



Tomas Bata University in Zlín
Library

Waste bunker size optimization under uncertainty: Application of inventory models with real data simulation

Citation

ZDRAŽIL, Jan, Marek MAŤCHA, Dušan HRABEC, Radovan ŠOMPLÁK, Jan KRŇÁVEK, and Josef JADRNÝ. Waste bunker size optimization under uncertainty: Application of inventory models with real data simulation. *Sustainable Energy Technologies and Assessments* [online]. vol. 60, Elsevier, 2023, [cit. 2025-04-25]. ISSN 2213-1388. Available at

<https://www.sciencedirect.com/science/article/pii/S221313882300471X>

DOI

<https://doi.org/10.1016/j.seta.2023.103478>

Permanent link

<https://publikace.k.utb.cz/handle/10563/1011726>

This document is the Accepted Manuscript version of the article that can be shared via institutional repository.



TBU Publications

Repository of TBU Publications

publikace.k.utb.cz

Waste bunker size optimization under uncertainty: Application of inventory models with real data simulation

Jan Zdražil^a, Marek Mařcha^a, Duřan Hrabec^{a,*}, Radovan řomplák^b, Jan Krňávek^a, Josef Jadrný^c

^aFaculty of Applied Informatics, Tomas Bata University in Zlín, Nad Stranemi 4511, 760 05 Zlín, Czech Republic

^bFaculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic

^cTERMIZO, a.s., Dr. M. Horakove 571/56, 460 06, Liberec, Czech Republic

*Corresponding author: E-mail address: hrabec@utb.cz (D. Hrabec).

ABSTRACT

Waste-to-Energy (*WtE*) technologies play a prominent role in recovering energy from waste. One of the aspects ensuring the operability and economic sustainability of *WtE* plants is the size optimization of a waste bunker assigned to each *WtE* plant, whose main target is to ensure waste homogeneity for effective operation. Each *WtE* plant faces various uncertain challenges, such as planned and unplanned shutdowns during which the plant is inactive and not ideally coordinated with waste collection companies, further importing the collected waste into the waste bunker, mainly due to existing contracts. This work aims to develop a scenario-based model to support strategic capacity planning by capturing various uncertain attributes and optimizing the waste bunker size while minimizing the total costs composing the investment, inventory, and waste shortage costs. The model is tested on a case study from the Czech Republic. The main result can be summarized such that for a specific case of a newly situated *WtE* facility with a considered capacity of 100 kt/y, the model suggests a bunker of size ca. 4, 200 m³ for a middle scenario. However, this is strongly related to other attributes of a particular *WtE* project (e.g., waste properties or cost parameters).

Keywords: Size allocation, Waste-to-energy, breakdown and maintenance, shutdown uncertainty, Monte Carlo simulation

Introduction

Due to continuous population growth and increases in waste production per capita, municipal solid waste (*MSW*) production is increasing globally [1,2]. This waste needs to be processed to avoid its accumulation. There are many different methods for its processing, such as recycling, material recovery, and incinerating. Waste management is geared towards a circular economy to increase the system's sustainability by reducing waste production, reducing landfilling, and increasing recycling [3]. In some cases, waste, due to its management, excessively damages the entire ecosystem of the planet;

especially, it is the emissions generated and emissions from landfilling or incineration [4]. For this reason, the European Union introduces new measures and targets, such as reducing *MSW* landfilling to a maximum of 10% of its total production by 2035 [5] or increasing the recycling rate of *MSW* [6].

Green and economic goals include the constructed, coordinated, and structured organization of energy production, transfers, delivery, and usage to satisfy demands [7]. The European Commission has indicated the Waste-to-Energy (*WtE*) technologies as suitable to play a prominent role in recovering energy from waste in the near future.

Several types of *WtE* plants exist, some being less and some more environmentally friendly [8]. Waste reduction, re-utilization, recycling, and energy recovery are more sustainable for efficient waste management than conventional waste disposal methods. *WtE* plants represent a key infrastructure for efficient waste management operating on a circular economy basis [9]. This is because not all waste produced can be recycled [10]. However, a large amount of these non-recyclable wastes contain significant energy potential that can be used. *WtE* produces heat and electricity, thus saving primary resources and emissions production while processing waste in an efficient and environmentally friendly method.

The operation of the *WtE* plant has been planned for at least several decades, documented by both professional publications [11] and state regulations [12]. Therefore, factors that show time variability must be included in its design. Typically, these include energy demand and prices, waste production and composition, competitive environment, etc. The choice of the site and the processing capacity are the basic points on which all other steps in *WtE* planning are based. Waste management can be included in supply chain strategy, including production, collection, separation, transportation, distribution, and waste treatment.

Nomenclature	<i>m</i>	the amount of <i>MSW</i> that is transported to the <i>WtE</i> plant
	<i>p</i>	probability of realizing the scenario
Abbreviations	<i>r</i>	exponent determining the development of the price with increasing size
<i>MSW</i>	<i>s</i>	unit sanction
<i>WB</i>	<i>u</i>	unplanned shutdowns
<i>WtE</i>	<i>Y</i>	length of the year
Sets	ε	shape parameter
<i>t</i>	μ	mean
	σ^2	variance of the values
Parameters	δ	scale parameter
<i>a</i>		
<i>A</i>		
<i>b</i>		
<i>B</i>		
<i>c</i>		
<i>h</i>		
<i>J</i>		
<i>k</i>		
<i>L</i>		
	Variables	
	<i>w</i>	the amount of waste that needs to be transported after filling the <i>WB</i>
	<i>x</i>	unit of the <i>WB</i> capacity
	<i>y</i>	level of filling of the <i>WB</i>
	<i>z</i>	the amount of <i>MSW</i> that is transported to the <i>WtE</i> plant
	Functions	
	<i>I(x)</i>	investment function

Due to several approaches in municipal waste management and different technologies, finding an optimal solution is very complicated [13]. The most common approaches to describe these problems are network flow [14] and location problems [15].

The actual design of the individual subsystems is also given attention in the literature. Typically, problems with the turbine [16], boiler [17], and flue gas cleaning [18] are investigated. Furthermore, the waste bunker (*WB*) is a substantial part of the *WtE* plant. It has two main functions: 1) It is used to store the imported waste, where it is homogenized through draglines, to ensure important properties,

which is mainly a stable heating value. 2) It is used to store the waste during shutdowns (planned/unplanned) so that the waste does not have to be transported long distances to other facilities or even to a landfill. A badly dimensioned *WB* results in considerable inconvenience during planned shutdowns when the *WtE* plant needs to be put into operation as quickly as possible. Considerable costs are also involved in processing waste that can no longer be stored in the *WB*. Conversely, an oversized *WB* represents an unnecessary initial investment and has high space requirements, which are often scarce. The issue of *WB* oversizing has not received enough attention in the literature so far (see Section 2). This paper aims to present an optimization model for the design of *WB* capacity in *WtE* facilities. In its character, the problem is similar to well-known newsvendor problems (e.g., [19]). A necessary requirement for optimal *WB* capacity is a good estimation of key parameters associated with the waste import and distribution of unplanned *WtE* shutdowns over time.

The article is further organized as follows. The upcoming section reviews the literature on analyses and optimizations related to the design and operation of the *WtE* facility as a whole and individual subsystem. An original optimization model for sizing the *WB* is developed and presented in Section 3. Section 4 presents a case study based on real data from *WtE* installations in the Czech Republic. Then, energy and economic sustainability are discussed in Section 5. Finally, the paper concludes with a summary of the findings in Section 6.

Literature review

The operation of the *WtE* facility related to energy production depends on the proper functioning of all its subsystems: from the collection and delivery of waste to the plant to its storage at the associated *WB*. The operation of a *WtE* consists of the following main steps: incineration, energy generation, flue gas cleaning, and residue management. In the following, the individual subsystems of the *WtE* are discussed. Specifically, the available approaches to select their capacity and key characteristics related to operation are analyzed.

Analysis of existing approaches for WtE subsystems

First, to design the individual subsystems of the *WtE*, it is necessary to solve the situation concerning its location and capacity. In general, location problems are widely used in various areas, including the design of the *WtE* system [20]. When designing a *WtE* plant, the most important thing is to ensure the long-term economic sustainability of the plant. The first crucial aspect for the location and selection of *WtE* capacity is the availability of waste, which is related to the logistical issues related to the production and transportation of different types of waste [21]. The uncertainties associated with transportation costs and the evolution of waste production must already be taken into account when planning the location and capacity of the *WtE* facility. Two-stage interval stochastic programming in [22] or two-stage robust optimization in [23] are possible solutions to this problem. In the case of appropriate placement of *WtE* near waste generation sites, low transport distance can also be related to emission reduction [24]. Furthermore, the issue related to the heat demand that makes co-generation operation possible must be considered. This problem was discussed in detail in the article [25]. An important part of energy production is the heating value of waste, which is determined by its composition. Different types of waste are suitable for *WtE*; mixed municipal waste usually represents the largest proportion. Still, bulky waste and other wastes that are not currently recyclable or suitable are also acceptable [26].

The following text discusses the individual subsystems once the location and capacity of the *WtE* solution are usually known. It starts from transport and waste processing to residue management. The goal is to analyze existing approaches for optimizing or designing the subsystems described in the literature. Waste collection is mainly provided by transport companies that deliver the waste using lorries. For waste from more distant areas, transfer stations are often used to reduce transport costs. The optimization model presented in [27] can be used to place transfer stations in the context of distance reduction efficiently. In the context of waste collection, not only the problem related to transportation costs is often solved, but also the mode of transportation related to the capacity of the vehicles. Incorporating other alternative means of transport is analytically solved concerning the economic and environmental evaluation [28].

The imported waste to the *WtE* is further discharged to the *WB*, from which it is dosed into the incineration system. The main types include grate incineration, fluidized bed, and rotary kiln. Grate incineration is the most widely used type because it can process large quantities of differently composed waste without previous sorting and shredding [29]. The principle and behavior of waste in grate incineration can be described by stochastic and physical modeling of particle motion on a moving grate [30]. The incinerator's heat is transferred to the heat recovery part of the system, where the steam turbine is used to generate electricity and extract heat for water heating [31]. The produced energy (heat, electricity) is then sold to external customers or used internally. Determination of the processing capacity and sizing of a suitable heat recovery system according to its use can be solved using two-stage stochastic programming presented by [11]. The optimization of the cascaded heat recovery system can also be used to make the most efficient use of the waste heat generated, considering the cost reduction of *WtE* systems as presented by [32].

Last, it is important to look at emission production during waste processing. Flue gas cleaning is carried out in several steps: acid gas elimination, particulate matter elimination, and nitrogen oxide and mercury elimination [33]. Several methods can remove acid gases in flue gas, dry, semi-dry, or wet cleaning. A simulation model was used to compare these methods against the impact on the energy efficiency and economic sustainability of *WtE*, evaluating dry cleaning as the optimal solution due to its highest energy efficiency. However, the chemicals needed to remove the trapped solids make it more economically expensive in some cases [34]. The next step is trapping small solids, for which fabric filters or electrostatic precipitators are used. Due to better efficiency in capturing more particles, fabric filters are more commonly used [35]. The last step involves the elimination of nitrogen oxide and mercury, for which selective catalytic or non-catalytic reduction is used. Case studies show the advantages and disadvantages of these two reductions, where selective catalytic reduction has a higher efficiency in trapping nitrogen oxide. Still, on the other hand, due to the heating of the flue gas, *WtE* technology has a lower efficiency in energy production, which is associated with a higher impact on global warming [36]. The overall environmental impact of using a *WtE* technology compared to other waste treatment methods, mainly addressing the reduction of greenhouse gas emissions against the increase in costs, is illustrated using an optimization approach in [32].

The incineration also produces slag and fly ash (dangerous waste); both residues need to be processed further [37]. The preferred form of management is material recovery. Optimization methods suggest that mixing red mud and fly ash can produce a lightweight ceramic aggregate known as expanded clay, thereby minimizing slag disposal in landfills [38]. However, incineration processes are not without technical problems that need to be solved immediately. One way of preventing technical problems is through planned shutdowns. These shutdowns are planned in advance, and during these times, inspections and necessary repairs of individual equipment are carried out [31]. But planned shutdowns do not ensure continuous operation throughout the year, and unplanned shutdowns happen during

the process [39]. These shutdowns are key problems for the entire operation and need to be resolved in the shortest possible time interval. Unplanned shutdowns, therefore, significantly disrupt the continuity of individual *WtE* services and activities, posing a significant operational and economic threat [40].

Table A.1 (in Appendix A) provides an overview of the publications mentioned in the context of their focus on the individual *WtE* subsystems. From the literature review developed, it is evident that the areas of waste transport, *WtE* capacity and incineration systems, energy recovery, and flue gas cleaning represent complex problems that are addressed very often [41]. Therefore, only selected papers in the context of this section are included in **Table A.1**. In contrast, other subsystems have been addressed thoroughly and provide currently available approaches. In contrast, areas distinguished in bold are further investigated in this paper from the perspective of mathematical optimization (these provide areas where is a clear need for further research).

The literature review shows that the papers on the individual *WtE* subsystems contain partial analyses and approaches based on optimization methods. However, the shutdown issues are missing in the publications to the required depth. Shutdowns are crucial from the point of view of *WB* dimensioning. Optimization methods related to the design of *WB* capacity concerning future operation, which is crucial for *WtE* and its economic sustainability, are also not discussed. For this reason, it is appropriate to focus on developing a suitable approach to optimize the capacity design of the *WB* concerning shutdowns. The resulting model should include the uncertainties associated with *WtE* operation.

Novelty and contribution

The lack of addressing the issue of unplanned shutdowns related to the choice of *WB* capacity in *WtE* (see **Table A.1**) encourages the design of new approaches in this area. For this reason, an optimization model for the *WB* capability is developed in the following section (Section 3), considering the uncertainties of key aspects of *WtE* operation. Fundamental information is the investment costs and parameters associated with the operation of the *WtE* (waste import, waste processing, and shutdown problems). Real data from a specific facility in the Czech Republic (TERMIZO a.s.) were used to estimate the probability distribution for unplanned shutdowns and other parameters. The data provided are from 2004 to 2029, on a 12-hour basis (including data on the amount of waste imported and processed and planned and unplanned shutdowns). This allowed us to study and process the data properly, see histograms and statistical characteristics described in Section 4 (mean, standard deviation, percentiles, etc.), which gave us enough suitable information to synthesize the data (including some generated data for planned and unplanned shutdowns) and to determine the data distribution(s). This approach is properly described and mathematically expressed so that it can be adapted relatively simply for other *WtE* concrete projects. Moreover, due to the size of the available data, the presented approach is also robust. Although the result reflects the operation of a specific facility with a capacity of 96kt/y, its use is also suitable for the potential construction of new facilities with a different capacity but with only one operating line. As part of the case study in Section 4, a sensitivity analysis is performed for the key optimization parameters.

Using the newly developed model, selecting the optimal *WB* capacity that ensures the most continuous operation of the plant concerning the total *WtE* economics is possible. This will reduce the subsequent financial cost of the *WtE* and minimize the transport of waste for processing at another location in the case of *WB* fullness.

Problem description

Currently, *WtE* plants can still be considered among the most efficient approaches to the issue of residual waste, which cannot be recycled and possesses energy potential. One of the most pertinent concerns regarding *WtE* plants is the poorly sized WBs that are no longer adequate due to the vulnerability to failure of critical elements (e.g., the boiler); particularly for *WtE* plants of a smaller nature that rely on uniform combustion. The susceptibility to the problem in question is based on many years of monitoring data obtained in real operations. However, not enough attention has been given to the issue so far, as shown in the literature review (**Table A.1**). It is difficult to determine the appropriate size for the *WB* due to the high variation in the characteristics and quantity of *MSW* fractions and other industrial wastes. Further complications arise in unplanned shutdowns due to their stochastic nature.

Table 1 Results of the optimization model.

Input:		
	Value	Note:
price per unit of capacity c	3,020 [€/m ³]	Appendix D
Fine for storing waste in a landfill s	75 [€/t]	
Dataset of Waste Burned z	generated data	According to Table A.2
Dataset of Waste Imported m	generated data	
Exponent r	0.7	Appendix D
Probability of the scenario p	1/Number of years	
Output:		
50-year period		
Nr. optimization scenarios:	Mean (m) [m ³]	Std. dev. (σ) [m ³]
10	3,358	34.67
20	3,361	38.58
30	3,367	35.01
10 optimization scenarios		
Number of years	Mean (m) [m ³]	Std. dev. (σ) [m ³]
10	3,344	91.41
20	3,373	70.28
30	3,360	40.75
40	3,325	39.65
50	3,358	34.67
60	3,350	24.08
70	3,338	23.66
80	3,375	22.74
90	3,331	22.23

A major advantage in scaling essential components of the *WtE* plant (in this case, WB) is the availability of large quantities of data that were not available in the past. The accessibility of data worldwide provides a full understanding of the *WtE* plant system, leading to enabling more accurate optimization. The problem can therefore be described as follows: The objective is to find the optimal size of the *WB*, so the optimization variable x , which denotes the unit of the *WB* capacity, is defined. The resulting price for the construction of the *WB* is given by the expression $I(x) = cX^r$, hereafter referred to as the investment function where c is the price per unit of capacity and r is the exponent

determining the development of the price with increasing size (concrete parameter values are applied in Section 4). Furthermore, the amount of waste that needs to be transported after filling the *WB* w in a given time period t is penalized by a unit sanction s . To determine the amount of waste transported to the landfill or processed in a different *WtE* plant w , a variable y that shows the level of filling of the *WB* is implemented. The variable z refers to the amount of *MSW* that is transported to the *WtE* plant, while m is a parameter presenting the mass that is incinerated at the plant. The parameter m refers to the amount of *MSW* that is transported to the *WtE* plant, while \mathbb{Z} is a variable representing the mass that is incinerated at the plant. Next, p gives the probability of realizing the scenario coinciding with a specific time period t and is associated with all the uncertain parameters of the problem. The result of the objective function (1) in the later sections will be regarded as an optimization scenario result where the entire calculation will be repeated several times to estimate important characteristics of the model result as a whole (mean, variance, etc.).

$$\min cx^r + s \sum_{t=1}^n p_t w_t \quad (1)$$

$$\text{s.t. } z_t - y_t \leq 0 \text{ for } \forall t \in T \quad (2)$$

$$y_1 + w_1 = m_1 \quad (3)$$

$$y_t + w_t - (y_{t-1} - z_{t-1}) = m_t \text{ for } t = 2, \dots, n \quad (4)$$

$$x, y_t, z_t, w_t \geq 0 \text{ for } \forall t \in T \quad (5)$$

The objective function (1) minimizes the total cost; this finds the optimal size of the *WB* when minimizing the total costs, which are the costs of its construction and the sum of fines for waste transfer to the landfill (or another *WtE* plant) in case of overfilling of the *WtE* plant. Constraints (2) ensure the non-negativity of the *WB* level (it is impossible to store a negative amount of waste). Constraints (3) are used to initialize the *WB* level in the first iteration. Expression (4) is an auxiliary equation for calculating *MSW* transported to a landfill or another *WtE* plant. Constraints (5) guarantee non-negativity for all necessary variables. Overall, model (1)-(5) presents a linear model that ensures obtaining a global maximum. This paper capitalizes on synthetic data derived from authentic datasets (see Appendix B), meticulously generated to closely parallel the original data. These synthetic data extend over extensive timeframes, granting a distinct advantage over real data. This characteristic enhances research by comprehensively understanding long-term trends while safeguarding sensitive information.

Case study

With the theoretical knowledge from the previous sections, the problem is now applied to a practical case. The following situation is considered: Construction of a *WtE* plant with an estimated processing capacity of 96 kt/y is under development; the objective is to determine the optimal initial investment

in the *WB* to ensure the minimum financial loss over the plant's life cycle. Due to the calculations' complexity and the creation of sufficiently large datasets, the Python programming language and its imported libraries (Pyomo, Ipopt) are used. Furthermore, it is important to acknowledge that the Weibull, uniform, and normal distribution parameters are determined using data provided by the Liberec *WtE* plant (TERMIZO a.s.) from 2004 to 2019. The data provided include the amount of waste imported, the amount of waste processed, and information about planned and unplanned shutdowns and their length, all twice a day. This means that the data involve quite a long time period with well-documented information needed; therefore, the suggested approach is clearly based on credible data. The developed model is generally valid for other capacity solutions; the only condition is that the *WtE* plant has only one combustion line.

Parameters generation

In order to generate some needed data such as waste quantity imported, waste burned, and unplanned shutdowns, some statistical distributions (such as normal and uniform, e.g.) have been applied. The whole process of data generation is described in Appendix C.

Other parameters estimation

With the possibility of generating datasets that serve as part of the input values to the optimization model, the remaining parameters need to be specified.

The optimal choice of the capacity of a *WB* is often determined by two variables, which are the size of the bunker (m^3) and the total possible quantity of waste stored (tonnes). This ratio is characterized for most *WtE* plants as $1 \text{ m}^3 = 0.5$ tonnes of waste (see [42]). However, for some *WtE* plants, this ratio is different (see [43]), which may be primarily due to the distribution of waste, which varies from country to country. According to other sources, it can also be considered $1 \text{ m}^3 = 0.3$ tonnes of waste (more specifically, $1[t] = 3.3 [\text{m}^3]$, see [44]); in further text, the first one (0.5 tonnes per cubic meter) is considered. The price per unit of capacity $c = 3,020\text{€}/\text{m}^3$ is determined in Appendix D with the cooperation of the construction company IP system a.s.

Furthermore, the fine for storing waste in a landfill varies according to the country where the *WtE* plant is located; for this study, consider $s = 75\text{€}/\text{t}$. The fine in the scenario is set for the Czech Republic, where, due to the lack of *WtE* plants, transferring waste to landfills is common after *WB* overfilling.

The remaining parameter is the exponent in the investment function, determining the evolution of the price depending on the size of the capacity r . Its value ranges from (0.5; 0.7) in realistic cases [45]. Herein, the value $r = 0.7$ is chosen (the described values are therefore further considered as basic settings for scenario testing, see **Table 1**). However, further, in this study, a range on the interval (0.4; 0.8) is considered to illustrate the behavior of the variance. It is important to add that the effect of inflation is neglected for established prices, and attention is primarily concentrated on the occurrence of unplanned and planned shutdowns.

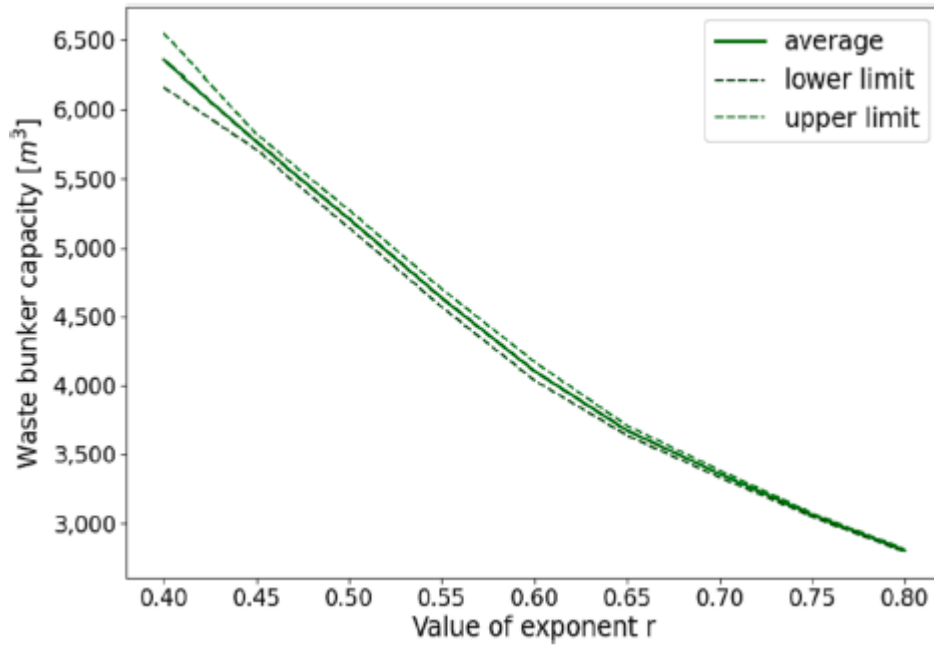


Fig. 1. Dependence of the size of the WB on the exponent.

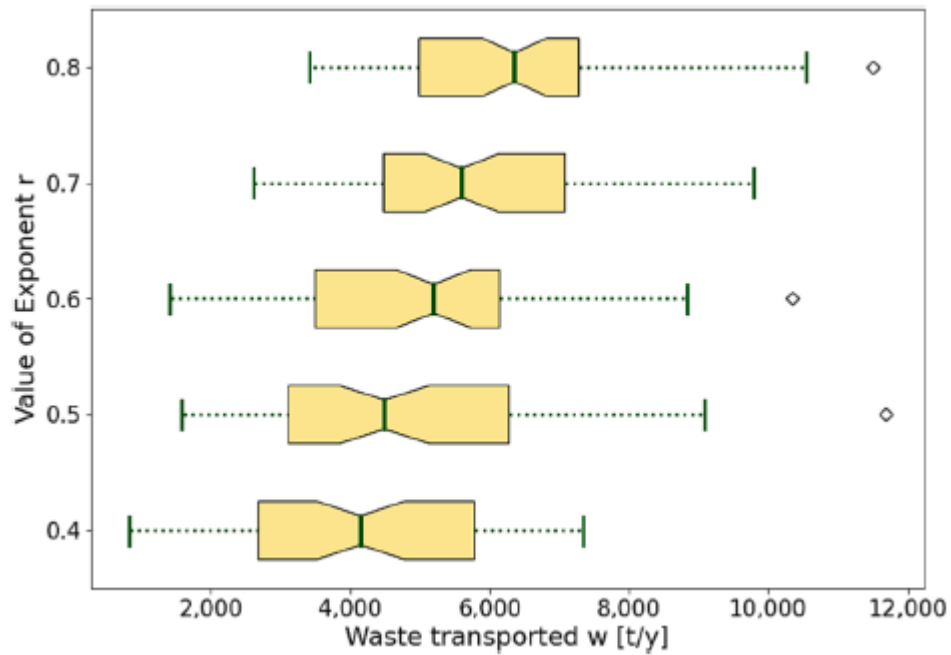


Fig. 2. Dependence of the amount of waste transported on the exponent.

The objective function thus assumes the form: $\min 3,0320x^{0.7} + 75 P_t \sum_{t=1}^n W_t$.

Results

To obtain the most accurate results, it is necessary to analyze the behavior of the implemented model. Results for the various number of scenarios (more specifically, 10-20-30, being a number of simulations) are examined. This number of scenarios was tested due to the need for convergence

assessment of the main characteristics; in other words, to verify the suitability of the number of scenarios to estimate the characteristic. For this case, the simulated period was determined to be a 50-year to eliminate some randomness in generating the unplanned shutdowns. In the case of choosing a short period, the estimations of the observed characteristics would give inaccurate results (see the convergence of standard deviation in **Table 1**). Subsequently, for the selected optimization method, results will be performed each time for a period of 10 to 90 years with a 10-year increment. For each group of measurements, the mean and standard deviation will be documented (**Table 1**).

Table 1 shows that the variances of the standard deviations for multiple scenarios (number of optimization scenarios 10-20-30) are close to each other. Therefore, in the lower part of **Table 1**, ten optimization scenarios for the upcoming calculations are always considered. It can also be seen that for a period of 60 years or more, the results of the means and standard deviations can be considered stable. For these reasons, the 60-year framework is considered a template for further calculations in subsequent analyses.

To conclude the case study, the behavior of the exponent r is verified. Therefore, for exponent values in the interval (0.4 — 0.8) (see [45]) with a step of 0.05, ten optimization scenarios (with 60 years period) are performed each time, and the obtained values are used to determine the interval estimate for the mean value. Since the WB is composed of various parts (e.g., construction and technology), various exponents are suitable for the various parts. Since the WB investment is mostly related to the construction part, it can be considered that a lower coefficient is suitable (see further).

In **Fig. 1**, it is possible to observe that increasing the exponent's value decreases the result's variability (interval estimate). This behavior is expected because as the investment cost increases (WB capacity increases), other effects are suppressed (penalization for transport to a landfill or to another WtE plant). The figure can be further divided into three areas: first (0.4 — 0.45) which is characterized by considerable variance, and the costs associated with bunker overfilling play a significant role. Second (0.45 — 0.65) the variance of the result can almost be considered constant. The final (0.65 — 0.8) variability of the result is almost negligible and consists of slight deviations (the curve breaks slightly and is flatter). More details on determining the value of the exponent to the investment cost can be found in [46]. Next, the dependence of the exponent value on the amount of waste transported (to the landfill or another WtE plant) is analyzed.

As can be seen in **Fig. 2**, as the value of the exponent increases, the amount of waste transported also grows. This phenomenon can be expected because of the lower sensitivity to the secondary effects when increasing investment costs. It is important to add that the transport values always converge over a period of one year.

Insights and discussion: Energy and economic sustainability

The optimal design of the WtE plant subsystem results in several different benefits. In the case of an optimally sized bunker at the WtE plant, the benefits are as follows:

It leads to material and space savings if oversized bunker size is avoided. The CO_2 produced in its production is reduced by using only the necessary amount of concrete. Another aspect related to this point is that the limited space at WtE plants often limits the use of modern technologies, an example of which is the slag recycling line. Lastly, it also saves on the initial investment, significantly improving the project's overall economics.

It brings financial cost savings for available bunker capacity for *WtE* plant shutdowns. Taking the waste to another facility is unnecessary in such a situation. Alternatively, in a worst-case scenario, there is no need to divert waste to landfills, where greenhouse gas production increases in addition to the financial costs.

It optimizes/maximizes the use of waste for energy production, ideally in a co-generation mode with simultaneous production of heat and electricity.

Insights

All of the aspects described above affect the economics of the *WtE* plant [47]. An optimally designed bunker contributes significantly to the sustainability of such projects. The results on the choice of bunker capacity from Section 4 are put in the context of existing *WtE* plants. A specific comparison is shown in **Fig. 3** related to annual processing capacity and energy production.

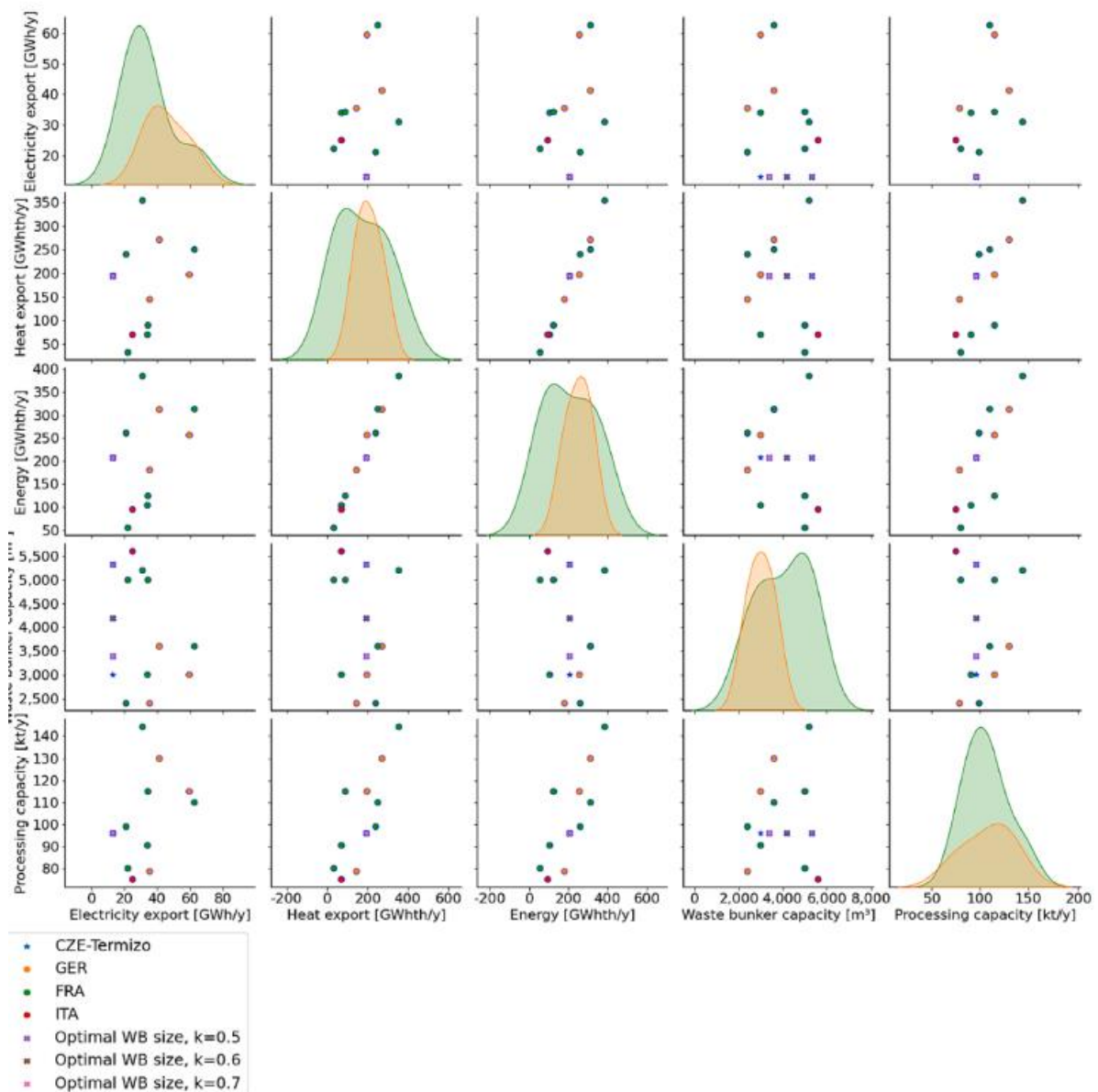


Fig. 3. Comparison of main *WtE* plant characteristics with optimization results.

Fig. 3 depicts important characteristics of *WtE* plants, such as heat, electricity, and energy production. In addition, the *WB*'s size and the *WtE* plant's processing capacity can be observed. It is important to note that the *WtE* plants that are plotted in **Fig. 3** have a processing capacity ranging from ± 20 [kt/y] from the processing capacity of TERMIZO.

Another essential feature is the representation of the three settings for the exponent $r = \{0.5, 0.6, 0.7\}$ and its values of the *WB* capacity that were obtained in the case study. The adjustment of the exponent r mainly depends on the circumstances of the specific *WtE* factory, but in general, the value of the exponent $r = 0.6$ can be considered the most appropriate (see [45] or the discussions in sections 4.1 and 4.2). The size of the *WB* of the TERMIZO *WtE* plant compared to the optimized values achieved using the established model is significantly smaller. This under sizing of the *WB* is also supported by the operating experience, which shows frequent overfilling during shutdowns.

The sizes of *WB* capacities across the selected *WtE* plants take on significantly diverse values. **Fig. 3** shows that the highest value is more than twice as large as the lowest value of the *WB* capacity, which supports the need to address the problem. The values obtained using the optimization model are in the middle of the range, apparently indicating that a fair number of *WtE* plants chose the size of the *WB* "reasonably." One of the reasons for the diversity of *WB* sizes is that the capacity depends not only on the plant's processing capacity but also on the characteristics of the imported waste, which can differ significantly from country to country. From this perspective, only the comparison with the *WtE* TERMIZO factory can be considered exact. However, in EU countries, waste can often be considered "similar" (even if often uncertain, in general), and therefore, a comparison with other *WtE* plants brings at least an interesting perspective [48].

The optimal results for various values of k are: $k = 0.5 \Rightarrow 5,322 \text{ m}^3$, $k = 0.6 \Rightarrow 4,191 \text{ m}^3$, $k = 0.7 \Rightarrow 3,389 \text{ m}^3$ such that the most probable value of the exponent k seems to be $k = 0.6$ due to it being approximately in the middle of values of *WB* sizes for *WtE* facilities like TERMIZO considered herein (see **Fig. 3**, see [45]).

Table A1 A summary of publications.

	Waste transport		Waste bunker		WtE capacity and incineration systems		Energy recovery		Flue gas cleaning		Processing of slag and ash		Operation shutdowns	
	A	O	A	O	A	O	A	O	A	O	A	O	A	O
[22]	○	●	●	○	○	●	○	○	○	○	○	○	○	○
[21]	●	○	○	○	○	○	●	○	○	○	○	○	○	○
[30]	○	○	○	○	●	○	○	○	○	○	○	○	○	○
[34]	○	○	○	○	●	○	○	○	●	○	○	○	○	○
[39]	●	○	●	○	●	○	●	○	●	○	●	○	●	○
[11]	●	○	○	○	○	●	○	●	○	○	○	○	○	○
[20]	○	●	○	○	○	○	●	○	○	○	○	○	○	○
[35]	○	○	○	○	●	○	○	○	●	○	●	○	○	○
[36]	○	○	○	○	○	○	○	○	●	○	○	○	○	○
[33]	○	○	○	○	●	○	●	○	●	○	●	○	○	○
[23]	○	●	○	○	○	●	○	○	○	○	○	○	○	○
[31]	●	○	●	○	●	○	●	○	●	○	●	○	●	○
[29]	○	○	○	○	●	○	○	○	●	○	○	○	○	○
[24]	○	●	○	○	○	○	○	○	○	○	○	○	○	○
[27]	○	●	○	○	○	○	○	○	○	○	○	○	○	○
[32]	○	○	○	○	●	○	●	○	○	●	○	○	○	○
[40]	○	○	○	○	●	○	○	○	●	○	○	○	○	○
[26]	●	○	○	○	●	○	○	○	○	○	○	○	○	○
[25]	○	●	○	○	○	●	○	○	○	○	○	○	○	○
[49]	○	○	○	○	○	○	○	○	○	○	○	○	○	○
[38]	○	○	○	○	○	○	○	○	○	○	○	○	○	○
[28]	○	●	○	○	○	○	○	○	○	○	○	○	○	○
Σ	5	7	3	0	10	4	10	3	9	1	4	1	3	0

Table A2 Parameters of Normal and Weibull distributions.

Normal distribution	Mean (μ)	Standard deviation (σ)	Days (t)
Waste Imported (J_t)	364 t	76 t	Working days for $\forall t \in T^v$
Waste Burned (L_t)	260 t	40 t	Working days for $\forall t \in T^v$
Waste Burned (L_t)	260 t	40 t	Weekends for $\forall t \in T^w$
Uniform distribution	Minimum	Maximum	
Waste Imported (J_t)	0 t	30 t	Weekends for $\forall t \in T^w$
Weibull distribution	Shape parameter ϵ	Scale parameter δ	
Unplanned shutdowns (u_t)	1.00070962	55.88252270	for $\forall t \in T$

It is worth noticing that the results are supported by data from 2004 to 2019. Therefore, the presented approach ensures the robustness of our results for similar *WtE*, but it can also be used for any other *WtE* with just a few modifications of the model parameters and data generation (depending on some concrete *WtE* attributes, like the number of boilers, imported waste, etc.).

Regarding energy production, the optimal capacity values show significantly lower values per unit compared to existing plants. The calculated values of the exponent r and energy support this statement. The values of the exponents $r = \{0.5, 0.6, 0.7\}$ are assigned successively to the energy results $\{19.917, 21.483, 26.567\}$ MWh/m³. Considering the variability of *WB* capacities at existing plants and TERMIZO's operational experience, it can be concluded that the presented approach for choosing bunker capacity is beneficial and can significantly increase the sustainability of the waste-to-energy project.

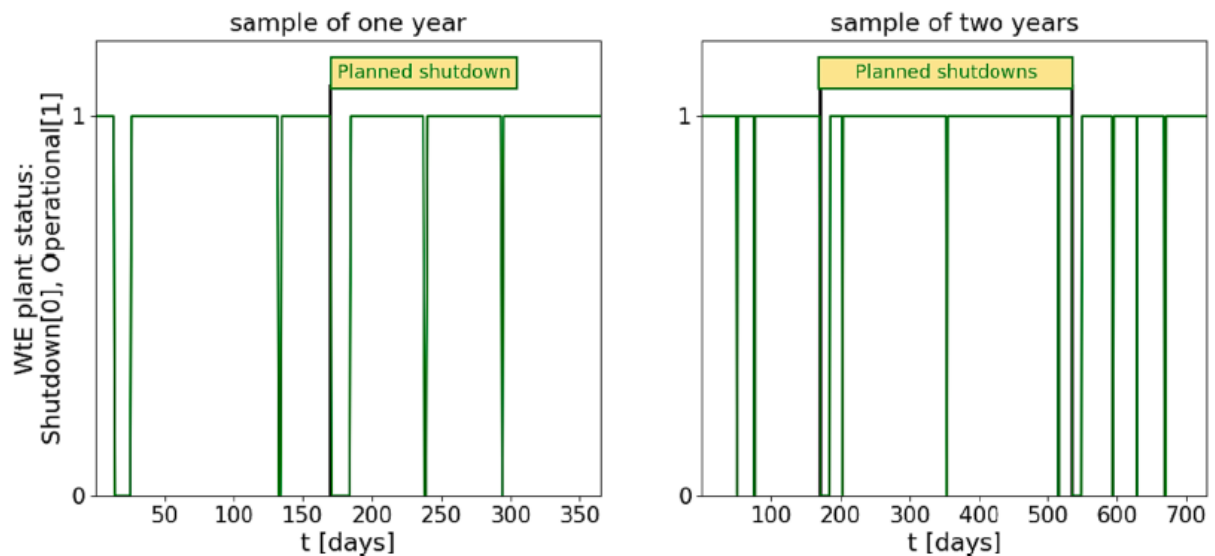


Fig. A1. Planned and unplanned shutdown generator.

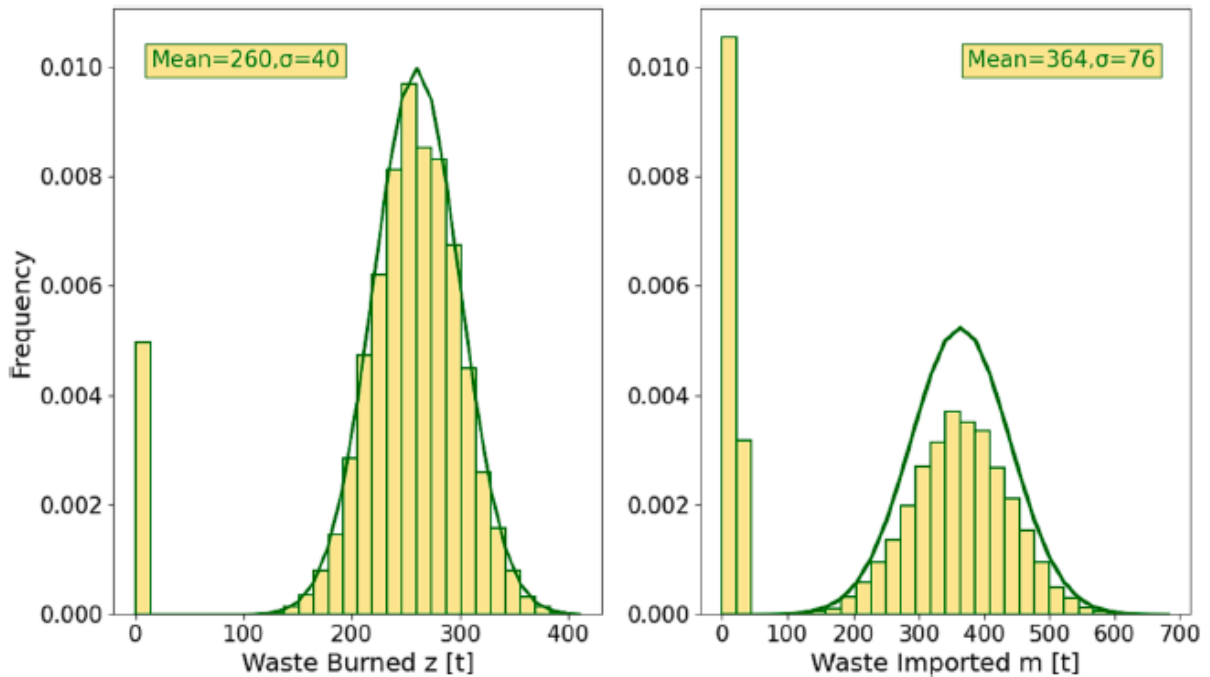


Fig. A2. Waste imported and burned datasets for 18,250 days.

Discussion of the results

The paper develops and suggests a mathematical model as a supporting tool for strategic decision-making about the WB capacity for the WtE plant. This capacity is given after the related decision and can not change once it is under operation. In real-time, waste import is then particularly coordinated [47]. In a real operation, waste is imported until there is a space in the bunker; when it is full, the waste must be rerouted to other facilities. However, there is no space for further optimization of the operation; therefore, the paper does not investigate this part of the chain.

The mathematical model applied to make the computation is given in Section 3. Into this model, an arbitrary operational (or expert-given) data are applied to optimize such particularly defined case/example. Since real data has been used for the case study, it can be considered that WtEs with a continuous operation, one “boiler,” and a yearly planned shutdown, will have similar results as described in the paper. It means, that according to the obtained (robust) results, WtE with the capacity of ca. 100kt/y is suggested to have a WB with a size of ca. 4,200m³.

Conclusions

The paper presents a new approach for optimizing the waste bunker (WB) capacity of the Waste-to-Energy (WtE) plant. An existing inventory optimization model is modified and applied to the particular allocation problem. The aim is to optimize the WB size while minimizing the total costs composing the investment, inventory, and waste shortage costs. The mathematical model is developed and described in a general approach. It can be used for other similar structural components without the need to restrict to WtE plants. A significant contribution of this paper is a case study that is based on data from a real operation of a WtE plant in the Czech Republic. The statistical analysis of the data resulted in a model for estimating the probability distribution of unplanned shutdowns in WtE plants. Unplanned shutdowns were divided into three categories (one day, two days, and more days). Despite the

characteristics of each plant, the probability distribution obtained can be used for analyses and models of other *WtE* plants. The condition is the existence of only one operating line.

The available data (2004-2019) allowed us to obtain robust enough results. The results are provided for various parameter values in the investment function, represented by an exponent determining the price evolution depending on the size of the capacity. Although, for the exponent values varying from 0.5 — 0.7, the suggested *WB* capacities are in the range of ca. 5,322 — 3,389 m³, the most probable scenario is the middle value of 0.6, leading to a *WB* capacity of 4,191 m³. The results are applicable to other *WtE* projects; however, some modifications of model parameters and data generation are obviously needed.

In future work, it will be useful to focus on the development of a more comprehensive model, including devices with multiple lines. Furthermore, it would be beneficial to consider the operating conditions, such as boiler fouling, in more detail.

Appendix A

Here, two criteria are specified for each subsystem, determining whether a given problem is analyzed in a publication without optimization (A) or if optimization is used (O).

Appendix B

Description of datasets for *WtE* plant.

The mathematical model subsection provides a general model of the *WB* optimization problem. The next milestone for developing a realistic model is the generic representation of its inputs (datasets). In this case, it is necessary to simulate the daily operation of the *WtE* plant using data representing the import and incineration of waste concerning planned and unplanned shutdowns. In addition, subsets T^\wedge (weekends) and T^\vee (working days) are introduced to distinguish whether the waste is collected on a working day or on a weekday ($T^\wedge, T^\vee \subseteq T$). The daily incineration and import of waste can therefore be expressed using the following formulas:

$$z_t = \begin{cases} y_t & \text{for } h_t u_t L_t > y_t \\ h_t u_t L_t & \text{for } h_t u_t L_t \leq y_t \end{cases} \quad \text{for } \forall t \in T \quad (6)$$

$$m_t = h_t J_t \quad \text{for } \forall t \in T \quad (7)$$

$$J_t \in \begin{cases} N(\mu_J, \sigma_J^2) & \text{for } \forall t \in T^\vee, \\ U(a, b) & \text{for } \forall t \in T^\wedge, \end{cases} \quad (8)$$

$$L_t \in N(\mu_L, \sigma_L^2) \quad \text{for } \forall t \in T \quad (9)$$

Where L is the incineration value and J the waste import value belonging to the normal and uniform distribution in which μ represents the mean, σ^2 the variance of the values and a, b the minimum and maximum of the uniform distribution (8,9). The specific characteristics of the distribution applied are estimated based on data from the operation of the *WtE* plant (see more in Section 4). It is also important to point out that the *MSW* is collected only in very limited quantities on weekends.

Therefore, the value of J must differ significantly from a normal working day (8). A binary variable u represents unplanned shutdowns with a probability of occurrence calculated using the Weibull distribution (10), and planned shutdowns are denoted by h where their occurrence is determined using the expression (12). Planned shutdowns are also considered for the waste return dataset due to the overall limitation of the WtE plant operation (7). The fault condition is considered as "0" and the normal operation status as "1". Further, for equations (10,11,12), it is considered for $\forall t \in T$.

$$P(u_t = 0) = \frac{\varepsilon}{\delta} \left(\frac{t}{\delta}\right)^{\varepsilon-1}, \quad t \notin \cup_{k \in \mathbb{N}_0} (Yk + B, Yk + B + A), \quad u \in \{0, 1\} \text{ for } k = 0, 1, \dots, n-1 \quad (10)$$

$$P(u_t = 1) = 1 - P(u_t = 0) \quad (11)$$

$$h_t = \begin{cases} 0 & \text{for } t \in (Yk + B, Yk + B + A) \\ 1 & \text{for } t \notin (Yk + B, Yk + B + A) \end{cases} \text{ for } k = 0, 1, \dots, n-1 \quad (12)$$

Operator ε is a shape parameter, δ represents the scale parameter, and t the value time, in this case, one day. An unplanned shutdown should not occur within the time specified for a planned shutdown, and therefore a collision-avoidance constraint is added to the formula (10). Where Y denotes the length of the year, k the number of years, A the duration of the planned shutdown, and B the start of the reserved time in the year for general maintenance. It is also worth noting that k in (10) must start from 0 for the function to work algorithmically. In addition, the model must include a mechanism to reset the WtE plant failure probability after a planned or unplanned failure event is encountered (see Algorithm 1 in Appendix C). Equations (6)-(12) present input parameters for the developed model presented above. The equations define all the parameters; there is no specific assumption of any of them.

Description of parameters generation.

In addition, a date for the start of the planned shutdown is set on every 171st day of the year for 14 days. The date is based on the heat demand according to the data obtained in the real operation of the WtE plant (TERMIZO a.s.). Now, using equations (10)-(12) and **Table A2**, a dataset representing the operation of the plant with planned and unplanned shutdowns is generated, see **Fig. A1**.

Fig. A.1 shows the possible distribution of planned and unplanned shutdowns for one and two years. It can be observed that in each year, according to the specified interval (in this case, the 171st day of each year is a 14-day planned shutdown) and in the other cases, there are "random" unplanned shutdowns following the parameters of the Weibull distribution in **Table A.2**. It is also possible to note that the most frequent group of unplanned shutdowns are one-day (with the probability of occurrence of 65.52%) and two-day (28.32%) breakdowns (forming the vast majority). The riskiest unplanned shutdowns fall into the last group (three or more days, 7.15%), which are not as frequent but can cause the most trouble for the WtE plant (an example of such unplanned shutdown is in **Fig. A.1** on the left side starting on day 15). The mechanism for generating unplanned shutdowns can be expressed using the illustrative (see Algorithm 2 in Appendix C).

Importantly, the shutdown probabilities and WB capacity transition smoothly between the two time periods even though it is a discrete problem. Furthermore, based on the data from TERMIZO a.s., the imported and incinerated waste values can be considered "uniform" throughout the year. With the

shutdown generator and the normal, uniform distribution parameters from **Table A.2**, sample MSW importation and incineration datasets are generated.

Fig. A2 is a histogram of waste import and incineration data over 50 years (each year is assumed to have 365 days). Where zero values for the “Waste Burned” histogram denote planned and unplanned shutdowns and values ranging on the interval $\{0,30\}$ in the “Waste Imported” histogram represent weekend values. With the graphical representation of the frequencies of zero values for waste burned (overfilling of the *WB* and its consequent transfer to another *WtE* plant or to a landfill), it is now more evident that there is an effort to prevent such a situation by appropriately determining the capacity of the *WB*.

Appendix C

Algorithm 1

```

scenarios = [Years[1], ..., Years[v]]
WteCycle = 1
UnplannedShutdown = [0,1]
SizeOfYear = 365
for scenario in range(len(scenarios)) :
    for index, TimePeriod in enumerate((scenario)) :
        u = 1
        h = 1
        Probability = (eq. 12)
        InvProbability = (eq. 13)
        if index%SizeOfYear == StartOfPlannedShutdown :
            h = 0
        Decision = random.choices(UnplannedShutdown, weights(Probability, InvProbability))
        u = Decision
        if h == 0 or u == 0 :
            WteCycle = 1
        else :
            WteCycle += 1

```

(The algorithm serves only as an example, WteCycle substitute *t* in the algorithm)

Algorithm 2

```

scenarios = [Years[1], ..., Years[v]]
UnplannedShutdown = [0, 1]
variation = [1, 2, 3]
cycleWtE = []
for scenario in range(len(scenarios)) :
    for index, TimePeriod in enumerate((scenario)) :
        Probability = (eq. 12)
        InvProbability = (eq. 13)
        decision = random.choices(UnplannedShutdown, weights = (Probability, InvProbability))
        if decision[0] == 0 :
            decision2 = random.choices(Variation, weights = (one_dayP, two_dayP, threeORMore_dayP))
            if decision2[0] == 1 :
                cycleWtE.append(0)
            elif decision2[0] == 2 :
                cycleWtE.append(0)
                cycleWtE.insert(TimePeriod + 1, 0)
            elif decision2[0] == 3 :
                PickLenght = random.randint(3, n)
                for z in range(PickLenght - 1) :
                    cycleWtE.insert(TimePeriod, 0)
        else :
            cycleWtE.append(1)

```

(The algorithm serves only as an example, WteCycle substitute t in the algorithm)

Appendix D

The size of the waste bunker	
The size of the waste bunker [m^3]	6,000
<hr/>	
The size of the waste bunker [t]	1,820
All factors in the construction of WB and their cost	
Total price set by IP system a.s. [€]	612,000
Price per cubic meter [€]	100
Price per tonne [€]	335
Excavation work [€]	261,700
Establishing [€]	172,000
Horizontal structures [€]	65,000
Other construction and demolition [€]	3,500
Transfer of masses [€]	4,000
Value-added tax [€]	106,300
Transformation to Investment function form	
Investment function	$I(x) = cx^r$
Using the formula	$I_2 = I_1 \left(\frac{x_2}{x_1}\right)^{0.7}$ $I_2 = 612,000 \left(\frac{1}{1,820}\right)^{0.7}$ $I_2 = 3,020[\text{€}]$

References

- [1] Khan S, Anjum R, Raza ST, Bazai NA, Ihtisham M. Technologies for municipal solid waste management: Current status, challenges, and future perspectives. *Chemosphere* 2022;288(1):132403. <https://doi.org/10.10Wj.chemosphere.2021.132403>.

- [2] Zahedi R, Daneshgar S, Golivari S. Simulation and optimization of electricity generation by waste to energy unit in tehran. *Sustainable Energy Technologies and Assessments* 2022;53:102338. <https://doi.org/10.1016/j.seta.2022.102338>.
- [3] Abdel-Shafy HI, Mansour MSM. Solid waste issue: Sources, composition, disposal, recycling, and valorization. *Egyptian Journal of Petroleum* 2018;27(4):1275-90. <https://doi.org/10.1016/j.ejpe.2018.07.003>.
- [4] Ríos A, Picazo-Tadeo AJ. Measuring environmental performance in the treatment of municipal solid waste: the case of the european Union-28. *Ecological Indicators* 2021;123:107328. <https://doi.org/10.10Wj.ecolind.2020.107328>.
- [5] Directive (EU) 2018/850 of the European Parliament and of the Council of 30 May 2018 Amending Directive 1999/31/EC on the Landfill of Waste (Text with EEA Relevance), 100-108.
- [6] Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2008/98/EC on Waste, 109-140.
- [7] Huang J, Koroteev DD. Artificial intelligence for planning of energy and waste management. *Sustainable Energy Technologies and Assessments* 2021;47:101426. <https://doi.org/10.1016/j.seta.2021.101426>.
- [8] Gabbar HA, Darda SA, Damideh V, Hassen I, Aboughaly M, Lisi D. Comparative study of atmospheric pressure DC, RF, and microwave thermal plasma torches for waste to energy applications. *Sustainable Energy Technologies and Assessments* 2021;47:101447. <https://doi.org/10.10Wj.seta.2021.101447>.
- [9] Maki S, Ohnishi S, Fujii M, Goto N, Sun L. Technical and economic analysis of potential steam supply from waste treatment plants to industries in aichi prefecture. *Japan Optimization and Engineering* 2021;22:1755-82. <https://doi.org/10.1007/s11081-021-09637-9>.
- [10] Lino FAM, Ismail KAR. Alternative treatments for the municipal solid waste and domestic sewage in campinas, brazil. *Resources, Conservation and Recycling* 2013; 81:24-30. <https://doi.org/10.1016/j.resconrec.2013.09.007>.
- [11] Šomplák R, Ferdan T, Pavlas M, Popela P. Waste-to-energy facility planning under uncertain circumstances. *Applied Thermal Engineering* 2013;61(1):106-14. <https://doi.org/10.1016/j.applthermaleng.2013.04.003>.
- [12] Energy from waste - a guide to the debate, Department for Environment Food & Rural Affairs, 2013, <https://www.gov.uk/government/publications/energy-from-waste-a-guide-to-the-debate> [Accessed: 25-January-2022].
- [13] Abbasi G, Khoshallhan F, Hosseininezhad SJ. Municipal solid waste management and energy production: A multi-objective optimization approach to incineration and biogas waste-to-energy supply chain. *Sustainable Energy Technologies and Assessments* 2022;54:102809. <https://doi.org/10.1016/j.seta.2022.102809>.
- [14] Mahyari KF, Rafiee S, Keyhani A, Jafari A, Mahyari MF, Khorasanizadeh Z, et al. Optimal economic planning for the development of waste management system by a superstructural model. *Computers and Chemical Engineering* 2022;157:107634. <https://doi.org/10.1016/j.compchemeng.2021.107634>.

- [15] Ilbahar E, Kahraman C, Cebi S. Location selection for waste-to-energy plants by using fuzzy linear programming. *Energy* 2021;234:121189. <https://doi.org/10.1016/j.energy.2021.121189>.
- [16] Bianchi M, Branchini L, Pascale AD. Combining waste-to-energy steam cycle with gas turbine ; units. *Applied Energy* 2014;130:764-73. <https://doi.org/10.1016/j.apenergy.2014.03.028>.
- [17] Eboh FC, Ahlstrom P, Richards T. Evaluating improvements in a waste-to-energy combined heat and power plant. *Case Studies in Thermal Engineering* 2019;14: 100476. <https://doi.org/10.1016/j.csite.2019.100476>.
- [18] Su X, Zhang L, Xiao Y, Sun M, Gao X, Su J. Evaluation of a flue gas cleaning system of a circulating fluidized bed incineration power plant by the analysis of pollutant emissions. *Powder Technology* 2015;286:9-15. <https://doi.org/10.1016/j.powtec.2015.07.038>.
- [19] Liu C, Letchford AN, Svetunkov I. Newsvendor problems: an integrated method for estimation and optimization. *European Journal of Operational Research* 2022;300 (2):590-601. <https://doi.org/10.1016/j.ejor.2021.08.013>.
- [20] Tan ST, Hashim H, Lee CT, Lim JS, Kanniah KD. Optimal waste-to-energy strategy assisted by GIS for sustainable solid waste management. *IOP Conference Series: Earth and Environmental Science* 2014;18:012159. <https://doi.org/10.1088/1755-1315/18/1/012159>.
- [21] Chen X, Geng Y, Fujita T. An overview of municipal solid waste management in china. *Waste Management* 2010;30(4):716-24. <https://doi.org/10.1016/j.wasman.2009.10.011>.
- [22] Maqsood I, Huang GH. A two-stage interval-stochastic programming model for waste management under uncertainty. *Journal of the Air & Waste Management Association* (1995) 2003;53(5):540-52. <https://doi.org/10.1080/10473289.2003.10466195>.
- [23] Hu C, Liu X, Lu J. A bi-objective two-stage robust location model for waste-to-energy facilities under uncertainty. *Decision Support Systems* 2017;99:37-50. <https://doi.org/10.1016/j.dss.2017.05.009>.
- [24] Varbanov PS, Walmsley TG, Fan YV, Perry SJ. Spatial targeting evaluation of energy and environmental performance of waste-to-energy processing. *Frontiers of Chemical Science and Engineering* 2018;12:731-44. <https://doi.org/10.1007/s11705-018-1772-1>.
- [25] Hrabec D, Šomplák R, Nevrlý V, Viktorin A, Pluháček M, Popela P. Sustainable waste-to-energy facility location: Influence of demand on energy sales. *Energy* 2020;207:118257. <https://doi.org/10.1016/j.energy.2020.118257>.
- [26] Šomplák R, Nevrlý V, Smejkalová V, Šmídová Z, Pavlas M. Bulky waste for energy recovery: Analysis of spatial distribution. *Energy* 2019;181:827-39. <https://doi.org/10.1016/j.energy.2019.05.175>.
- [27] Kůdela J, Šomplák R, Nevrlý V, Lipovský T, Smejkalová V, Dobrovský L. Multiobjective strategic waste transfer station planning. *Journal of Cleaner Production* 2019;230:1294-304. <https://doi.org/10.1016/j.jclepro.2019.05.167>.

- [28] Zilka M, Stieberova B, Scholz P. Sustainability evaluation of the use of cargo-trams for mixed municipal waste transport in prague. *Waste Management* 2021;126: 97-105. <https://doi.org/10.1016/j.wasman.2021.02.053>.
- [29] Makarichi L, Jutidamrongphan W, Techato K. The evolution of waste-to-energy incineration: A review. *Renewable and Sustainable Energy Reviews* 2018;91: 812-21. <https://doi.org/10.1016/j.rser.2018.04.088>.
- [30] Nakamura MR, Castaldi MJ, Themelis NJ. Stochastic and physical modeling of motion of municipal solid waste (MSW) particles on a waste-to-energy (WTE) moving grate. *International Journal of Thermal Sciences* 2010;49(6):984-92. <https://doi.org/10.1016/j.ijthermalsci.2009.12.006>.
- [31] Kalogirou EN. *Waste-to-energy technologies and global applications* (1st ed.), CRC Press; 2017. <https://doi.org/10.1201/9781315269061>.
- [32] Nevrlý V, Šomplák R, Putna O, Pavlas M. Location of mixed municipal waste treatment facilities: Cost of reducing greenhouse gas emissions. *Journal of Cleaner Production* 2019;239:118003. <https://doi.org/10.1016/j.jclepro.2019.118003>.
- [33] Consonni S, Lombardi L, Vigano F. Municipal solid waste to energy technology. *Encyclopedia of Sustainable Technologies* 2017:389-401. <https://doi.org/10.1016/B978-0-12-409548-9.10105-8>.
- [34] Poggio A, Grieco E. Influence of flue gas cleaning system on the energetic efficiency and on the economic performance of a WtE plant. *Waste Management* 2010;30(7): 1355-61. <https://doi.org/10.1016/j.wasman.2009.09.008>.
- [35] Vehlow J. Air pollution control systems in WtE units: an overview. *Waste Management* 2015;37:58-74. <https://doi.org/10.1016/j.wasman.2014.05.025>.
- [36] Caneghem JV, Greef JD, Block C, Vandecasteele C. NO_x reduction in waste incinerators by selective catalytic reduction (SCR) instead of selective non catalytic reduction (SNCR) compared from a life cycle perspective: A case study. *Journal of Cleaner Production* 2016;112(5):4452-60. <https://doi.org/10.1016/j.jclepro.2015.08.068>.
- [37] Fedje KK, Andersson S. Zinc recovery from waste-to-energy fly ash - A pilot test study. *Waste Management* 2020;118:90-8. <https://doi.org/10.1016/j.wasman.2020.07.017>.
- [38] Sun Y, Li J, Chen Z, Xue Q, Sun Q, Zhou Y, et al. Production of lightweight aggregate ceramics from red mud and municipal solid waste incineration bottom ash: Mechanism and optimization. *Construction and Building Materials* 2021;287: 122993. <https://doi.org/10.1016/j.conbuildmat.2021.122993>.
- [39] Rogoff MJ, Screve F. O&M of WTE facilities. In: Rogoff MJ, Screve F, editors. *Waste-to-energy*. (2nd ed.). William Andrew Publishing; 2011. p. 145-51. <https://doi.org/10.1016/B978-1-4377-7871-7.10011-5>.
- [40] Tsai W-T. An analysis of operational efficiencies in the waste-to-energy (WTE) plants of kaohsiung municipality (Taiwan). *Resources* 2019;8(3):125. <https://doi.org/10.3390/resources8030125>.

- [41] Barbosa-Páovoa AP, Silva CD, Carvalho A. Opportunities and challenges in sustainable supply chain: An operations research perspective. *European Journal of Operational Research* 2018;268(2):399-431. <https://doi.org/10.1016/j.ejor.2017.10.036>.
- [42] Mullbunker. Zweckverband Mullverwertung Schwandorf, <https://www.z-m-s.de/muellkraftwerk/das-werk/muellbunker/index.html> [accessed 13 January 2023].
- [43] De aanvoer en opslag van afval. Ivm milieubeheer, <https://www.ivmmilieubeheer.be/afval-verwerken/afval-verwerken/het-ivm-proces/de-aanvoer-en-opslag-van-afval> [accessed 13 January 2023].
- [44] Palanivel TM, Sulaiman H. Generation and composition of municipal solid waste (MSW) in muscat. Sultanate of Oman APCBEE *Procedia* 2014;10:96-102. <https://doi.org/10.1016/j.apcbee.2014.10.024>.
- [45] Dysert LR. Sharpen your cost estimating skills. *Cost Engineering* 2003;45(6):22-30.
- [46] Garrett DE. *Chemical Engineering Economics*. Springer Science+Business Media; 1989. <https://doi.org/10.1007/978-94-011-6544-0>.
- [47] Filimonova IV, Krivosheeva OI, Mishenin MV. the economic effect of public-private partnerships in the implementation of climate projects for the disposal of municipal solid waste. *Energy Reports* 2023;9:996-1002. <https://doi.org/10.1016/j.jegy.2022.11.042>.
- [48] Pluskal J, Šompláák R, Hrabec D, Nevrlý V, Hvattum LM. Optimal location and operation of waste-to-energy plants when future waste composition is uncertain. *Operations Research* 2022;22:5765-90. <https://doi.org/10.1007/s12351-022-00718-w>.
- [49] Ni T, Si J, Lu F, Zhu Y, Pan M. Performance analysis and optimization of cascade waste heat recovery system based on transcritical CO₂ cycle for waste heat recovery in waste-to-energy plant. *Journal of Cleaner Production* 2022;331: 129949. <https://doi.org/10.1016/j.jclepro.2021.129>.

