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Economic Optimization of Medical Waste Treatment: A Case Study of Podlaskie Province

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1. Introduction

The term medical waste includes all the waste generated within health-care facilities, research centres and laboratories related to medical procedures. Between 75% and 90% of the waste produced by health-care providers is comparable to domestic waste and usually called "non-hazardous" or "general medical waste". It comes mostly from the administrative, kitchen and housekeeping functions at health-care facilities and may also include packaging waste and waste generated during maintenance of health-care buildings (Chartier et al. 2012, Kocak et al. 2017). The remaining 10-25% of health-care waste is regarded as "hazardous" and may pose a variety of environmental and health risks. Effective and efficient healthcare waste management is required to reduce the amount of hazardous and infectious wastes produced in the hospitals. Effective healthcare waste management not only helps the community and people, but also helps the hospitals and can bring in financial benefits along with health and environmental benefits (Marczak 2016, Michlowicz 2012, Teleszewski et al. 2018, Windfeld et al. 2015).

Medical waste management is a major challenge for cities of developing nations. Selecting the best treatment technology for medical waste can be regarded as a complex multi-criteria decision making issue involving a number of alternatives and multiple evaluation criteria. Minoglou et al. (Mingolou et al. 2017) developed the dependence of the healthcare waste (HCW) generation factor on several social-economic and environmental parameters. The statistical analysis included the examination of the normality of the data and the formation of linear multiple regression models to further investigate the correlation between those indices and HCW generation factors. Pearson and Spearman correlation coefficients were also calculated for all pairwise comparisons. Delmonico et al.

(Delmonico et al. 2018) has proposed to investigate the barriers in healthcare waste management and their relevance. For this purpose, this paper analyses waste management practices in two Brazilian hospitals by using case study and the Analytic Hierarchy Process method (AHP). The barriers were organized into three categories - human factors, management, infrastructure and the main findings suggest that cost and employee awareness were the most significant barriers. Shi et al. (Shi et al. 2009) has presented a Mixed Integer Linear Programming model with minimizing costs for medical waste reverse logistics networks. The total costs for reverse logistics include transportation cost, fixed cost of opening the collecting centers and processing centers and operation cost at these facilities over finite planning horizons. An improved genetic algorithm method with a hybrid encoding rule is used to solve the proposed model. Hu et al. (Hu et al. 2002) has presented a cost-minimization model for a multi-time-step, multi-type hazardous-waste reverse logistics system. A discrete-time linear analytical model is formulated that minimizes total reverse logistics operating costs subject to constraints that take into account such internal and external factors as business operating strategies and governmental regulations. Mantzaras et al. (Mantzaras et al. 2017) has presented an optimization model to minimize the cost of an accumulation, transport, treatment and disposal system for infectious medical waste (IMW). The model calculates the optimum locations of the treatment facilities and transport stations, their capabilities (Mg/d), the number and capacities of all waste accumulation, transport and their optimum transport path and the minimum IMW management system cost. For the execution of the optimization routine, two completely different software were used and the results were compared. The first software was Evolver, which is based on the use of genetic algorithms. The second one was Crystal Ball, which is based on Monte Carlo simulation. Lu et al. (Lu et al. 2016) has proposed a new hybrid decision making approach combining interval 2-tuple induced distance operators with the technique for order preference by similarity to an ideal solution (TOPSIS) for tackling HCW (Health-care waste) treatment technology selection problems with linguistic information. The proposed interval 2-tuple induced TOPSIS (ITI-TOPSIS) can not only model the uncertainty and diversity of the assessment information given by decision makers, but also reflect the complex attitudinal characters of decision makers and provide much more complete information for the selection of the optimum disposal alternative.

This paper describes the optimization studies aime dat analysing the impact of the parameter described by the discount factor on the cost of the system and its structure.

2. Case study

In this paper, the optimization model of the transport and disposal of medical waste is presented in the dynamic version, taking into account expected changes of input and output parameters of the waste management system as well as its status in given periods of time.

This paper usues the optimization model of disposal and treatment of municipal waste (Biedugnis et al. 2003), as well as a computer software MRGO+ (Model for Regional Waste Management), through which the model was implemented. It has been verified by the author and adapted to the needs of the proposed model to optimise the disposal and treatment of medical waste on the example of the Podlaskie Province.

The scope of operational research carried out under the optimization study was divided into two stages of optimization calculations with assumed technical and economic parameters of the system. In the first stage, the lowest cost of functioning of the analysed system was generated, whereas in the second one the influence of the input parameter of the system, i.e. the discount factor on the economic efficiency index (E) and the spatial structure of the system was determined.

The object of optimization studies were the influence of the input parameter of the system, i.e. the discount factor on the economic efficiency index (E) and the spatial structure of the medical waste system was determined.

18 sources of waste generation and accumulation (hospitals) within the studied area of the Podlaskie Province were selected for the analysis after taking into account the above mentioned assumptions and environmental conditions. The study also included: four intermediate objects (medical waste incinerators), respectively: IF1 (Suwalki), IF2 (Lomza), IF3 (Bialystok) and IF4 (Hajnowka), where pyrolytic decomposition process of waste will take place, and four end objects (respectively FF1, FF2, FF3, FF4) - areas for temporary storage of post-process waste from the incineration process located in the area of waste incineration facility. The model did not include restrictions on the capacity of intermediate and end objects (Walery 2017).

The scope of operational research carried out in the framework of the optimization study was divided into successive stages in order to present options of the proposed model:

Stage I – includes optimization calculations, assuming fixed technical and economic parameters. Sequence 1, made in this stage, was also a comparative course – a benchmark for other solutions and obtained results to compare.

Stage II – included a number of additional cours aimed at determining the impact of the model input parameters of the system on the indicator of expenses of economic efficiency index (E) and the spatial structure of the system (system location of objects and their associated waste disposal routes).

The following input data were taken into account:

- economic parameters describing the system (waste transport unitary costs, inflation and discount factor),
- economic parameters describing the objects of the system (capital and operating costs),
- the size reduction of medical waste in the system of indirect objects expressed in the form of the output factor of the process – wwp [%],
- the planned time horizon [t], (duration of model process) (Walery 2017).

The data relating to the costs of transport, investments and operation of the system objects, necessary for optimisation calculations, derived from existing plants, located in the model region. The calculation was performed by the unit cost of the work presented in Biedugnis et al. (Biedugnis et al. 2003) taking into account the current prices and fees. The cost of medical waste removal from the source unit to the disposal site, with the adopted technical and operational conditions is K_{ij} = 9.57 PLN, and when expressed in unit cost of 1 ton of transport per 1 minute (k) = PLN 1.33/t/min.

The economic efficiency calculations of the method were presented in the work by Biedugnis et al. (Biedugnis et al. 2003) whose dynamic model related to inflation and discounting of the annual capital and operating costs in each model period. Transport costs are also discounted and adjusted for inflation.

The discount factor and inflation factor of the capital cost (Z_N^t) and the current cost (Z_E^t) for the t model period can be expressed (Biedugnis et al. 2003):

$$Z_N^t, Z_E^t = \sum_{i=1}^{m_t} (d_t \cdot q_t)^i \tag{1}$$

where:
$d_t = 1/(1+r)^i$, discounting factor,
$q_t = 1/(1+e)^i$, inflation factor,
r – discount factor,
e – inflation factor.

Finding the best solution from the point of view of economic efficiency index was set as a priority. The above mentioned criterion takes into account both the selection of waste treatment technologies, as well as search for the best relationship between the location of objects used and the associated waste transport route network, depending on the amount of waste transported in each model periods.

3. Results and discussion

Calculations were carried out in the following courses:

Stage I – course 1 – the course like in the solution with the following parameters: duration of model period, respectively $t_1 = 5$ and $t_2 = 15$ years, the unitary cost of transportation of medical waste in the first and second model period, respectively, 1.33 and 0.44 PLN/Mg/min, the level of reduction of medical waste in the intermediate facilities expressed as a coefficient of the process output, wwp = 10%.

Stage II – in courses 2-5 – the impact of changes in the discount factor on the cost of the system and its spatial structure was examined. The discount factor has a significant impact on the cost of operating the system and, consequently, the change in the economic efficiency index (E).

As a result of optimization calculations for the course 1 (Stage I) of the pre-established model system of the 26 facilities (18 – the source of the medical waste, 4 – incineration, 4 – storage of hazardous waste, 55 – possible routes for waste transport), the was a number of facilities selected in model periods I and II: 3/3 incinerators, 3/3 of the landfills and 21/21 waste transport routes, in consequence minimizing the cost of the system. Process levels in intermediate and final facilities in each model period for Stage I are presented in Table 1.

Table 1. The level of processing activities of intermediate and final objects for the 1stcourse [Mg/year]

System facilities	Process	Processing activity level [Mg/year]	Duration of model studies I = 5 years, II = 15 years
IF1	incineration	140.400	I
IF1	incineration	148.800	II
IF2	incineration	210.400	I
IF2	incineration	222.400	II
IF3	incineration	434.400	I
IF3	incineration	450.900	II
FF1	storage	14.040	I
FF1	storage	14.880	II
FF2	storage	21.040	I
FF2	storage	22.240	II
FF3	storage	43.440	I
FF3	storage	45.090	II

For courses 2, 3, 4 and 5 – the impact of change of the discount factor on the final solution has been studied. This change was not accompanied by any modifications in the structure of the system or levels of processing activities in intermediate and final facilities in particular model periods.

The system layout of the system objects, the amount of transported waste and the related transport routes are shown in Fig. 1. The highest value of the economic efficiency index E = 2332.60 PLN/Mg was obtained (increase E by approx. 46% in relation to course 1) with the assumed discount factor = 0.980 (course 2), while for the discount factor = 0.909 (course 5) the lowest value of the economic efficiency index was E = 1164.20 PLN/Mg (E decrease by approx. 27% in relation to course 1).

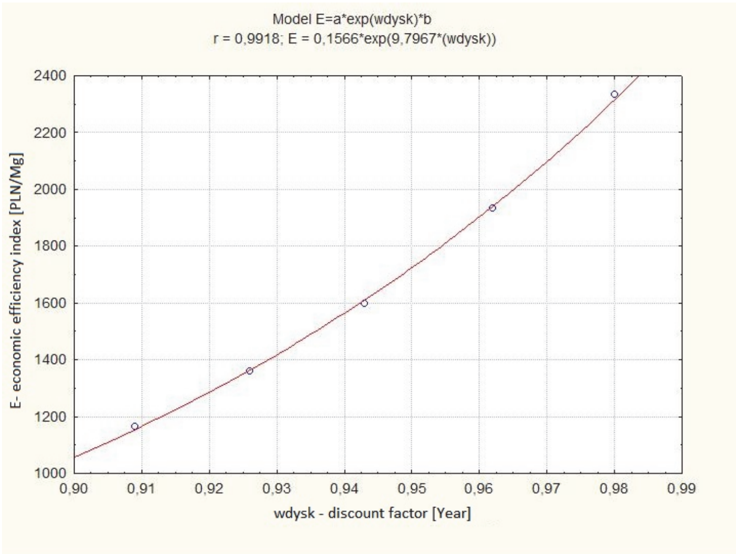

Fig. 1. Correlation of the economic efficiency index (E) and discount factor

4. Conclusions

This paper presents the optimisation model of the medical waste disposal and neutralisation system in the dynamic version, taking into account the expected changes in the input and output parameters of the waste management system and the status of the system at specific time intervals. This allows the system to be considered as an investment project, i.e. assuming the implementation of a system from scratch, modernisation or a project including modernisation of existing facilities as well as implementation of new system solutions, enabling application of the solution with the lowest total system cost.

The dynamic model includes inflation and discounting of annual capital expenditures and current costs. These costs are included in the model as time-varying values for subsequent model periods, i.e. with the assumed duration of the first and second model period respectively: $t_1 = 5$ years and $t_2 = 15$ years and *wwp* (input parameter) = 10%. Transport costs, like capital and current costs, are discounted and include inflation.

Taking into account the discount factor causes a significant change in the system's operating costs and consequently a change in the economic efficiency index (E). It does not, however change the spatial structure of the system, i.e. the location scheme of the system objects, the quantity of waste transported and the associated waste transport routes. With the assumed discount factor in the range of 0.980 to 0.909, the highest cost of the system was achieved at the level of E = 2332.60 PLN/Mg (increase of economic efficiency index E by ca. 46% in comparison with course 1, and discount factor = 0.980). The lowest cost of the system was achieved at the level of E = 1164.20 PLN/Mg (increase of economic efficiency index E by ca. 27% in comparison with course 1, and discount factor = 0.909).

The increase in the discount factor is accompanied by an increase in the economic efficiency index (E), which can be described by the following correlation:

$$E(wdysk) = 0.1566 * \exp(9.7967 * (wdysk) \ [\text{PLN/Mg}]$$

The final decision about choosing a variant of system operation does not have to coincide with the obtained solution being the result of modelling. The obtained results of optimisation studies should be treated as an aid in decision-making, taking into account a number of complex environmental conditions and the dynamics of economic factors and the socio-political conditions.

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Abstract

This paper describes the optimization studies aime dat analysing the impact of the parameter described by the discount factor on the cost of the system and its structure. The study was conducted on the example of the analysis of medical waste management system in north-eastern Poland, in the Podlaskie Province. The scope of operational research carried out under the optimization study was divided into two stages of optimization calculations with assumed technical and economic parameters of the system. In the first stage, the lowest cost of functioning of the analysed system was generated, whereas in the second one the influence of the input parameter of the system, i.e. the discount factor on the economic efficiency index (E) and the spatial structure of the medical waste management system was determined. With the assumed discount factor in the range of 0.980 to 0.909, the highest cost of the system was achieved at the level of 2332.60 PLN/Mg (increase of economic efficiency index E by ca. 46% in comparison with course 1, with discount factor = 0.980); furthermore, discount factor = 0.909 produced the lowest value of the economic efficiency index, i.e. E = 1164.20 PLN/Mg (a decrease of E by ca. 27% in comparison with course 1).

Keywords:
medical waste, transport, disposal of medical waste, discount factor,
economic efficiency index

Optymalizacja ekonomiczna systemu przetwarzania odpadów medycznych: studium przypadku województwa podlaskiego

Streszczenie

W artykule opisano badania optymalizacyjne, których celem była analiza wpływu parametru opisanego poprzez współczynnik dyskontowy na koszt funkcjonowania systemu i jego strukturę. Badania przeprowadzono na przykładzie analizy systemu gospodarki odpadami medycznymi w północno-wschodniej Polsce, w województwie podlaskim. Zakres badań operacyjnych, wykonany w ramach studium optymalizacji został podzielony na dwa etapy obliczeń optymalizacyjnych z założonymi parametrami techniczno-ekonomicznymi systemu. W pierwszym etapie wygenerowano najniższy koszt funkcjonowania analizowanego systemu, natomiast w drugim określono wpływ parametru wejściowego systemu, tj. współczynnika dyskontowego (wdysk) na wskaźnik efektywności kosztowej (E) oraz strukturę przestrzenną systemu gospodarowania odpadami medycznymi. Przy założonym współczynniku dyskonta w przedziale od 0,980 do 0,909, najwyższy koszt systemu został osiągnięty na poziomie 2332,60 zł/Mg (wzrost wskaźnika efektywności kosztowej E o ok. 46% w porównaniu z przebiegiem 1, przy założonym wdysk= 0,980), natomiast przy wdysk = 0,909 osiągnięto najniższą wartość wskaźnika efektywności kosztowej E = 1164,20 zł/Mg (spadek E o ok. 27% w stosunku do przebiegu 1).

Słowa kluczowe:
odpady medyczne, transport, unieszkodliwianie odpadów medycznych,
współczynnik dyskontowy, wskaźnik efektywności kosztowej