, where also supplementary file was included. The infrastructure can be obtained using API from Google or other map services.

The included waste types are mixed municipal waste and other combustible waste that is currently landfilled, but is suitable for a WtE facility (together ca. 3.2 Mt). Fig. 7 provides an illustration of the data set (map) used in this paper.

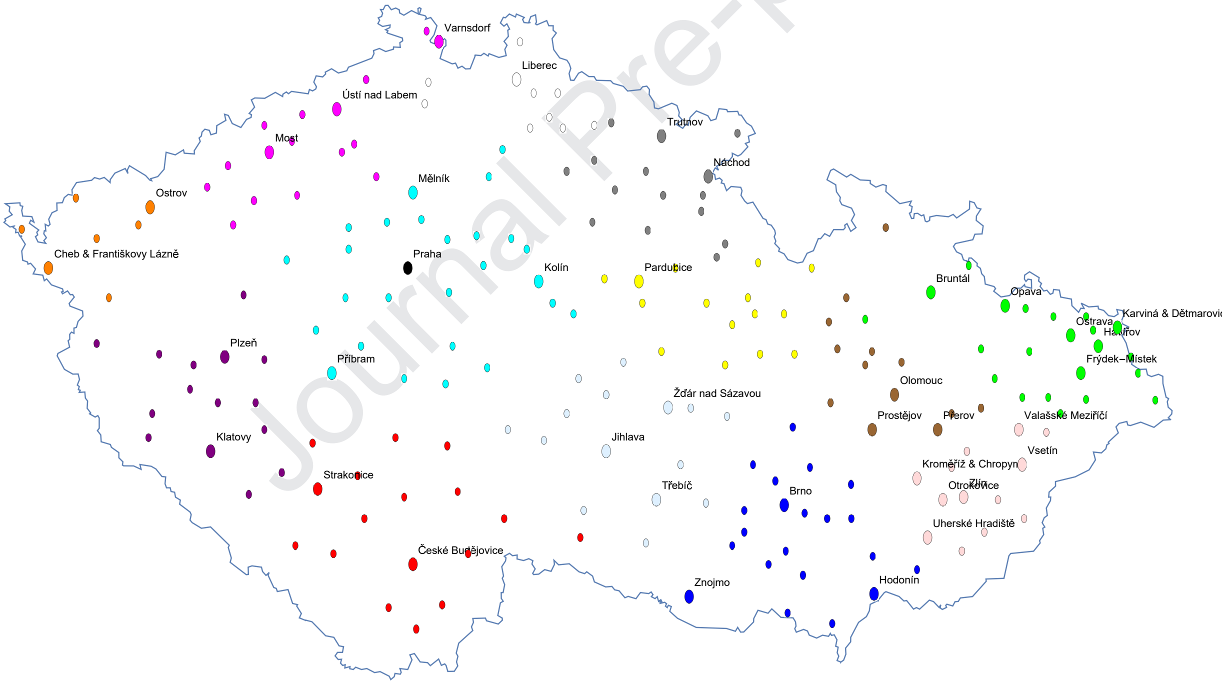


Figure 7: Case study data: 206 municipalities (represented by the dots, various colors define regions), 36 potential (labelled with the municipality name and bigger dot) and 4 existing WtE facilities (Praha 310, Brno 240, Liberec 96, and Plzeň 95 kt)

3.1. Model I

The developed MILP can be solved with commercial algorithms. The CPLEX solver that is implemented in the GAMS software was utilised for this purpose [41]. Since realisation of the optimal solution in practice for the whole country is often impossible, this section tackles the problem of how to determine where to build new WtE facilities for multiple variants of clustered regions as well as for the whole country.

The resulting maps illustrating the assignment of producers to particular WtE facilities are shown in figures 8a and 8b (1 and 3 regions), while Fig. 8c sillustrates a result for the whole country (14 regions).

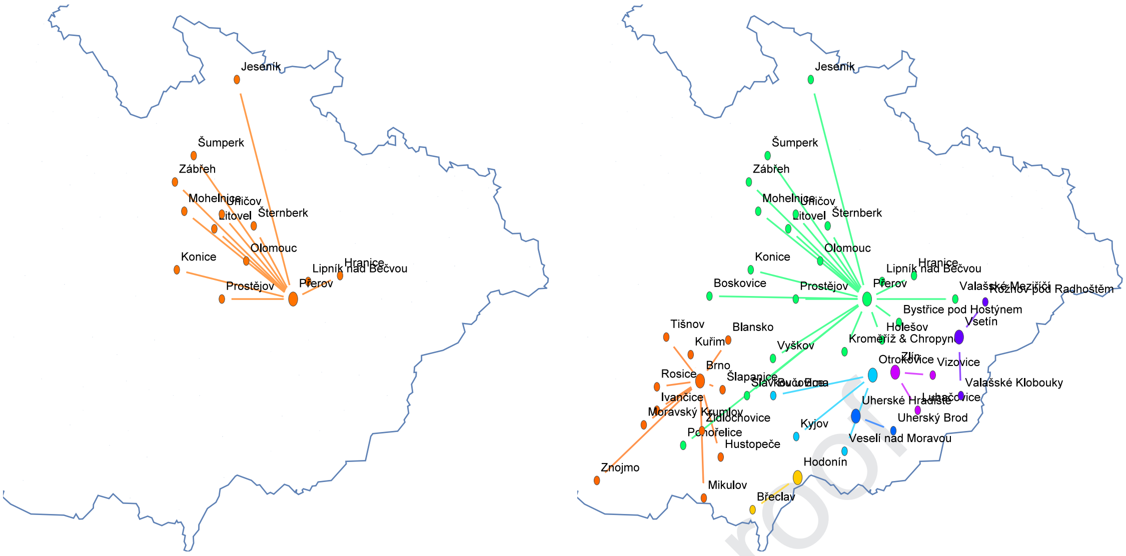
Detailed numerical results for the 3 aforementioned examples are listed in Appendix A. For the whole country (14 regions), the optimal solution suggests to locate 19 WtE facilities. Turning attention to figures 8a-8c it can be seen that solving isolated regions without considering its neighbourhood leads to significantly different results than the all-embracing solution; see, e.g., Olomouc region, where significantly different capacity in Přerov is clearly suggested, or see also suggested facilities in Uherské Hradiště and Otrokovice in Appendix A. Although, the total utilisation is generally high (average 99.36% for 14 regions but 97.80% for 3 regions case), some of the capacities seem to be excessive (e.g., utilisation ca. 96.12% at Hodonín for 14 regions and 92.5% in Vsetín for 3 regions). Therefore, a penalty (cost) function that should help to eliminate such excess capacities as well as a high number of WtE facilities and that was developed in subsection 2.2.2 seems to be reasonable. In the case of stochastic approach, the situation would be adapted according to largest waste production case scenario and the utilisation rate would be even lower for other scenarios.

3.2. Model II by DICOPT

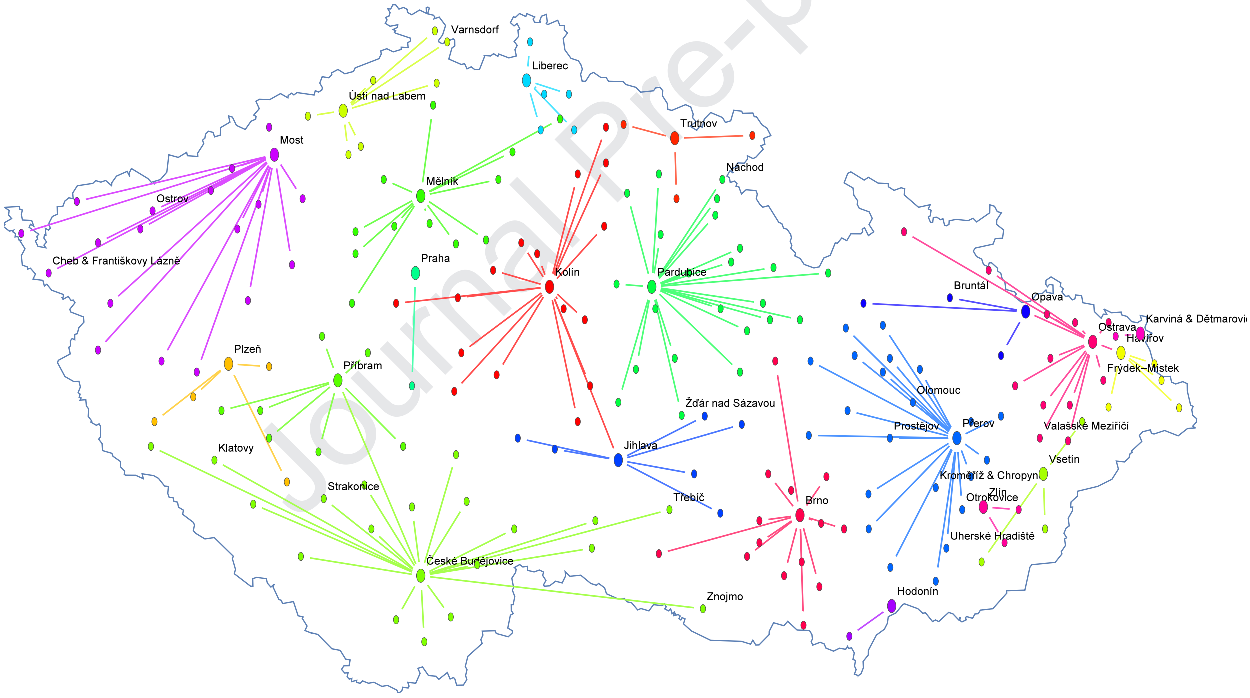
Since the model becomes MINLP, solvers tested for the exact solution computation have been changed to DICOPT [42] and BARON [43], respectively. BARON did not perform well for our problems (e.g., it has not found any feasible solution for medium-sized as well as some small-sized problems in the sense of the number of municipalities and regions in the order of several tens of hours) while DICOPT did for small as well as medium size instances. Therefore, the solutions observed by the DICOPT solver are further discussed. In each instance, different coefficients were taken into account in regression functions based on the given locality of potential WtE facility site (see illustrative Fig. 6 for Přerov locality). The DICOPT solver was consequently tested for $1-14$ number of regions. However, the last problem that was clearly solved to optimality (i.e., with a relative gap set to 0) was the 9 region case.

For 1 selected region, models I and II suggest the same solution (one WtE facility with a capacity 200 kt located at Přerov, see Fig. 8a). A different, but similar situation appears for 2 particular regions: although the overall utilisation is equal for both models (meaning that the WtE facility capacities are equal in total), the localities vary and so the objective function as well even if we subtract the penalty cost. In the case of 3 regions and further, model II prefers a lower number of WtE facilities (e.g., 4 vs. 7 for 3 regions) of higher capacities. This is a significant result, even with such small tasks, it is clear that the issue of lower profits from non-produced energy leads to a fundamentally different distribution of capacities. It turns out that this is crucial for the appropriate allocation of capacities. Initial results show that the previous approaches described in the introduction neglect a significant factor. It is recommended to implement this aspect into mathematical models that deal with strategic planning of WtE facilities. Table 1 provides a comparison of models I and II for 1, 2, 3, 9 and 14 regions. More detailed numerical results are provided in Appendix A. Clearly, model II reduces the number of suggested WtE facilities whose utilisation is greater or equal compared to to model I. This is compensated by the value of the objective function that is greater or equal for model II, which is caused by the penalty cost included in the objective function. Note that if there is any regional restriction of the number of WtE facilities (e.g., 1 or no more than 1, respectively), the total number of facilities will be even less (e.g., as in [12] that can reflect a real situation as well). For example, the case of 9 regions includes 157 municipalities that are assigned to 14 WtE facilities, while there were 30 potential WtE facility locations.

In addition, Table 1 involves some additional computational results that serve as a clear illustration of model II importance, even if utilisation of facilities proposed by model I does not seem to be significantly less than by model II at the first sight (see Appendix A). First, it involves values of objective function of the model I, where, additionally, a penalty function on the basis presented in subsection 2.2.1 is added. It clearly shows that the solution of model I leads to significantly worst solution than model II provides with respect to economical sustainability. For example, the difference is around 4.6% for the case of 9 regions. This means that extra millions of Euros have to be gained from the gate-fee in order to keep the economic sustainability of the project. This results in more expensive waste treatment for producers. The big difference is mainly due to the lack of profits from heat sales in localities with low capacity. The consequence of the penalty function is also the change of locations for the construction of WtE facilities. Second, it presents values of objective function of model II however with subtracted penalty function costs.



(a) 1 region (Olomouc region). (b) 3 regions (Olomouc, South Moravian, and Zlín).



(c) Whole Czech Republic (14 regions).

Figure 8: Model I solved by CPLEX solver: examples of various groups of regions.

Since the solution by the DICOPT solver is incomplete (more specifically, for 10-14 regions) due to its extreme time and memory requirements, the heuristic DR_DISH algorithm is further developed and suggested.

3.3. Meta-heuristic approach

This section provides a computational approach that is suitable to solve large instances of the MINLP model II, where commercial solvers does not provide acceptable results (see Section 3). The ***D***istance

	Model I (CPLEX)			Model II (DICOPT)		
Nr. of regions	Objective function [M€]	Nr. of fac. [-]	Objective with penalty [M€]	Objective function [M€]	Nr. of fac. [-]	Objective without penalty [M€]
1	20.8	1	24.8	21.0	1	20.8
2	42.7	5	52.5	46.3	5	42.9
3	60.3	7	75.5	61.6	4	61.6
9	203.0	17	220.7	211.0	14	210.8
14	291.8	19	306.8	–	–	–

Table 1: Computational results samples: comparison of results for model I by CPLEX and model II by DICOPT

Random ***DI***stance based parameter adaptation for ***S***uccess-***H***istory based differential evolution (DR_DISH) is a three-step algorithm designed to solve mixed-integer WtE facilities location and capacity allocation with respect to penalties associated with reduced energy sales.

Preliminary testing [12] has shown a potential in using meta–heuristic algorithm for solving all parts of the problem (facility location, capacity and which waste producers should be treated by which facility). However, the meta-heuristic does not guarantee the optimality of the found solution. Therefore, exact-commercial solver DICOPT was used for smaller instances of the problem (up to 9 regions), but failed for larger instances. Meta-heuristic algorithm was able to find the solution in reasonable time, but the quality of the solution was approximately 30% worse [12]. Thus, a need for algorithm specifically designed to solve large instances of the WtE arose.

DR_DISH algorithm combines meta–heuristic (namely DISH [44]) with distance–based clustering–inspired allocation of waste producers to incinerator facilities and random sequences of waste producers managing. Three-step process:

1. **Location** – For each possible incinerator location, DISH algorithm determines whether or not to build the facility (binary vector (1 – build, 0 – do not build) of length J – maximum number of treatment nodes).
2. Repeat N–times
   (a) **Allocation** – Randomly go through waste producers (I) and allocate them to the nearest incinerator location (j_{near} - existence determined by DISH). If the maximum possible capacity ($C_{j,max}$) of the nearest facility would be overreached by currently processed waste producer (w_i), assign it to the nearest facility with sufficient maximum capacity.
   (b) **Capacities** – For each incinerator facility (J) select the smallest larger capacity than the waste amount summed over all waste producers assigned to this facility (t_j).
   (c) Evaluate the quality of the solution.
3. Out of N solutions, select the solution with the best objective function value.

3.3.1. Algorithm settings

For the purpose of experiments, the DR_DISH algorithm was run with the following settings:

- **General settings**
  - Number of runs – $runs = 10$.
  - Number of random sequences of waste producers – $N = 50$.
- **DISH settings**
  - Dimensionality of the problem – $D =$ number of possible facilities J.

- Maximum number of function evaluations – $MAXFES = 100{,}000$.
- Initial population size – $NP_{init} = 25\sqrt{D}\log D$.
- Final population size – $NP_f = 4$.
- Historical memory size – $H = 5$.

3.4. Model II by DR_DISH

In this section, the DR_DISH algorithm is tested and compared with DICOPT for all the previously solved cases ($1 - 9$ regions); however, its results for $10 - 14$ regions that was found only for the heuristic approach are also provided, see Table 2. For 1 region, the DR_DISH heuristic found the same (optimal) solution as the DICOPT solver. The solution by the heuristic is then worse for all of the other cases that are successfully solved by DICOPT to optimality (i.e. for $2 - 9$ regions) by 4.56% in average. A noticeable difference (ca. 13%) is obtained for the case of 3 regions; this is caused by getting stuck in a significant local optima of the search space which is, on the other hand, less probable for large size problems (as also seen from Table 2). Apparently, the heuristic suggests noticeably less number of WtE facilities. Fig. 9 illustrates the graphical results by DR_DISH algorithm for 14 regions.

Nr. of	Objective function value [M€]			Computing time [h:m:s]		Nr. of fac. [-]	
regions	DICOPT	DR_DISH	Difference [%]	DICOPT	DR_DISH	DICOPT	DR_DISH
1	21.0	21.0	0.00	0:00:04	0:01:48	1	1
2	46.3	47.3	2.16	0:00:15	0:03:38	5	2
3	61.6	70.0	13.6	0:00:28	0:05:31	4	4
4	94.5	102.4	7.94	0:01:15	0:08:22	9	4
5	105.5	111.5	4.72	0:01:39	0:09:46	6	4
6	119.7	127.2	5.83	0:10:09	0:12:50	10	5
7	138.5	146.3	5.04	0:02:14	0:14:54	10	5
8	159.8	162.1	1.25	3:55:32	0:17:09	12	6
9	211.0	211.9	0.47	5:54:08	0:22:21	14	8
10	–	241.9	–	–	0:23:44	–	9
11	–	252.3	–	–	0:26:19	–	10
12	–	268.0	–	–	0:31:58	–	11
13	–	292.4	–	–	0:38:01	–	12
14	–	301.7	–	–	0:40:53	–	12

Table 2: Computational results for model II: comparing the results for DICOPT and DR_DISH heuristic

The visualised results look meaningful while revealing some interesting moments. For example, the transportation of waste for long distances such as for municipality Trutnov (to facility in Ústí nad Labem) or Havířov (to facility in Zlín). This result is given by capacity setting according to reasonable combination of producers (their waste production). The extra transport costs of individual producers are not significant compared to wrong capacity establishment. This is all the more important in the case of larger capacities, when an incorrectly selected number of boilers can already have cruel impacts on the project's viability.

Differences in the objective function value are relatively small, which means that profitability between some of the facilities is small and so more variants of combinations of suggested facilities, which only have small differences in total costs, exist, see Appendix A. In order to test quality of the solution, further section provides discussion of other authors' algorithmic development and ideas (see Section 3.5) that, however, led to significantly worst solution regarding the objective function values. With regards to the complex approval process of locating and building of a new WtE facility, the results provided by the DR_DISH algorithm seem to be better from the real practicability. Both, model I and model II, provide the transition of the current treatment of mixed municipal waste from landfilling to energy recovery. Around 76% of mixed municipal waste has been moved from landfills to suggested WtE plants. See Appendix B for convergence curves of

Figure 9: Whole Czech Republic: model II solved by DR_DISH algorithm

the DR_DISH algorithm for the 14 regions case. It shows that the algorithm converged before exhausting function evaluations, therefore the $MAXFES$ parameter was set correctly. The convergence graph is very similar for other test cases, thus they are omitted from the appendix.

3.5. Other computational approaches

Other approaches to waste producer allocation and WtE capacities were also tested in order to improve the performance of the DR_DISH algorithm. However, none of them led to the improvement on all problem instances.

3.5.1. Small incinerator approach

DISH algorithm determines location of facilities and those are initialized with their smallest possible capacity. Then, during the allocation step, the waste from a producer is taken to the nearest facility with sufficient capacity. If there is none, then the capacity of the nearest facility is increased to accommodate that amount of waste. Thus, the capacities of facilities are determined by the amount of waste and the sequence of producers which is, as in DR_DISH, randomly generated N times and the best solution is given as a result. In comparison with DR_DISH, this approach led to 5.84% average cost reduction for small problem instances (1 to 4 regions), but increased the cost for larger instances (5 to 14 regions) by 3.47% on average.

3.5.2. Cost oriented approach

In this case, DISH algorithm solves only the sequence of producers to be processed. The waste from a producer is processed in the facility with the smallest cost for transport and incineration. Thus, the facility allocation is given by its cost effectiveness. This approach leads to a large number of facilities with small capacity, but overall is not very effective in terms of objective function value. On average, the cost of a problem instance is increased by 15.15% in comparison with DR_DISH.

3.5.3. Heuristic sequence approach

In this case, not only facility location but also the sequence of waste producers is optimized by the DISH algorithm. This approach leads to very similar results in comparison with DR_DISH algorithm, but the dimension of the optimized problem is much higher, and therefore it would not be suitable for larger problem instances. On average, the result given by this approach is 0.22% worse than DR_DISH result.

3.5.4. Iterative deterministic approach

The heuristic was left out completely. All facilities are set to be build in the initialization of the algorithm and waste producers are allocated to their nearest facility with sufficient maximum capacity. Then, the algorithm tries to iteratively remove each facility one by one and allocate its producers to the second nearest facility with sufficient capacity. This is done until the overall objective function value is improved by the removal of the facility. This approach led to the average increase of 5.63% in the overall cost.

3.5.5. Summary of the heuristic approaches

Table 3 provides a summary of results of the heuristic computational approaches and their results comparing to results of DR_DISH algorithm. It is obvious that the DR_DISH algorithm provides the best results for the MINLP model II; however, the other heuristic approaches also provides reasonable computational ideas and results for specific size and structure-related problems.

Nr. of regions	Objective function difference comparing to DR_DISH [%]				Number of facilities [-]			
	Small	Cost	Sequence	Iterative	Small	Cost	Sequence	Iterative
1	0.00	17.19	0.00	11.74	1	3	1	1
2	-8.63	-2.38	0.00	21.03	5	5	2	6
3	-10.10	2.63	0.16	15.94	4	10	4	9
4	-4.62	10.45	0.75	0.52	6	14	4	4
5	3.59	15.99	0.04	8.04	5	20	4	5
6	1.77	17.83	-0.02	0.82	6	23	5	5
7	3.72	18.19	0.13	3.68	5	25	5	5
8	3.24	19.98	0.24	3.30	6	27	6	6
9	3.69	18.11	0.16	3.37	8	28	8	8
10	3.76	19.37	0.43	2.63	9	28	9	9
11	3.95	17.02	0.24	2.91	10	28	10	10
12	3.77	17.60	0.37	1.43	11	31	11	11
13	3.81	19.36	0.20	0.94	12	34	12	12
14	3.43	20.73	0.38	2.45	12	34	12	12
Avg.	0.81	15.15	0.22	5.63				

Table 3: Computational results for model II: comparing the results for DR_DISH heuristic and other heuristic approaches

4. Conclusions and outlook

The paper deals with the optimal WtE facility location, its capacity allocation and economic sustainability. Two models are developed as a tool for strategic decision-making in the field of WM. The first model minimises the sum of transportation and investment costs and leads to MILP, for which the CPLEX solver was successfully tested and used. However, one significant drawback was identified: even if the capacities of the designed WtE facilities does not seem to be significantly high it leads to the groundlessly lower energy production of the WtE facility than it was designed for. This implies to the revenue loss which is not involved in the objective function.

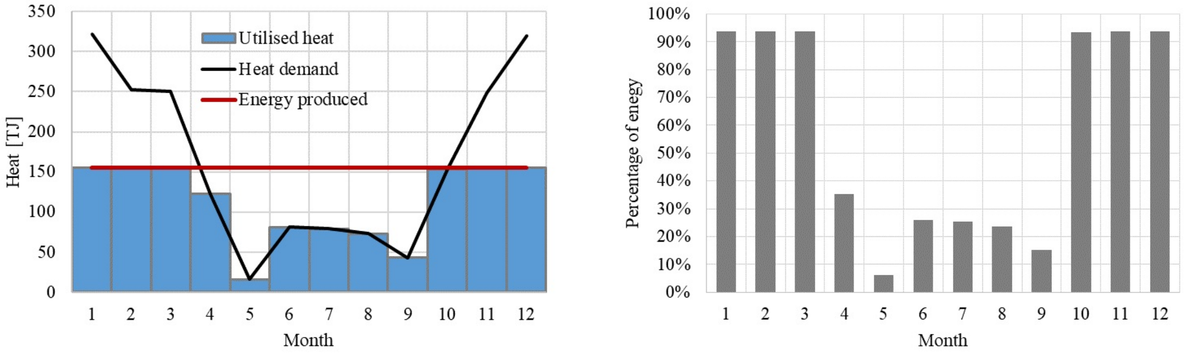
Therefore, the second model was developed. It jointly minimises transportation, investment, and penalty costs for the unused capacity of the WtE facility related to the revenue lost from the energy sales. Another important feature, where producers are bound with one subject, was newly implemented for both models.

It arises with signed contract between producer (municipality) and processing facility (WtE facility), which is usually in effect for a longer period of time. It basically assign the producer to single facility, meaning that all generated waste is transferred there. The proposed model led to the MINLP and was subsequently applied in several problems of various sizes (1-14 regions), where DICOPT solver performed well for small and medium-sized problems. For larger instances, it was suggested to use a heuristic algorithm. For the purposes of this paper, the DR_DISH, which is a combination of meta-heuristic with distance-based clustering, was implemented and applied for the proposed problem.

All of the models, as well as algorithms, were tested and compared on real WM data from the Czech Republic. The heuristic solution was generally worse (4.56% on average) than solution by the commercial solvers. However, these solvers were not able to reach a feasible solution for larger instances. The DR_DISH performed well not only from the computational time point of view, where a sufficient solution was obtained after 40 minutes for the network with 14 regions, but it also opens the possibility to compute some stability simulations related to changing of input parameters. This means that similar heuristic approaches are promising direction for future research.

While more facilities with smaller capacity are suggested by Model I, solution of DR_DISH meta-heuristic of the Model II leads to only 12 facilities with higher capacities. The average capacity is ca. 171 kt (Model I) compared to 272 kt (for Model II). The contribution of DR_DISH algorithm can be clearly seen comparing objective function value of model II with the value observed from the model I objective function plus its potential penalty costs. More specifically, it leads to the economic performance worsening by 1.7% (coming from ratio of the objective function values 306.8/301.7) when not employing the model II and DR_DISH, respectively. The heat demand at candidate location is very important aspect (regarding Figure 1) for the economic sustainability. Lower incomes from energy production due to unavailability of waste show a significant impact on the number of new facilities, capacity and its location. It is suggested to establish lesser amount of WtE facilities with higher capacity, where the loss from not produced energy would not be so big. It should be emphasized that the key parameter (due to economic sustainability of WtE facility) is the demand for heat in the potential location. Model II and developed approach propose a novel contribution in building a complex solution in the field of WM.

The computational results were processed following the schematic illustration presented in Fig. 5; see Fig. 10a, where it is compared for municipality of České Budějovice. It clearly shows, how the produced energy is used during a year depending on the heat demand. Finally, Fig. 10b presents the percentage of produced energy, which is used in the central heating system during the year.



(a) Energy produced vs. heat demand

(b) Produced energy percentage to meet heat demand

Figure 10: Results of computations on a case study (České Budějovice)

For the whole Czech Republic (14 regions), 19 facilities were proposed in model I, compared to only 12 for model II (meta-heuristic). Currently, only 4 facilities with different capacities from 95 kt to 310 kt are in operation. The increase to almost five times the amount is very complicated from the implementation point of view with regard to all the necessary administrative acts and permissions from national and international authorities. In addition, due to the lack of a guarantee of a sufficient waste supply, the economic sustainability of small facilities is more endangered than for large ones. Waste availability in these projects is hampered mainly by the EU's goals of increasing the separation and subsequent recycling of recoverable waste fractions.

The recent waste management problems does not only involve large-scale problems but also uncertain parameters and dynamic information or big data. Therefore, the approach presented herein asks for further research development. As the most important further challenging issues and topics, the authors identified: stochastic or simulation-based approach into uncertain waste production and heat demand [21] and multi-objective optimization approach/model in order to separate particular parts of the objective function defined herein (e.g., transportation costs and investment costs) [45]. Hence, the authors believe that recent real-world management problem, combining strategical investment policy and operational decisions with respect to uncertain demands, it should further be investigated by extending presented research results.

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Appendix A. Numerical results

Nr. of regions	Facility location	Model I (GAMS) Cap. [kt]	Model I (GAMS) Used [kt]	Model I (GAMS) Util. [%]	Model II (GAMS) Cap. [kt]	Model II (GAMS) Used [kt]	Model II (GAMS) Util. [%]	Model II (heuristic) Cap. [kt]	Model II (heuristic) Used [kt]	Model II (heuristic) Util. [%]
1	Přerov	200	197.050	98.53	200	197.050	98.53	200	197.050	98.53
	Olomouc, Prostějov	0	0	-	0	0	-	0	0	-
	CPU time [m:s] (solver)	0:05 (CPLEX)			0:04 (DICOPT)			1:48 (DR_DISH)		
	Obj. fction value [EUR]	20,845,864			21,002,232			21,002,232		
3	· Přerov	270	268.882	99.59	270	269.999	100.00	0	0	-
	Olomouc	0	0	-	0	0	-	30	29.431	98.10
	Prostějov	0	0	-	0	0	-	0	0	-
	· Brno	240	239.889	99.95	360	353.202	98.11	360	356.249	98.96
	Hodonín	40	38.449	96.12	0	0	-	0	0	-
	Znojmo	0	0	-	0	0	-	20	18.117	90.59
	· Otrokovice	40	39.666	99.17	0	0	-	0	0	-
	Uherské Hradiště	40	39.344	98.36	0	0	-	0	0	-
	Valašské Meziříčí	0	0	-	0	0	-	0	0	-
	Vsetín	40	37.000	92.5	40	39.621	99.05	0	0	-
	Zlín	40	39.344	98.97	40	39.995	99.99	300	299.021	99.67
	Chropyně	0	0	-	0	0	-	0	0	-
	Sum (* average)	710	702.817	97.80*	710	702.817	99.29*	710	702.818	96.83*
	CPU time [m:s] (solver)	0:05 (CPLEX)			0:28 (DICOPT)			5:31 (DR_DISH)		
	Nr. of facilities	7			4			4		
	Obj. fction value [EUR]	60,275,542			61,628,469			69,963,537		
9	· Přerov	300	299.873	99.96	0	0	-	300	298.890	99.63
	Olomouc	0	0	-	0	0	-	0	0	-
	Prostějov	0	0	-	0	0	-	0	0	-
	· Brno	240	239.654	99.86	360	355.342	98.71	360	358.854	99.68
	Hodonín	40	38.449	96.12	40	39.769	99.42	0	0	-
	Znojmo	0	0	-	0	0	-	0	0	-
	· Uherské Hradiště	0	0	-	0	0	-	0	0	-
	Vsetín	40	39.597	98.99	40	39.925	99.81	0	0	-
	Zlín	40	39.329	98.32	290	289.992	100.00	180	175.389	97.44
	Chropyně	0	0	-	0	0	-	0	0	-
	Otrokovice	0	0	-	0	0	-	0	0	-
	Valašské Meziříčí	0	0	-	0	0	-	0	0	-
	· Dětmarovice	0	0	-	40	39.556	98.89	0	0	-
	Havířov	40	39.690	99.23	40	39.690	99.23	0	0	-
	Karviná	40	39.517	98.79	0	0	-	0	0	-
	Opava	40	39.898	99.75	0	0	-	0	0	-
	Ostrava	300	298.910	99.64	300	299.969	99.99	300	298.845	99.62
	Bruntál	0	0	-	0	0	-	0	0	-
	Frýdek Místek	0	0	-	0	0	-	0	0	-
	· Pardubice	300	299.908	99.97	300	299.658	99.89	300	299.275	99.76
	· Jihlava	40	39.657	99.14	40	39.907	99.77	0	0	-
	Třebíč	0	0	-	0	0	-	0	0	-
	Žďár nad Sázavou	40	39.204	98.01	40	39.841	99.60	0	0	-
	· České Budějovice	290	289.594	99.86	300	299.624	99.87	260	257.534	99.05
	Strakonice	0	0	-	0	0	-	0	0	-
	· Náchod	0	0	-	0	0	-	0	0	-
	Trutnov	40	39.820	99.55	40	39.820	99.55	180	176.211	97.90
	· Kolín	40	39.773	99.43	0	0	-	0	0	-
	Mělník	300	299.753	99.92	300	299.257	99.75	300	297.151	99.05
	Příbram	40	39.522	98.81	40	39.796	99.49	0	0	-
	Sum (* average)	2,170	2,162.148	99.14*	2,170	2,162.146	99.57*	2,180	2,162.149	99.02*
	CPU time [h:m:s] (solver)	0:32:01 (CPLEX)			5:54:08 (DICOPT)			0:22:21 (DR_DISH)		
	Nr. of facilities	17			14			8		
	Obj. fction value [EUR]	202,972,203			211,011,739			211,880,850		

Nr. of regions	Facility location	Model I (GAMS)			Model II (GAMS)			Model II (heuristic)		
		Cap. [kt]	Used [kt]	Util. [%]	Cap. [kt]	Used [kt]	Util. [%]	Cap. [kt]	Used [kt]	Util. [%]
14	· Přerov	300	299.760	99.92				300	297.141	99.05
	Olomouc	0	0	-				0	0	-
	Prostějov	0	0	-				0	0	-
	· Brno	240	239.517	99.80				360	358.612	99.61
	Hodonín	40	38.449	96.12				0	0	-
	Znojmo	0	0	-				0	0	-
	· Otrokovice	0	0	-				0	0	-
	Vsetín	40	39.597	98.99				0	0	-
	Zlín	40	39.587	98.97				220	219.313	99.69
	Uherské Hradiště	0	0	-				0	0	-
	Chropyně	0	0	-				0	0	-
	Valašské Meziříčí	0	0	-				0	0	-
	· Frýdek Místek	0	0	-				0	0	-
	Havířov	40	39.690	99.23				0	0	-
	Karviná	40	39.517	98.79				0	0	-
	Opava	40	39.898	99.75				0	0	-
	Ostrava	300	299.768	99.92				290	289.289	99.75
	Bruntál	0	0	-				0	0	-
	Dětmarovice	0	0	-				0	0	-
	· Pardubice	300	299.312	99.77				300	298.583	99.53
	· Jihlava	0	0	-				0	0	-
	Třebíč	0	0	-				0	0	-
	Žďár nad Sázavou	0	0	-				0	0	-
	· České Budějovice	300	299.789	99.93				300	299.718	99.91
	Strakonice	0	0	-				0	0	-
	· Trutnov	40	39.744	99.36				0	0	-
	Náchod	0	0	-				0	0	-
	·Mělník	300	299.575	99.86				300	298.913	99.64
	Příbram	40	39.338	98.35				0	0	-
	Kolín	0	0	-				0	0	-
	· Praha	430	428.785	99.72				430	428.785	99.72
	· Liberec	96	95.998	100.00				96	94.468	98.40
	· Plzeň	95	94.691	99.67				95	92.123	96.97
	Klatovy	0	0	-				0	0	-
	· Františkovy Lázně	0	0	-				0	0	-
	Cheb	0	0	-				0	0	-
	Ostrov	0	0	-				0	0	-
	· Most	290	289.839	99.94				300	297.509	99.17
	Ústí nad Labem	280	279.322	99.76				270	267.724	99.16
	Varnsdorf	0	0	-				0	0	-
	Sum (* average)	3,251	3,242.176	99.36*				3,261	3,242.178	99.22*
	CPU time [h:m:s] (solver)	23:51:31 (CPLEX)						0:40:53 (DR_DISH)		
	Nr. of facilities	19						12		
	Obj. fction value [EUR]	291,807,382						301,657,390		

Table A.1: Numerical results of the 4 aforementioned examples. The non-integer used capacities are rounded (in tonnes); dots · denote beginning of new region.

Appendix B. Convergence curves for DR_DISH algorithm

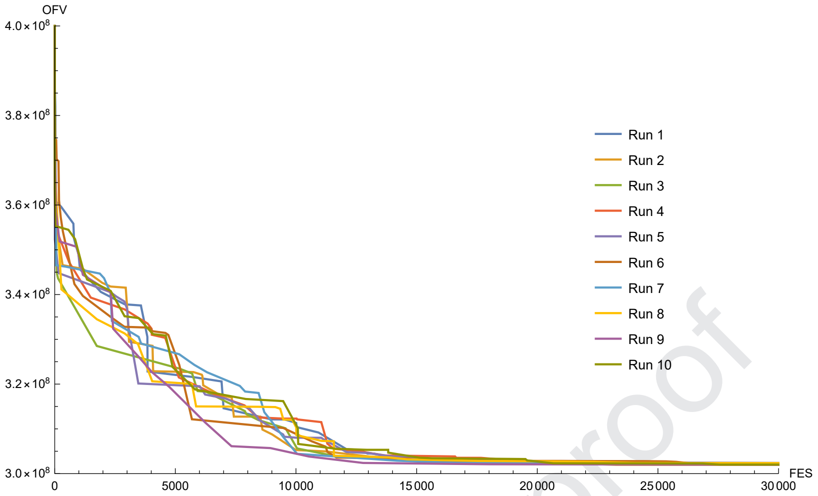

Figure B.1: Example of the convergence curves (14 region case). FES - function evaluations, OFV - objective function value.

- Mathematical programming used to suggest an optimal site for Waste-to-Energy plants.
- Two models were developed and their results compared to evaluate sustainability.
- Energy utilisation included through its real sales to enhance economic performance.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: