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A Multi-Commodity Mathematical Modelling Approach—Hazardous Waste Treatment Infrastructure Planning in the Czech Republic

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Abstract: This paper presents an analysis of infrastructure for the processing of Czech hazardous waste and pays attention to predictions of waste management development in the upcoming years. For this purpose, a unique complex approach to modelling future waste management changes is applied. The method uses a multi-commodity network flow model with reverse flows between treatment facilities to consider complete waste management of hazardous waste. The future outlook (2030) for the forecasted generation of different types of hazardous waste in the Czech Republic requires decisions on waste treatment facility infrastructure. The uniqueness lies in using real data for such a wide scope of a task, further enhanced by concurrent analysis of more types of waste interconnected through limited processing capacities. The results indicate the insufficiency in hazardous waste thermal treatment and stabilization. A suggestion is to extend the incineration capacity because it influences the stabilization units, which must process the remaining waste. The recommended increase is 100% with different proportions in individual regions.

Keywords: hazardous waste; multi-commodity; waste network flow; reverse logistics; capacity allocation; sustainable processing planning; self-sufficiency; demulsification; biodegradation; stabilization

1. Introduction

Much attention in waste management (WM) is paid to municipal solid waste (MSW), but hazardous waste (HW) treatment is of great concern because of various environmental risks [1]. The determination of the most advantageous structure of waste treatment facilities for different types of HW (recyclables, biodegradable, hazardous, and residual) became an essential result of this complex project. The study and results presented in the paper are based on a complex analysis for the Ministry of Environment of the Czech Republic (CR) that was carried out in 2020, where the current HW processing infrastructure was considered. An optimal HW treatment network was proposed for CR regions regarding the treatment hierarchy, which is based on the environmental impact.

The study presents WM in the CR, an EU Member State with 10.5 million inhabitants and ca. €212 billion GDP (in 2018). The task covers various waste groups and a series of different suitable methods of HW processing, as shown in Figure 1. The optimization task itself, which is the main subject matter of this paper, tracks HW streams suitable only for incineration, demulsification or neutralization, biodegradation, stabilization, and HW streams that may be processed by more than just one of these HW treatment methods. This paper proposes infrastructure planning for HW treatment that takes place as close to its production site as possible and that is in compliance with the environmental criteria of the waste treatment hierarchy. The objective is to redirect the, nowadays, landfilled HW into other treatment facilities and, at the same time, comply with the waste treatment hierarchy. Hospital waste is a specific type of HW and has been excluded from the analysis. Hospital waste in the CR is chiefly eliminated at its origin. Hospitals have relevant and sufficient capacities to do so, and their production cannot influence other types of HW. For example, biodegradation is one of the most used methods of HW treatment in the CR. In total, 165 kilotons of HW were biodegraded in the CR in 2018, which represented almost 12% of all HW [2]. Other methods of HW treatment rely on the expansion of existing facilities and not on the construction of new ones since building new facilities faces major legislation obstacles.

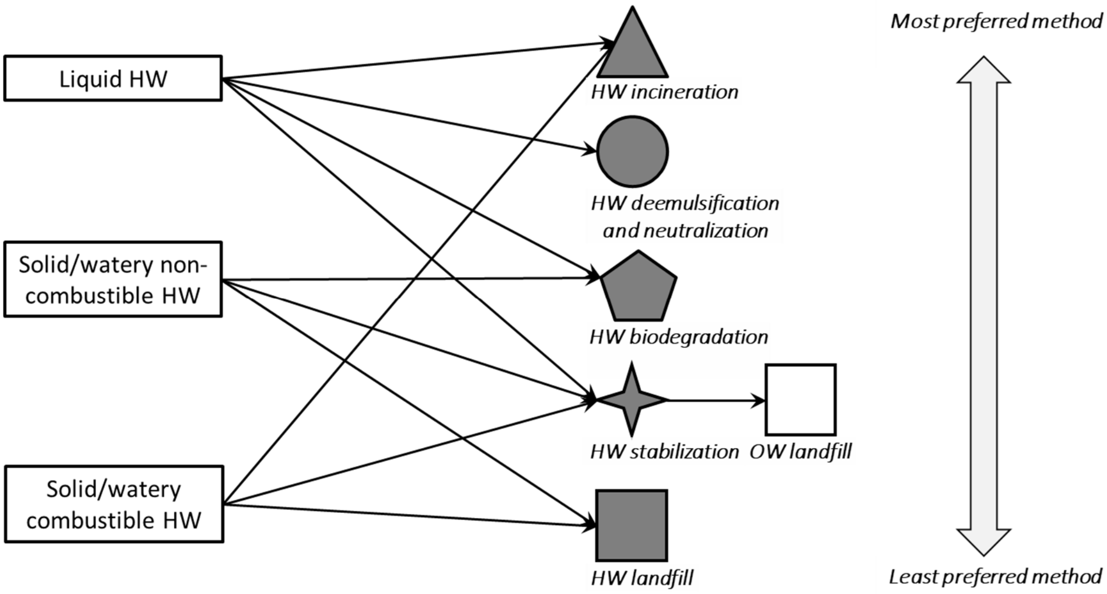

Figure 1. Basic diagram of options for processing various types of HW (OW = other, non-hazardous waste). Data source from [2].

Based on existing infrastructure in the CR, the assessment considers economic and environmental aspects and further evaluates the potential for expanding existing capacities so that the expected amounts of HW production may be eliminated. The task for HW treatment in the CR included important types of HW production, as seen in Figure 1. All types of waste may be processed in several facilities. The processing of residual waste may be a by-product of HW processing, as presented in Section 3.2. These facts, combined with limited processing capacities, lead to implementing all the aspects into one complex optimization task. The analysis resulting in the design of an optimal network for HW treatment facility included:

HW generation forecasts for 206 Czech micro-regions, which follow the administrative structure of the country. Waste generation forecasts were discussed in [3], where the data reconciliation for territories and waste codes is described in Section 3.2.

The expansion and utilization of existing processing capacities were forecasted. Scenarios with various capacities of plants were analyzed. The following processing facilities are examined: Incinerators, biodegradation plants, demulsification or neutralization plants, stabilization plants, and HW landfills. Figure 2 shows the distribution of HW plants within 14 regions. The analysis further concerned other waste (OW, i.e., non-hazardous) landfills for the disposal of stabilized non-hazardous residuals from HW incinerators. Individual HW treatment types are discussed in Section 3.1.

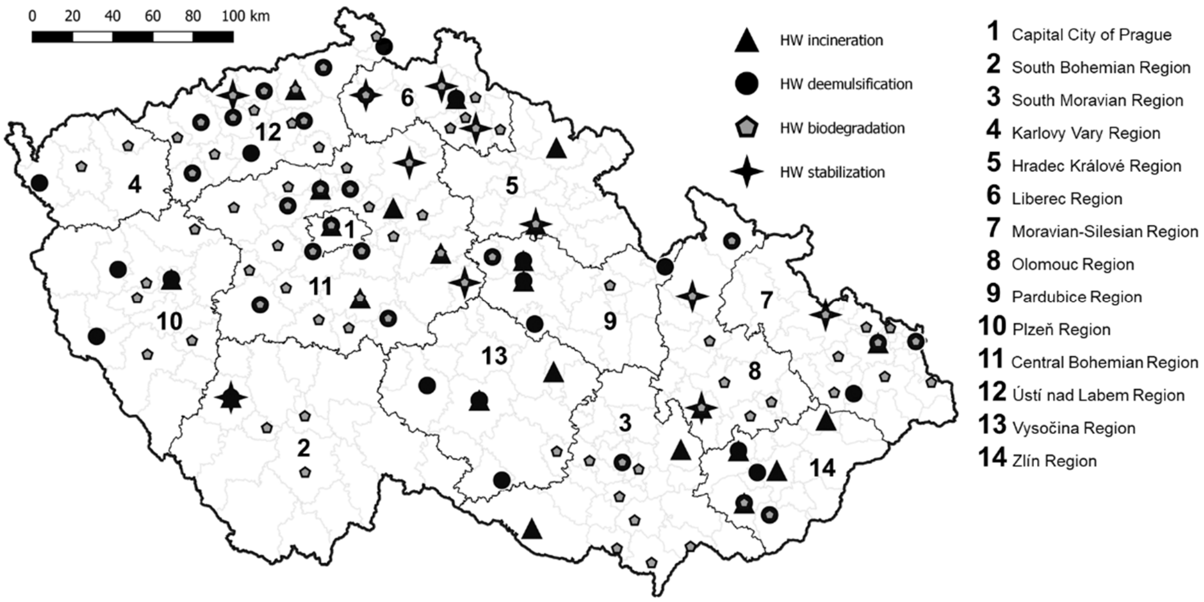

Figure 2. Distribution of HW treatment units in the CR (existing locations as locations for potential capacity expansions without landfills). Data source from [2].

The optimization represents the transport logistics allocation task with various transportation routes and residual flows between related processing facilities. The approach contains a treatment hierarchy according to the environmental impact, which is further adjusted by transport distance. The adjustment calculation is described in Section 4.

2. Literature Review and Paper Contribution

This section provides a general research study of approaches and applications in the WM, especially regarding HW. Analyses of HW management were usually rather specialized (only specific types of produced waste were considered). Issues of HW treatment were presented in general by [4]. More up-to-date HW management was reviewed by [5]. Solid WM challenges for cities in developing countries were specified by [6], and inadequate infrastructure was stated as one of the significant factors. The potential of innovations and supply chain redesign of HW with connection to the circular economy is discussed in [7]. An overall review of existing HW management systems, related legislation, and other relevant quantitative and qualitative information was presented by [5]. The challenges in HW treatment and its impact on the environment were reviewed in [1]. Since methods of HW processing are well described in the literature, this paper focuses on the sustainable planning of processing infrastructure and supply chains.

A comprehensive review of sustainable supply chain models [8] defined potential future directions in strategic planning, and one of them is the consideration of waste composition and dealing with various waste streams separately due to specific properties. Processing infrastructure planning should cover all streams and designs of capacities. The review analyzed over 200 articles presented after the year 2000. The articles were grouped according to decision levels in the supply chain, the monitored criterion, and the selected solution procedure. Another review [9] was focused on reverse logistics and closed supply chain management. The content analysis shows that the gaps and research opportunities lie primarily in working with real data or studies based on real industrial cases.

The general approach to modeling supply chains was used in [10], where the intelligent control of HW management was developed using an input–output method. The key feature of designing a supply chain is the HW transport, which was the subject of study with risk minimization [11]. A previous paper [12] focused on the design of multimodal transport, but the task size is limited to several nodes. A case study by [13] presented an assessment of a suitable location for a facility producing biofuels from waste oils, and only 12 potential sites were assessed in the study. Another paper [14] addressed a task of HW in the Chinese province of Sichuan. The authors developed a multi-objective mixed-integer linear programming model based on a computational network with 44 nodes (waste producers or processors) and 82 transportation edges. More complex logistic studies were introduced in [12,15]. Another paper [15] used binary programming to evaluate a collection system concept and establish transfer stations for ca. 50 waste producers. A literature review revealed that analyses are usually partial and describe a specific micro-region that is taken out of context without interregional relations. The details of the task and the interconnection between regions represent a crucial feature in designing an adequate processing infrastructure. It is also essential for further application in the real world.

A previous study [16] discussed model-size reduction techniques. Their paper focused on biomass processing and not on waste, but the case study and type of computational network presented are close to the task examined further below. In contrast to other methods discussed above, the network incorporated more levels for various facilities where the output from one facility (network level) may be further processed in another facility (that is, another network level). The network structure even allowed for the incorporation of residual waste that was a subject of the case study presented in that paper. It further showed ways of increasing the speed of computations, for example, by clustering more waste producers into a single node or by excluding transportation edges above a certain limit distance. The application potential of the method discussed in [16] for complex tasks is limited due to many binary variables that are part of mathematical models in most studies. Binary variables are usually employed to describe the hierarchy and interconnectedness of the network (with the link between the nodes defining the processing potential of the given type of waste). This method has not been fully and successfully researched, and its use significantly increases the computational time, as proved by [17].

The critical part of strategic planning lies in the complex assessment of the existing supply chain, its efficiency, and capacity sufficiency. Previous authors [18] assessed the efficiencies of watermelon production units with an appropriate recommendation for future development. Regarding industrial HW [19], there was an effort to incorporate the whole processing chain considering waste collection, transport, transfer stations, environmental protection, and necessary disposal sites. According to the double-path planning model, the optimization improves the efficiency of HW transport in environmental protection enterprises and promotes the green management of HW in procurement and disposal. Another paper [20] presented a proposal for HW infrastructure planning in China, focused on designing chemical parks and implementing new systems. Furthermore, another paper [21] dealt with incineration and landfill systems' energy consumption and the impact on the environment. The results showed that incineration led to waste toxicity reduction, and natural gas extraction from waste is vital for global warming and acidification reduction.

The new method developed and described in this paper takes advantage of the specific properties of the network design for the description of the task without using binary variables. Moreover, the network allows various rules to prefer a particular type of waste processing, namely HW processing in a facility at a fixed distance. The uniqueness of the solution lies in the task scope, which is further enhanced by concurrent analysis of several types of waste, including residual waste. Links in the system are usually implemented at the expense of the detail of the investigated territory to ensure solvability in a reasonable timeframe. Several above-mentioned studies deal only with a few production nodes and sites for treatment facilities. The use of real data is another specific feature of the task described here—the data from the real production of various types of HW in this scope may be considered unique.

The method is further enhanced so that types of waste processing related to the transport distance may be preferred. The waste treatment hierarchy is respected only up to a certain distance leading to processing close to the HW origin. The preferences and assumptions of the study are further discussed in Section 4 in more detail. The aim is to propose the most beneficial structure of waste treatment facilities for different types of waste in various Czech regions. The case study presents the HW production analysis and the related optimal facility network proposal.

3. Materials and Methods

The presented study aims to assess the current HW treatment infrastructure when future development and conditions of WM are applied. This is conducted via mathematical programming, which requires a complex dataset as the input information for optimization. The task considers several commonly used technologies for treating HW. The same type of HW (identical catalogue code in the waste catalogue) may be treated by various technologies, which thus become competitors to each other. In this part, the most common methods for HW elimination are mentioned with detailed descriptions of input data for the case study.

3.1. HW Treatment Methods

Incineration facilities are usually designed to process solid and liquid combustible waste, and they are intended to eliminate a whole spectrum of HW production according to catalogue codes [22]. The primary purpose of HW thermal treatment is to dispose of problematic materials. Energy production can only reduce operating costs and external energy consumption [23]. The basic design of waste incinerators entails two-stage incineration under conditions stipulated by valid legislation (pyrolysis is also plausible) and heat recovery from flue gas. Bottom ash must be further processed, as discussed in [24]. The technological design of the incinerator may have many modifications, depending on the requirements of the facility owner. Existing incinerators of industrial waste and HW in the CR are usually within the premises of industrial facilities. There is significant interconnectedness between the energy systems of the incinerator and the industrial facility. Technologies and performances of thermal treatment systems are reviewed by [25].

Demulsification and neutralization plants are designed to treat liquid water-based HW (liquid waste) and eliminate its hazardous properties. A list of papers on demulsification technology in the petroleum industry was published in [26]. The efficiency of different sorbent materials for oil removal from wastewater was investigated by [27,28]. The system consists of separate tanks to store various types of waste equipped with a homogenization unit. After the sedimentation of the components, the water-deprived sludge is drained into sewage. After that, it is no longer treated under legislation related to waste management. The sludge is then drained, mostly using a sludge filter press, and the solid waste leaving the plants is commonly classified as hazardous, depending on the properties of the stabilization products. More information about HW neutralization can be found in [29], where the authors also discussed other treatment possibilities.

Basic principles in biotechnology that are often applied for waste treatment are aerobic processes. Primarily, biodegradation areas are intended for contaminated waste, especially soil, construction, and demolition waste. Under certain conditions, facilities also accept inorganically contaminated waste. The high content of heavy metals is a limiting factor for the successful biodegradation process. Biodegradation can be defined as a biologically catalyzed reduction in chemical complexity compounds. Organic compounds are very often completely decomposed in the biodegradation process. The process of biodegradation concerns all-natural processes carried out by bacteria and other microorganisms or higher organisms that lead to the destruction of organic molecules. Composting technology can be used for the wide stabilization of pallets of hazardous biodegradable waste (such as sewage sludge) and the preparation of organic fertilizers. A more detailed description of HW biological treatment can be found in [30]. A review of biodegradation was presented in [31], and recent advances in biological technologies were described in [32].

Waste stabilization is a treatment based on the physical and chemical properties of waste and it re-categorizes waste. Stabilization causes homogenization of the waste with suitable materials, other additives, and water, leading to changes in the physical and chemical properties of waste entering the process. Waste solidification is a similar technology, but the waste is not transferred into a different category. These technologies are utilized for liquid waste and specific solid waste. Stabilization (or solidification) aims to permanently decrease the mobility of harmful substances contained in the waste before it is landfilled. Different reagents for the reductive solidification and stabilization of chromate in municipal solid waste incineration fly ash were investigated by [33]. Fly ash from solid waste incineration consists of various substances, including a large share of heavy metals. The stabilization of chlorine-rich incineration fly ash was studied by [34]. There are two methods commonly used for chemical stabilization processing of waste incineration fly ash [35]. The wastewater stabilization system design was reviewed by [36].

Landfills are the last resort for HW elimination once the waste complies with the qualitative criteria for admittance to the specifically designated HW landfills in the CR. Multi-criteria decision analysis and a geographical information system for HW landfills enable siting with regards to land scarcity for waste disposal [37].

3.2. Inputs for the Case Study

The CR produced, from 2009 to 2018, totaled 1.504 to 1.768 Mt/a of HW. For this paper, the total HW production is divided into eight categories, the so-called sub-streams, which cover 373 HW waste catalogue codes registered in the CR. The Czech waste catalogue is in accordance with the European waste catalogue [22]. Hospital waste is a special type of HW that is excluded from this analysis. Currently, there is a well-functioning infrastructure for HW treatment in incinerators located on the hospital premises. The sub-streams that are included in the calculation are characterized by the potential processing method, as indicated in Figure 1. The division is as follows [2]:

HW incinerator (163 waste catalogue codes).
Demulsification unit (10 waste catalogue codes).
Biodegradation unit (19 waste catalogue codes).
Stabilization unit (115 waste catalogue codes).
HW incinerator or stabilization unit (21 waste catalogue codes).
Demulsification unit or stabilization unit (2 waste catalogue codes).
Neutralization unit or stabilization unit (32 waste catalogue codes).
Biodegradation unit or stabilization unit (11 waste catalogue codes).

The "Waste Management Information System" database, which is run by CENIA for the Ministry of Environment of the CR [38], is used for generating forecasts. The database contains waste generation and processing data in Czech municipalities following the waste catalogue. Data from the database are validated before the calculations and pre-processed (false data are eliminated, values according to the information from regional authorities are added). Forecasting future commodity production in hundreds of nodes represents an essential input for many applications of supply-chain models with spatially distributed and uncertain data. A separate study was conducted evaluating these material streams via the forecasting method [3]. The available timelines from 2009 to 2018 for particular sub-streams are entered into the forecasting. A prediction is made for each sub-stream for the years 2025, 2030, and 2035. Each timeline is forecasted using trend analysis for various territorial units and levels and later balanced for consistent forecasts for various territorial units.

Current and forecasted values for sub-streams are given in Table 1 for aggregated data of the CR. Forecasts respect preferred methods in the waste treatment hierarchy. In the case of the HW material streams, the design of the infrastructure's capacity is a subject of forecasting (this falls under the disposal category). HW undergoing a more preferred treatment method is not included in the optimum HW treatment network calculations. Data in Table 1 are categorized using current HW production from the "Waste Management Information System" database and the Ministry of Environment of the CR [38]. The amount of HW entering the optimization (HW for treatment data in Table 1) is determined using values in the region where waste undergoing more preferred treatment methods is excluded. The mathematical model works with the following treatment codes [2]:

Table 1. HW sub-streams: Assessment of HW production suitable for optimization.

HW Sub-Stream	2018	2025	2030	2035
Incineration	83,140	84,049	90,799	97,096
Demulsification	0	2	2	2
Biodegradation	323	1192	1140	1063
Stabilization	166,829	153,502	151,599	150,496
Combustion or stabilization	86,097	88,487	94,650	100,283
Demulsification or stabilization	83,721	101,307	110,615	118,732
Neutralization or stabilization	45,553	44,130	46,148	48,132
Biodegradation or stabilization	572,249	410,685	379,229	344,630
Total	1,037,912	883,354	874,182	860,434

Energy recovery of waste (code XR1).

Waste disposal (disposal codes: XD1, XD3, XD4, XD5, XD8, XD9, XD10, XD12, XD13, XD14, excl. XD8 with cat. code 01 05 05, 05 01 03, 05 01 05, 05 01 06, 10 02 11, 13 05 02, and 16 07 08).

Other treatment methods (disposal code XN14, no cat. code 01 05 05, 05 01 03, 05 01 05, 05 01 06, 10 02 11, 13 05 02, and 16 07 08).

The total amount of HW produced is decreasing according to the performed forecast. On the other hand, individual sub-streams show various developments, and the sufficiency of capacities needs to be evaluated separately (with links between sub-streams). Values from the 2030 forecast are used in the optimization.

The distribution of HW processing facilities is displayed in Figure 2. The existing capacity of processing plants is entered into the calculations (the capacity is adjusted according to the particular scenario) [2]. The number of facilities is adjusted for each micro-region such that units in the same micro-region are merged. The plants entering the calculation are the following:

HW incinerators: 23 units with a current total capacity of 117,004 t/a.

Demulsification and neutralization stations: 40 units with a current total capacity of 547,907 t/a.

Biodegradation stations: 84 units with a current total capacity of 2,667,525 t/a.

Stabilization and solidification units: 11 units with a current total capacity of 292,000 t/a.

HW and OW landfills are not directly included in the optimal facility network. HW landfills are included in calculations, but not used in the analysis because of the sufficient capacities with the preferred HW treatment. The capacity for the current amounts of landfilled HW is adequate. The study aims for preferred HW treatment methods (based on the waste treatment hierarchy defined below in Section 4.1). Residual waste from HW treatment plants needs to be considered. The rates of residual waste (based on data from real Czech facilities) related to the input waste weight are presented in Table 2.

Table 2. List of residual waste production rates related to input waste mass.

Waste Treatment Technology	Residual Waste	Residual Waste Production (% Weight of Input Waste)	Residual Waste Final Treatment
Incineration	Bottom ash	20	HW or OW landfill
Incineration	Fly ash	5	Stabilization
Demulsification	Sludge	5	Biodegradation or stabilization
Neutralization	Neutralized sludge	5	Stabilization
Biodegradation	Combustible gas	5	Incineration
Biodegradation	Biodegraded waste	65	HW or OW landfill
Stabilization	Stabilized waste	70	OW landfill
Stabilization	HW	70	HW landfill

4. Optimization

The method reflects the environmental and economic requirements of particular waste treatment methods. The assumptions are applied to HW and residual waste streams produced during the HW treatment (see below).

4.1. Assumptions

The setting of calculation preferences based on the assumptions uses the computational coefficient *K* (the coefficient was applied in the mathematical model, see Section 4.3). The coefficient *K* is similar for all facilities once the distance exceeds 100 km. The transport distance is the critical decisive factor. The waste can be transferred to all preferred and available capacities within the 100 km radius. The distance of 100 km is roughly the average distance between NUTS 3 central cities in the CR, and it is adequate for waste treatment at the NUTS 3 level. The coefficients differ among preferred waste treatment methods for less than 100 km (Table 3). All types of facilities are connected, and all eight types of waste streams are included. The interconnection ensures that the results are complex and individual types of waste are not assessed separately. A total of five preferred relations are set by the coefficient *K*.

Table 3. Coefficient *K* values used to set the computational preferences.

HW Treatment Type	Incineration		Demulsification		Neutralization		Biodegradation		Stabilization	
	<100 km	>100 km	<100 km	>100 km	<100 km	>100 km	<100 km	>100 km	<100 km	>100 km
Incineration	1	10,000	-	-	-	-	-	-	-	-
Demulsification	-	-	100	10,000	-	-	-	-	-	-
Biodegradation	-	-	-	-	-	-	100	10,000	-	-
Stabilization	-	-	-	-	-	-	-	-	10,000	10,000
Combustion or stabilization	1	10,000	-	-	-	-	-	-	10,000	10,000
Demulsification or stabilization	-	-	100	10,000	-	-	-	-	10,000	10,000
Neutralization or stabilization	-	-	-	-	100	10,000	-	-	10,000	10,000
Biodegradation or stabilization	-	-	-	-	-	-	100	10,000	10,000	10,000

The environmental criteria provide preferences among plants (in terms of advantage). Preferences are applied only up to a collection distance of 100 km. The aim is to treat the HW in the region where it was produced. The treatment preference is as follows.

HW incinerator, *K* = 1.
Industrial wastewater treatment, *K* = 100.
Stabilization unit, *K* = 10,000.
OW (non-hazardous), *K* = 1,000,000.
HW landfilling, *K* = 1,000,000.

4.2. Selection of Network Type

It is necessary to select a suitable type of transportation network and its setting to evaluate the task and comply with the requirements set in Section 4.1. The model works with more types of waste that may be treated only in specific facilities. The bipartite graph with the multi-layered structure of the network allows us to mathematically describe these requirements (see Figure 3). The first layer of nodes represents the waste producers. Fictitious nodes in the second layer differentiate various types of waste from particular producers from the first layer. The more types of commodities there are, the more fictitious nodes there are in the second network layer. The third layer contains the locations of all the units, and one node may include more HW treatment units. Further, there are arcs between the produced waste (second layer) and units in the third layer. The network reflects that not every waste stream may enter every unit (see Figure 1).

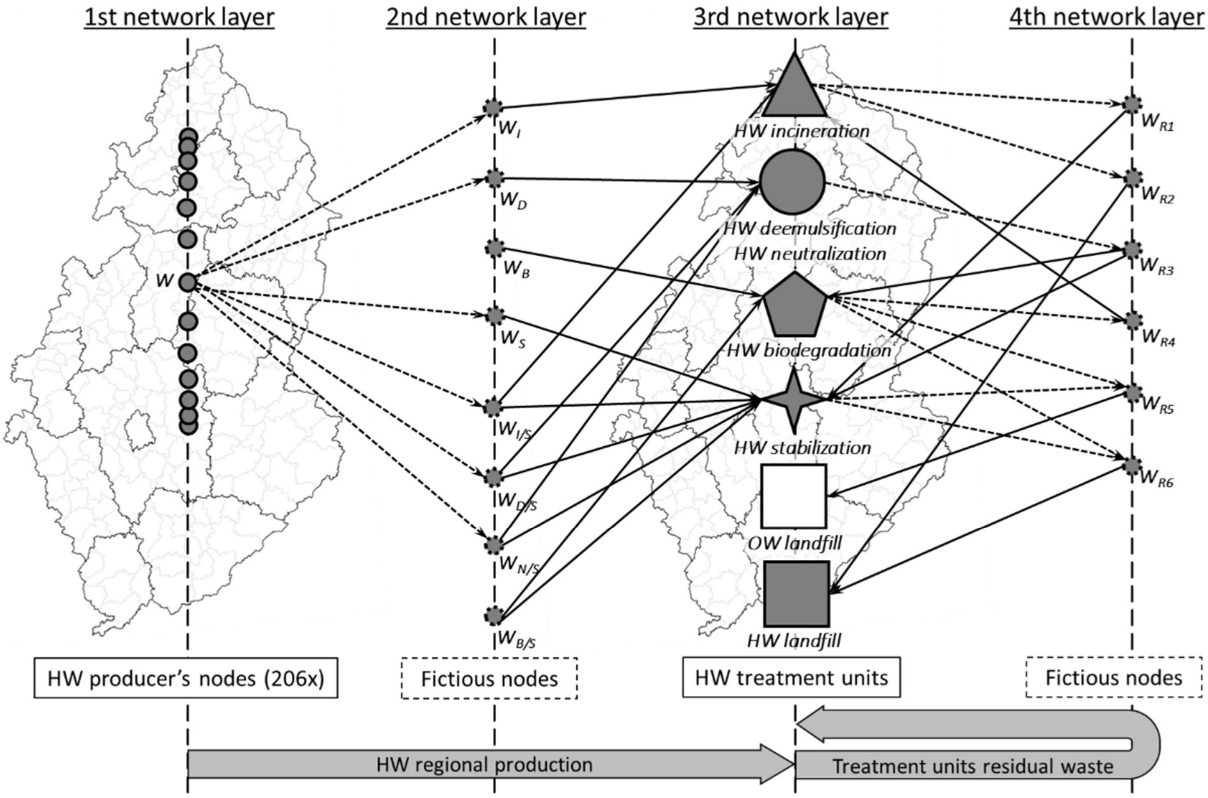

Figure 3. Simplified display of the multi-layered computational network.

In the calculations, a price advantage over other units is granted to all units with arcs of less than 100 km (in the order defined in Section 4.1). The penalization of units based on the environmental criteria and waste treatment hierarchy ensures a preference. Arcs between the second and third layers (and fourth and third layers for the residual waste) allow for the entrance of a particular type of waste into a particular facility and correspond to actual transportation possibilities in the CR. Fictitious arcs between the first and second layers are not necessary. The second layer can be set up as a starting layer in the pre-processing phase.

Another factor of the task is the issue of residual waste, as seen in Table 2. Residual waste is modelled using fictitious nodes in the fourth layer, as seen in Figure 3. The amount of produced residual waste is defined by a transformation vector. The residual waste can be treated afterward, only in a specific way and with a specific waste treatment unit. This is ensured by arcs between the fourth and third layers, as seen in Figure 3.

Compared to the literature research in Section 2, the network type used in this paper is unique in terms of its scope and allows it to work with:

The preference change between economic and environmental criteria based on the transported distance.

Limitations related to the type of waste (type of a unit according to the waste catalogue code).

Production of residual waste for particular regions.

Specific prices of waste treatment for a random pair of a "producer—processing unit".

Changes to transportation prices depending on the distance and amount of waste.

More types of transportation.

4.3. Mathematical Model

First, it is crucial to introduce the model's necessary sets, parameters, and variables. The designation of particular types of waste in Figure 3 in the mathematical model is not needed. The task is conducted for one commodity since the waste streams do not intersect in the network, except the treatment facilities. The set of nodes is divided into subsets for easier orientation in the model.

Sets:

$e \in E$	set of arcs (transportation infrastructure).
$i, j \in I$	set of nodes (waste producer—territorial unit).
$I^P \subset I$	set of nodes in the 2nd network layer (waste producer—territorial unit).
$I^T \subset I$	set of nodes in the 3rd network layer (HW treatment units—territorial unit).
$I^R \subset I$	set of nodes in the 4th network layer (residual waste—territorial unit).

Parameters:

$A_{e,i}$	incidence matrix of transportation infrastructure, describes the existence of the arc between the second and third layers of the network, [-].
$B_{i,j}$	incidence matrix of residual waste, describes the connection between the third and fourth layers of the network, [-].
C_i^{MAX}	maximum available capacity of the unit [t/a].
H_i	coefficients of waste transformation, describes the amount of formed residual waste, [-].
K_e	weight penalization, describes the treatment preference, [EUR/t].
V_e	sum of transportation and processing costs, [EUR/t].
P_i	waste production in production nodes, [t/a].

Variables:

c_i	used capacity of the unit, [t/a].
r_i	output (residuals) from the non-final units, [t/a].
x_e	waste amount, [t/a].

There are three boundary conditions in the mathematical description due to the structure of the network used. A balance limitation for nodes such as the waste producer (including residual waste) is described in constraint (1). Rules concerning processing particular types of waste in specific units are not necessary for the task due to the bipartite graph. Equations (2) and (3) limit the capacity of treatment units.

$$P_i + r_i + \sum_{e \in E} A_{e,i} x_e < 0, \quad \forall i \in I^P, \forall i \in I^R, \tag{1}$$

$$c_i = \sum_{e \in E} A_{e,i} x_e, \quad \forall i \in I^T, \tag{2}$$

$$c_i \leq C_i^{MAX}, \quad \forall i \in I^T. \tag{3}$$

An option for the transport of output from units that are residual waste r_i, is introduced with fictitious nodes (4th layer in Figure 3). The production of r_i is given by coefficients of waste transformation H_i. Values of H_i comply with Table 2. Thanks to the matrix $B_{i,j}$, it is possible to appropriately set up the residual waste and assign them corresponding treatment methods. It is described in Equation (4).

$$\sum_{j \in I^T} B_{i,j} H_j c_j = r_i, \ \ \forall i \in I^R. \tag{4}$$

Objective function has parameters related to treatment costs, transport, and penalization for the treatment hierarchy defined in Section 4.1. The costs of waste treatment only include weight coefficients with regards to the treatment preference. Therefore, different treatment prices may be implemented as parameters of the transportation arcs since each node (micro-region) has a unique transportation edge with the relevant treatment node. The objective function takes the following form:

$$\text{minimize} \ \sum_{e \in E} V_e x_e + \sum_{e \in E} K_e x_e, \tag{5}$$

where the parameter K_e is a properly adjusted weight function that reflects the preferences of a specific type of HW treatment and edits the preference in units more than 100 km away from the waste producer site (see Section 4.1). The transportation costs are calculated using an in-house computational model, as discussed in [39]. Two important parameters are the major inputs of the calculation: Transport distance and amount of transported waste. Transport distance is the information from an extensive transportation network that is generated in the pre-processing phase. The last condition for proper optimization is the non-negativity of variables, which is ensured by Equations (6) and (7).

$$x_e \geq 0, \ \ \forall e \in E, \tag{6}$$

$$c_i \geq 0, \ r_i \geq 0, \ \ \forall i \in I. \tag{7}$$

5. Results

Calculation of the optimization task involves 206 micro-regions in the CR (206 HW production nodes). The majority of waste types are commonly produced in every region, and rarely are there only two types of waste. In order to present comprehensive and illustrative results of 206 nodes, they are grouped into 14 Czech regions (the level of NUTS 3 regions). The boundaries of 206 micro-regions and 14 NUTS 3 regions are evident in Figure 2, which also shows the distribution of existing waste treatment capacities in the CR.

Network development (see Figure 3) allows working with one type of waste (in terms of mathematical modelling), leading to the incorporation of large amounts of fictitious nodes that include all other types of waste (primary and residual). The transportation task concerns roughly 2000 nodes and circa 90,000 edges. The model was implemented in the GAMS software system using the solver CPLEX 12 [40]. The computational complexity of one scenario took approximately 20 s. Another 30 s was necessary to load the input data (to create the gdx file, etc.). Specific time requirements of the calculation differ, depending on the boundary conditions. The more similar the processing requirements are, the more time-consuming and complex obtaining the solution is.

The direct comparison of HW production and processing capacity (Section 3.2) shows that the processing network for certain sub-streams is transparent. The maximum capacities in this task are increased in various scenarios. The construction of new facilities is, nowadays, impeded by cumbersome legislations and the discontent of the general public [41]. Therefore, expanding the existing facilities seems like a much more plausible option. In this task, current capacities are increased in existing facilities. This paper presents three scenarios mainly related to the increase in inadequate capacities of HW incinerators.

SC1—current processing capacity.
SC2—increasing the processing capacity by 50%.
SC3—unlimited capacities in existing locations.

The HW flow designed for individual treatment plants is described below. The third scenario is considered to determine the optimal capacities. The first scenario is visualized in detail because it represents the most relevant outputs and shows the shortcomings of the current processing infrastructure. This mainly concerns the identification of regions with transport distances above 100 km, which are displayed in the diagram. Other scenarios increase the available capacity in regions, which, after all, leads to treatment in the closest one. Individual scenarios are compared via the processing capacity in regions.

5.1. HW Thermal Treatment

The HW flow for incineration is shown in Figure 4. The distribution of HW production into HW treatment units in the computational task was based only on assumptions discussed in Section 2 and the existence of HW treatment units in the appropriate location. Scenario SC1 identifies regions in the west especially, where the transportation distance is over 100 km. This could be proof of absent capacities or low efficiency of the transportation network. The non-existence of a suitable transportation network may often impede the transport of HW to an otherwise relatively close facility.

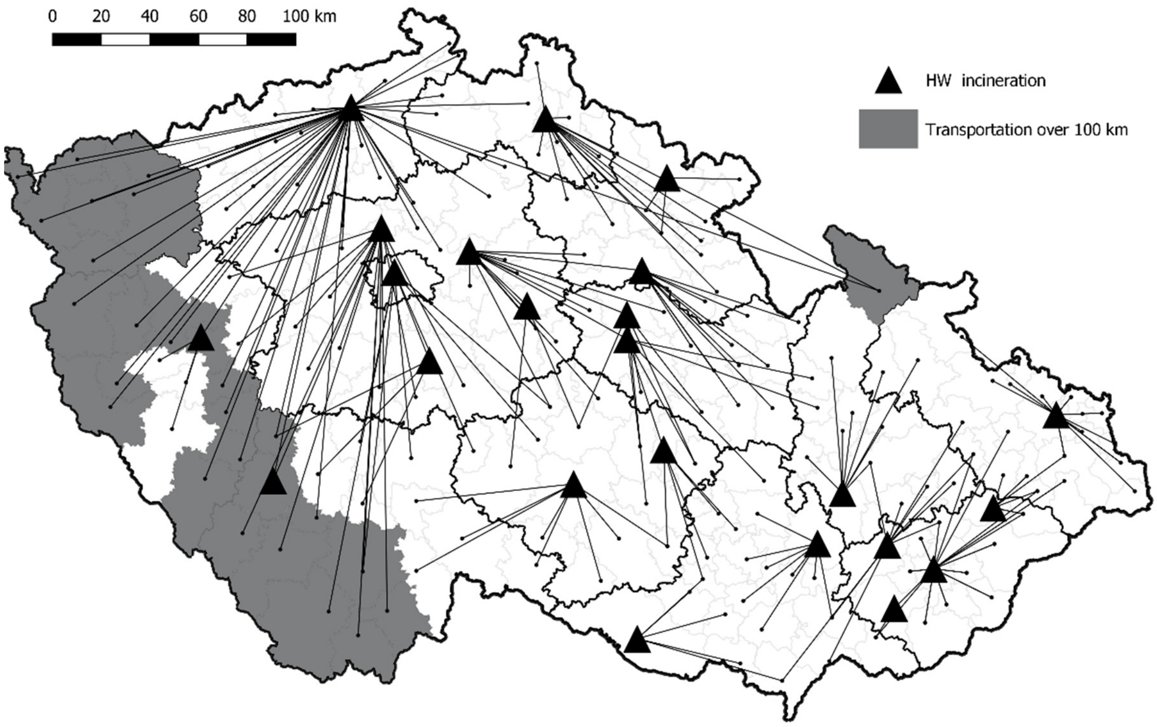

Figure 4. HW flow in scenario SC1 related to incineration with regions where the transportation exceeds 100 km.

From Figure 4, the current capacity of HW thermal treatment does not seem insufficient. On the other hand, it is enough for the sub-stream that can only be incinerated. If the total amount of possible incinerated waste is considered, there is over 180 kt of produced waste and only 117 kt of processing capacity. The insufficiency is proven in Figure 5, where all three scenarios with the used capacity and maximum capacity are compared.

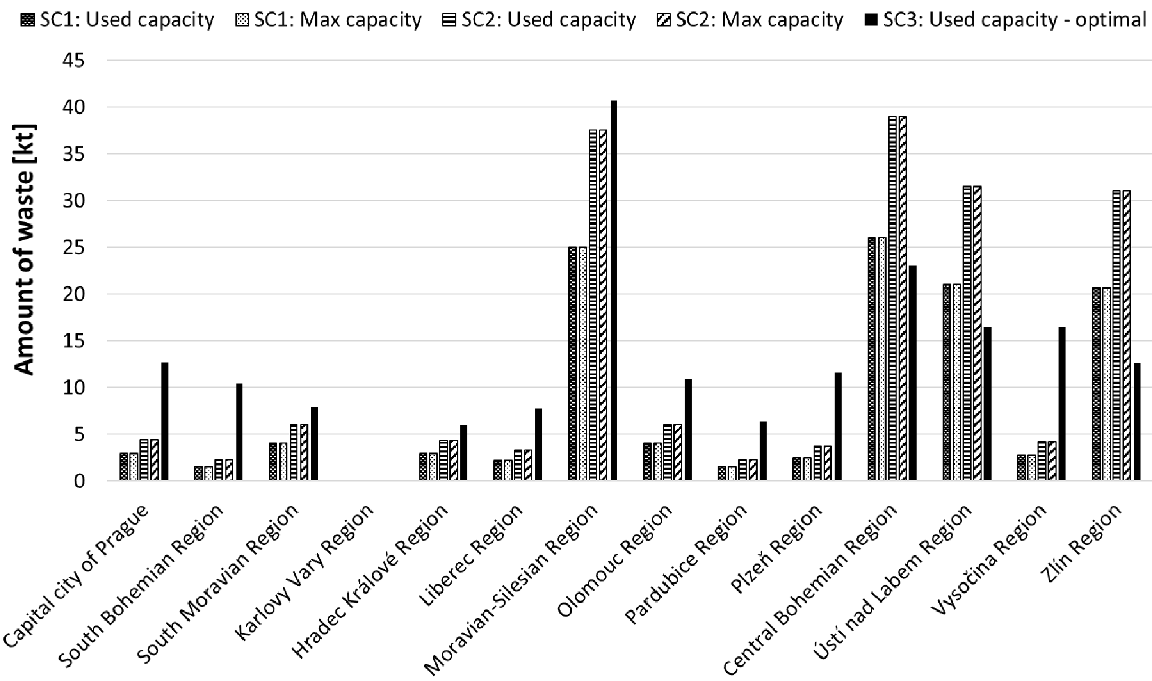

Figure 5. Comparison of HW thermal treatment capacities in three defined scenarios.

The current infrastructure can be evaluated as insufficient, and not even a 50% increase in available capacities can help. The growth should be around 100%. On the other hand, the optimal scenario, SC3, clearly shows that the capacity increase in all incinerators at once can be considered inefficient. Almost all regions have a facility for HW thermal treatment, but only three have a well-established infrastructure to reach self-sufficiency. The capacity should increase in other regions concerning the presented results and suggested capacities.

5.2. Demulsification and Neutralization

The HW flow for demulsification and neutralization is shown in Figure 6, where these two types of treatment are merged (the same location of processing facilities). Obviously, the distribution of 40 units covers the investigated territory well, and only one micro-region in the South Bohemian region must transport HW over 100 km.

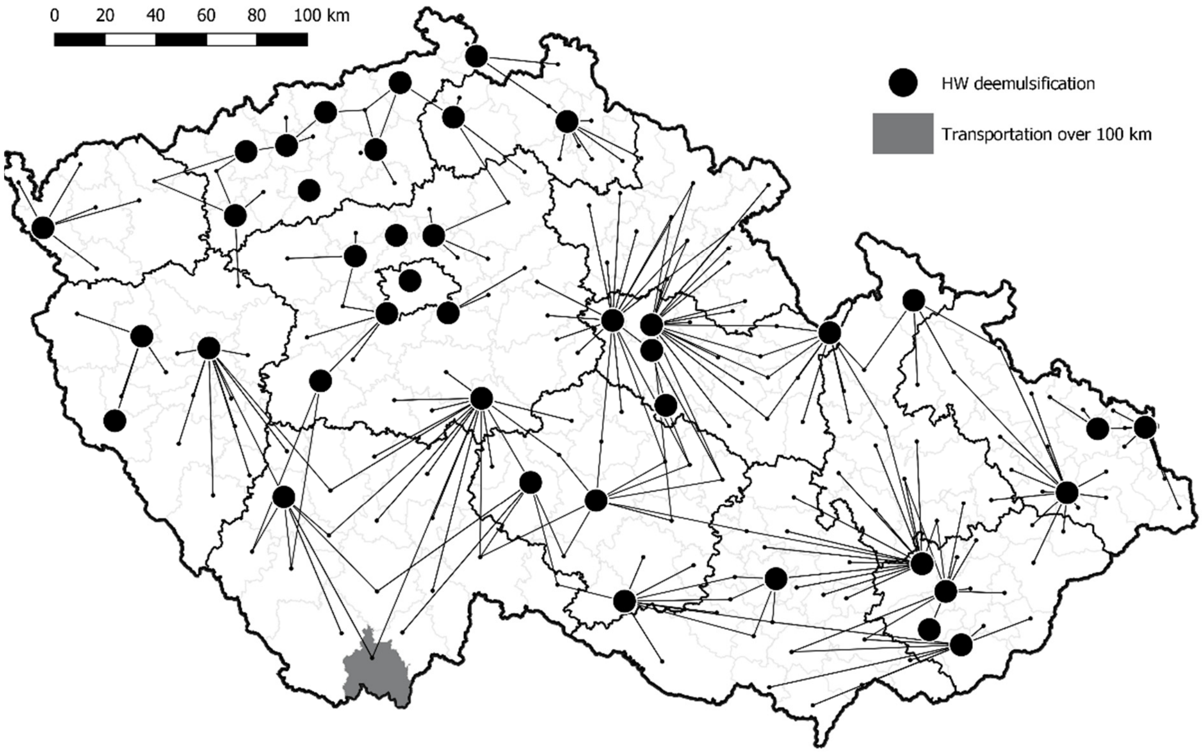

Figure 6. HW flow in scenario SC1 related to demulsification (neutralization) with regions where transportation exceeds 100 km.

The capacities for both types of treatment are compared in the following graphs. The demulsification capacities in regions are visualized in Figure 7, and capacities related to neutralization are shown in Figure 8. The ratio between regions is almost the same in both treatment types. An increase in all regions is unnecessary, and only a few selected regions can expand the processing infrastructure. The processing infrastructure for demulsification and neutralization does not require significant changes, and the capacities can be considered sufficient for the upcoming years.

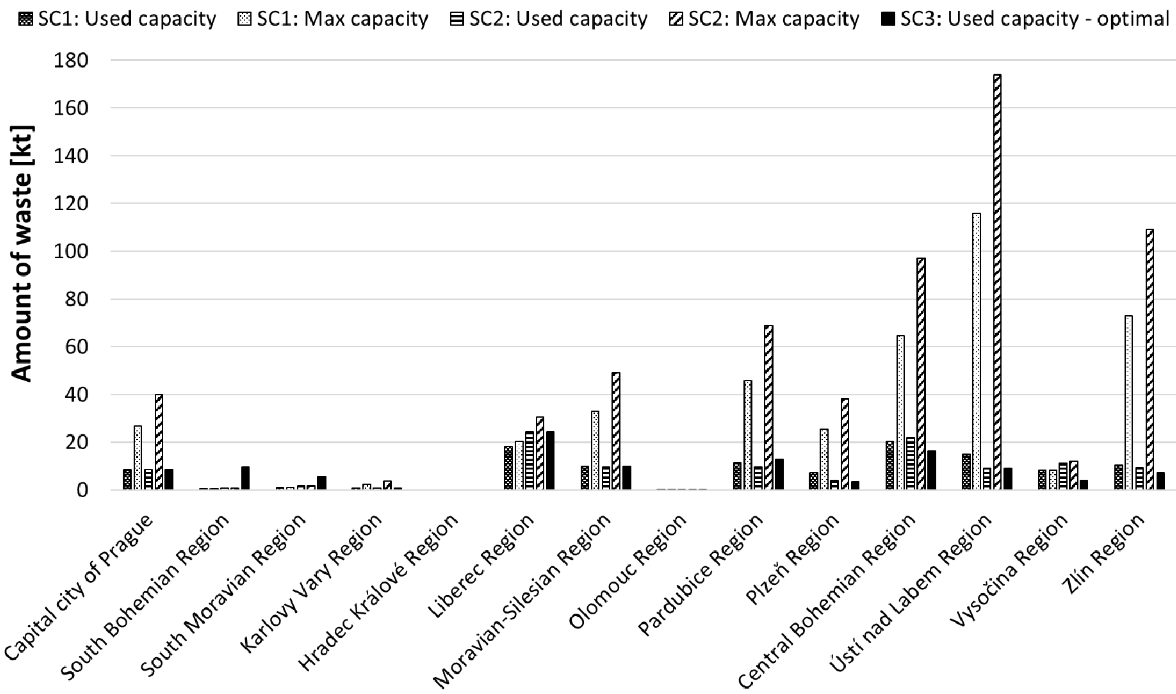

Figure 7. Comparison of HW demulsification capacities in three defined scenarios.

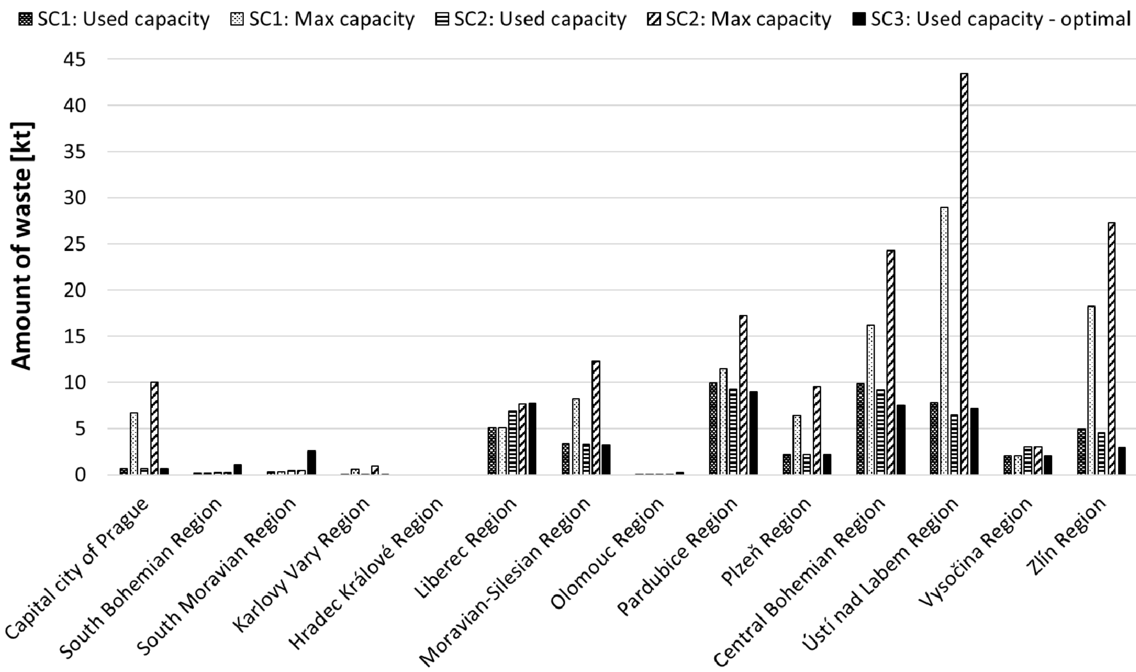

Figure 8. Comparison of HW neutralization capacities in three defined scenarios.

5.3. Biodegradation

The biodegradation infrastructure is oversized for the condition in the CR. The HW flow for biodegradation is shown in Figure 9. The total number of 84 units is sufficient to cover the entire territory without any problems with long transport distances. The comparison of capacities in individual regions is displayed in Figure 10.

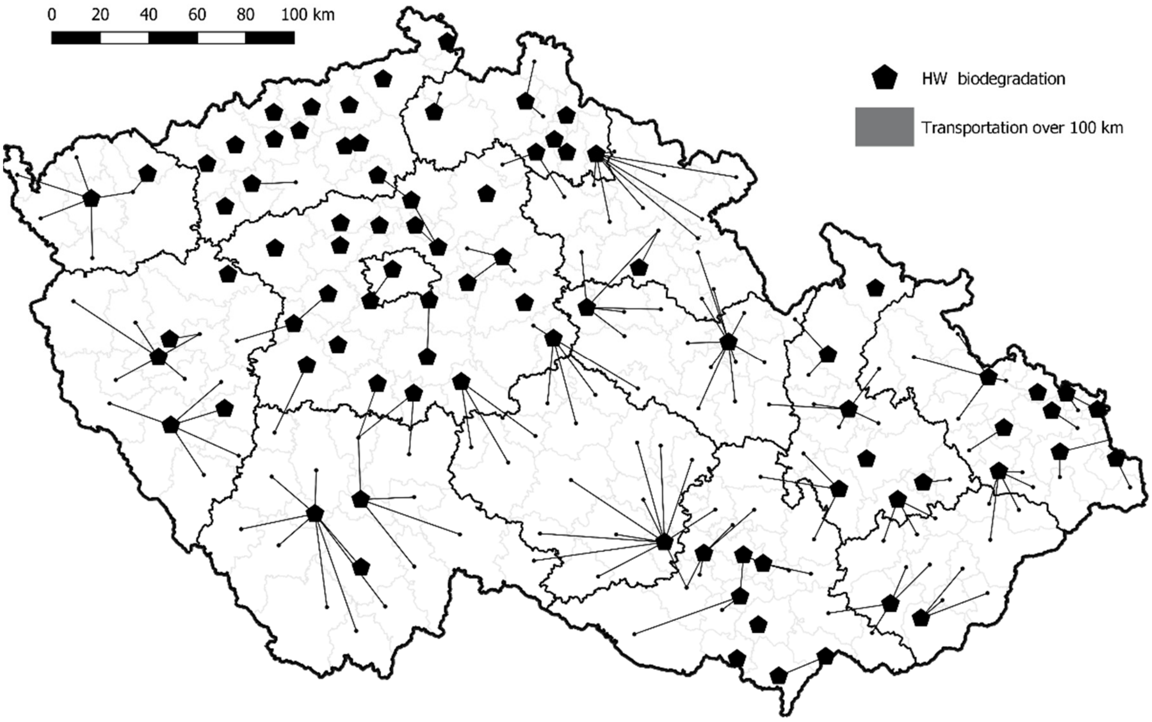

Figure 9. HW flow in scenario SC1 related to biodegradation with regions where transportation exceeds 100 km.

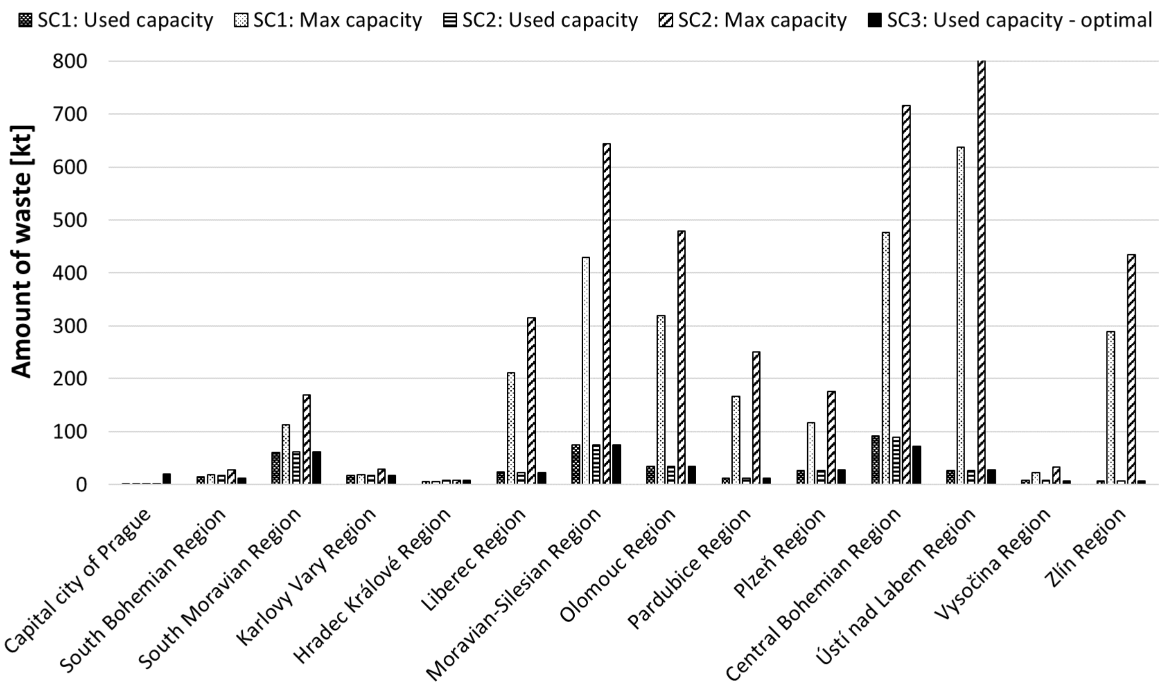

Figure 10. Comparison of HW biodegradation capacities in three defined scenarios.

Insufficiency can be observed only in the case of the capital city of Prague. Biodegradation units usually occupy extensive areas, which cannot be realized in the highly urbanized region. The necessary capacity is located in the surrounding Central Bohemian region. Overall, biodegradation can be considered self-sufficient, and no interventions or changes in the processing infrastructure are needed.

5.4. Stabilization

Figure 11 shows the HW flow determined for stabilization. The transportation distance is over 100 km in almost half of all micro-regions. There are only 11 micro-regions with a stabilization unit. Moreover, the capacity distribution is situated mainly in the northern part of the territory, which justifies long distances for transportation. The comparison of capacities in individual scenarios is shown in Figure 12.

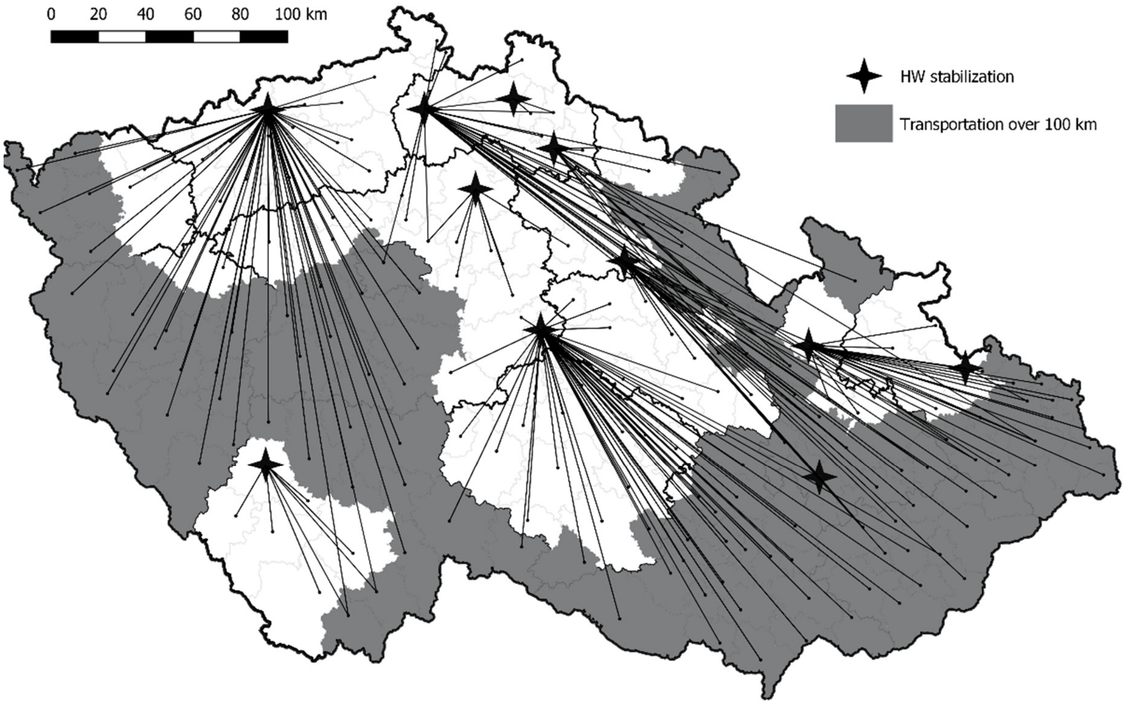

Figure 11. HW flow in scenario SC1 related to stabilization with regions where the transportation exceeds 100 km.

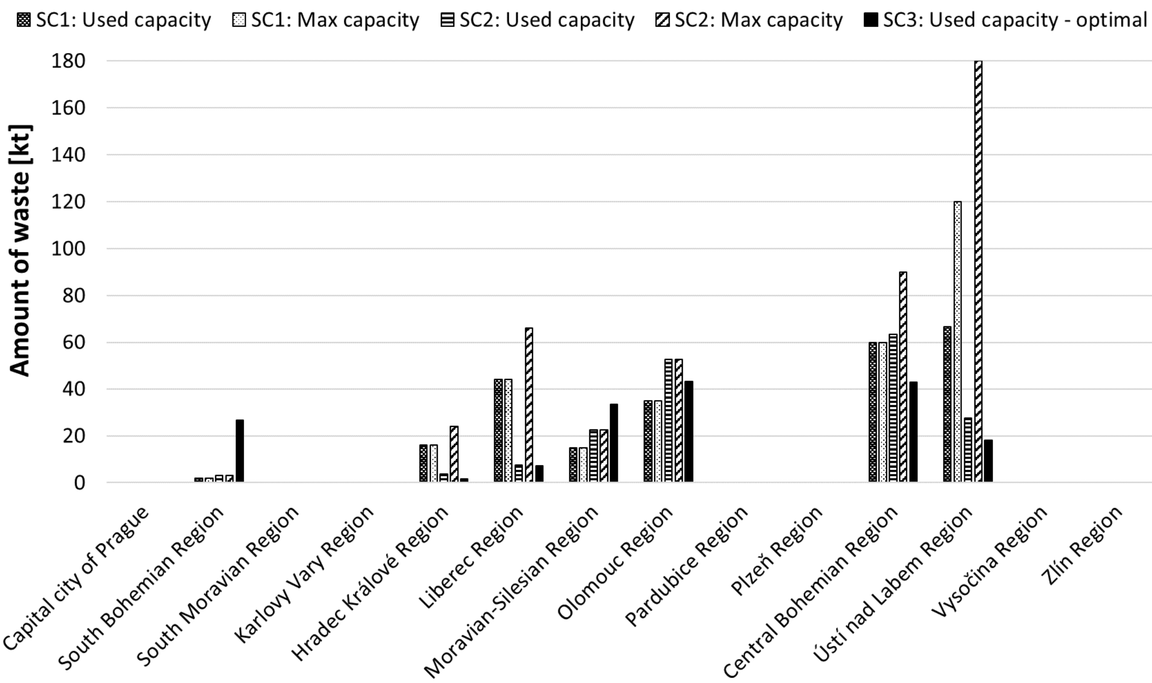

Figure 12. Comparison of HW stabilization capacities in three defined scenarios.

Stabilization capacities should be increased significantly in the eastern part of the CR. There are only three units with a capacity of around 50 kt/a. The increase in capacities can be evaluated as insufficient, and many more facilities must be established for an appropriate processing infrastructure. On the other hand, the stabilization units are significantly influenced by an inadequate capacity for the most preferred thermal treatment. The substream "incineration or stabilization" must be almost completely stabilized. Therefore, the extension of HW incineration can lead to a sustainable stabilization infrastructure with only a slight increase in capacities in some regions. This fact can be observed in Figure 12, where the optimal scenario, SC3, indicates an excessive capacity in some regions. However, a denser network with more stabilization units is still recommended.

6. Results Summary and Recommendations

The results of the optimization task were presented and discussed in the previous section. The main conclusions of the analysis concerning current infrastructure are the following:

The current capacity of demulsification, neutralization, and biodegradation are adequate.

The HW thermal treatment represents the most preferred option, and the capacity should be increased. There is insufficient capacity for this type of treatment, and a 50% increase in the operation of already-existing facilities is still not enough. The recommendation is to increase the total incineration capacity by 100%, but in proportion to the needs of each region.

The enormous lack of capacity and transportation distance is identified in the case of stabilization. Half of all considered micro-regions transport HW over 100 km. This is mainly caused by the insufficient capacity of HW thermal treatment, which means that the remaining waste must be stabilized. On the other hand, the infrastructure of stabilization should be redesigned due to the non-uniform distribution of capacities.

Overall, HW treatment infrastructure should be redesigned or extended, especially in the Moravian and Silesian regions. There are only a few facilities for HW treatment, in addition to the smallest capacity per annum.

The transportation distance of HW is currently 15% over 100 km, which does not meet the regional self-sufficiency goal. A histogram of the transportation distance in all scenarios is shown in Figure 13. It is clear that an optimal increase in individual capacities almost removes transport over 100 km. Without new facilities, self-sufficiency cannot be reached within a defined distance.

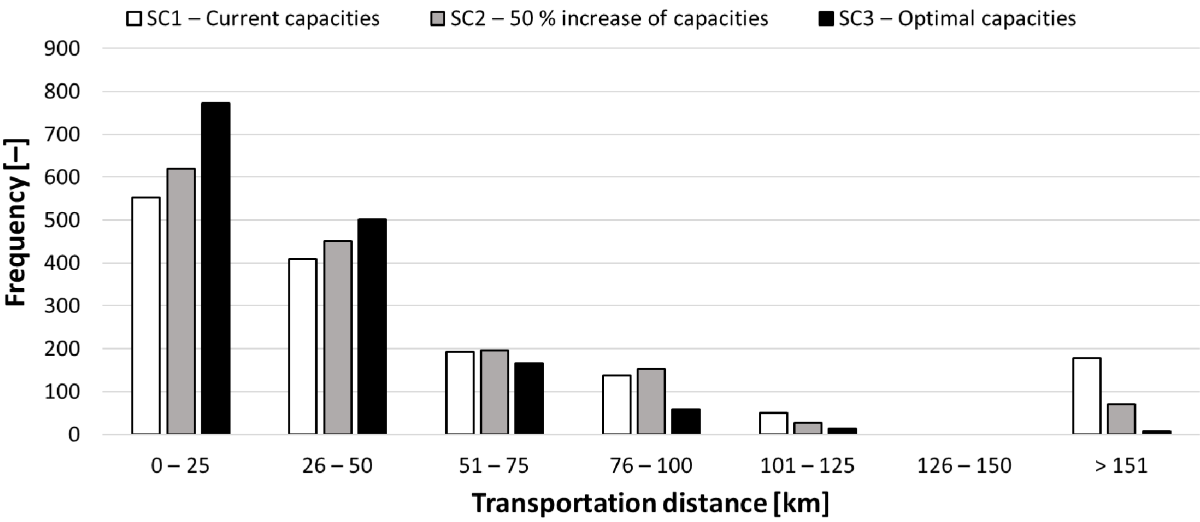

Figure 13. Histogram of transportation distance in individual scenarios.

7. Conclusions

This paper describes the application of a unique, complex approach to modelling future WM changes related to HW production and treatment. An optimal waste treatment facility network is proposed for different types of HW production in the CR. The uniqueness of the solution lies primarily in the scope of the task, which is further enhanced by concurrent analysis of more types of waste and treatment units. The amount of real data regarding waste production and treatment may also be considered remarkable. Due to the scope and complexity of the tasks, a special transport network based on a bipartite graph is designed, allowing us to optimize residual waste streams. The presented approach includes the HW treatment hierarchy, which is modified according to the transport distance.

This paper discusses the analysis of infrastructure for HW treatment, which included forecasts of WM in the upcoming years. The simplest way to make up for the current inadequate capacities is to promote an increase in existing HW incinerator capacities. This option is assessed in two scenarios with different levels of capacity increase. Further, the paper identifies locations where transport distances between HW production sites and facilities are too large. These locations fail to comply with the principle of regional self-sufficiency, which is visible in the presented maps. The results point to insufficient HW thermal treatment and stabilization capacities, which should be increased by 100% to reach self-sufficiency within these regions.

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