LOGISTICS NETWORK DESIGN FOR HEALTH-CARE WASTE

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Abstract: *Health-care waste represents, generally speaking, all the waste generated by healthcare facilities, laboratories, biomedical research facilities, etc. If health-care waste isn't properly treated and safely disposed of, it poses a serious risk for disease transmission among all involved actors in health-care waste management as well as the population in the vicinity of locations where health-care waste is inadequately disposed of. This paper presents an approach for health-care waste logistics network design. The aim of the proposed model is to determine the locations of collection and treatment centers for health-care waste, which is tested on a real-scale example for Belgrade city.*

Keywords: *health-care waste, logistics network, facility location.*

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1. INTRODUCTION

Health-care waste (HCW) represents waste generated in healthcare institutions such as hospitals, dental practices, veterinary clinics, laboratories, etc., regardless of its composition, characteristics and/or origin. About 85% of the HCW produced is non-hazardous generated from the administrative, kitchen and housekeeping functions of health-care facilities, while the remaining 15% of HCW is hazardous and can pose a number of health and environmental risks (WHO, 2017). Hazardous HCW includes infectious waste, pathological waste, sharps waste, chemical waste, pharmaceutical waste, cytotoxic waste and radioactive waste. If non-hazardous waste is not segregated at the point of generation, it must be classified and treated as hazardous waste, meaning that the quantity of waste categorized as hazardous is unnecessarily much higher than it needs to be – increasing not only the environmental impacts of disposal methods, but also the financial costs of disposal and treatment (HCWHE, 2022). For example, the number of new infections of hepatitis B, hepatitis C, and HIV caused by contaminated syringes have been 21 million, 2 million, and 260,000, representing almost 32%, 40%, and 5% of all new infections, respectively (WHO, 2018). Hence, it is necessary to establish a system for proper management and treatment of HCW, in order to minimize risk for involved parties (health-care workers, waste handlers, etc.). The risk associated with inadequate

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management of HCW usually regards exposure to infections, toxic effects and injuries. Also, the response to the COVID-19 pandemic has accelerated the demand, use, and disposal of HCW, especially discarded personal protective equipment (PPE) and single-use plastics (Singh et al, 2022).

The first activity in HCW management is the segregation of HCW based on its characteristics. The segregation of HCW at the point of generation through appropriate waste containers reduces the risk associated with HCW. WHO recommended a segregation and collection scheme based on a uniform color coding system (Table 1) which provides a visual indication of the potential risk posed by the HCW in the container and makes it easier to put waste items into the correct container and maintain segregation during transport, storage, treatment and disposal (WHO, 2017).

Table 1. A uniform color coding system for HCW (WHO, 2017)

Waste categories	Markings and container color	Container type	Collection frequency
Infectious waste	Yellow with biohazard symbol (highly infectious waste should be additionally marked *HIGHLY INFECTIOUS*	Leak-proof strong plastic bag placed in a container (bags for highly infectious waste should be capable of being autoclaved)	When three-quarters filled or at least once a day
Sharp waste	Yellow, marked *SHARPS* with biohazard symbol	Puncture-proof container	When filled to the line or three-quarters filled
Pathological waste	Yellow with biohazard symbol	Leak-proof strong plastic bag placed in a container	When three-quarters filled or at least once a day
Chemical and pharmaceutical waste	Brown, labeled with appropriate hazard symbol	Plastic bag or rigid container	On-demand
Radioactive waste	Labeled with a radiation symbol	Lead box	On-demand
General waste	Black	Plastic bag inside a container or container which is disinfected after use	When three-quarter filled or at least once a day

Choice of treatment method depends on local conditions and involves consideration of available resources including technical expertise, relevant national regulations and requirements, waste characteristics and volume, technical requirements for installation, operation and maintenance of the treatment system, safety and environmental factors and cost considerations (WHO, 2017). Treatment methods for HCW are presented in Table 2.

Table 2. HCW categories and treatment methods (The Global Fund, 2020)

Waste categories	Treatment methods
Infectious waste	Infectious waste can be incinerated or can be treated using thermal, chemical, biological and/or irradiative techniques. Treated wastes can then be disposed of in a sanitary landfill. Autoclaving is the most widely practiced method of infectious waste treatment where it is available. Other thermal waste treatment options include microwaving, electrothermal disinfection, frictional heating, and dry heating.
Sharp waste	This waste stream requires the use of secure, rigid, and impenetrable storage bins (ideally color-coded, with a secure one-way needle deposition system).
Pathological waste	Wastes of this type must be either buried or incinerated. Lab cultured pathological wastes should be autoclaved in the lab before disposal. Pathological wastes are often disposed of using the same channels as dead bodies (either incinerated, or buried), and in a health care setting are often handled by the same contractor/department responsible for those. Local culture also has an impact on disposal. In some areas of the world, certain pathological waste, such as placentas must be treated in a culturally appropriate fashion (for instance, placentas being taken home by the mother for home-burial). Some pathological wastes have been bio digested using Anaerobic Digestion (AD) technology.
Chemical and pharmaceutical waste	The health care implications of chemical waste depend on its nature. Less hazardous chemical wastes may be diluted and disposed of using sewage/wastewater drains in countries where there is adequate infrastructure (if allowed by local legislation). Where possible, chemical wastes should be returned to the supplier, or passed on to a licensed contractor, or suitable government body for disposal. Hazardous chemical wastes of different compositions should be stored separately to avoid unwanted chemical reactions. As with chemical waste, the properties of pharmaceutical waste can vary significantly. Ideally, hospitals should avoid allowing pharmaceutical products to expire, by using “just in time” procurement.
Radioactive waste	The treatment and disposal of radioactive waste are generally under the jurisdiction of a nuclear regulatory agency.
General waste	Typically, MSW may be incinerated, landfilled, or sent to a materials recovery facility to have any recyclable content sorted from it.

In the HCW management system, storage areas must have enough capacity to hold the waste generated until it can be disposed of properly which depends on generated quantities as well as the frequency of collection and disposal (The Global Fund, 2020). So, a proper HCW management system should include facilities for storage, transport and treatment of HCW in a safe and sound manner.

Many authors addressed the problem of logistics network design for HCW. Budak and Ustundag (2017) proposed mixed-integer programming model in order to make location-allocation decisions for transport, collection and treatment of HCW. Proposed model was tested on real-scale example in Turkey. Torkayesh et al. (2021) proposed a planning framework for HCW by minimizing the total cost of the system (establishment cost, operational cost, transportation cost) and its environmental pollutants as well as maximizing job creation opportunities. The proposed model was tested on an illustrative example. Yu et al. (2020) proposed a multi-objective mixed-integer linear programming model for reverse logistics network design in case oan f epidemic outbreak. The main goal of the proposed model was to locate temporary warehouses for HCW storage as well as define transportation routes for effective HCW management. The proposed model was tested for a pandemic outbreak of COVID-19 in Wuhan, China. Shi et al. (2009) developed a mixed-integer linear programming model to minimize the total logistics costs of the reverse network for HCW using the genetic algorithm. The subject of this paper is HCW and its disposal, while the aim of this paper is to design a logistics network for the collection, transport and treatment of HCW. The proposed model was tested on real-scale example for the city of Belgrade.

The paper is organized as follows. In Section 2, a description of the problem, as well as a mathematical formulation for logistics network design is described. Section 3 presents the numerical example while concluding remarks are given in Section 4.

2. PROBLEM DESCRIPTION

In this paper, we considered a problem of logistics network design for HCW. The proposed model determines the locations of two types of facilities: HCW collection centers (HCWCCs) and HCW treatment centers (HCWTCs). So, on the first, lowest level of the network, there are generators of HCW such as hospitals, medical centers, dental practices, etc. On the second level of the network, there are HCWCCs while on the third level there are HCWTCs. HCWCCs are facilities with a smaller capacity than HCWTCs in which sterilization of HCW (autoclaving) is performed. Some quantities of HCW from HCWCCs end up in HCWTCs, where the incineration process takes place. In our paper, there are 17 municipalities of Belgrade city as HCW generators, 10 potential locations for HCWCCs and 3 potential locations for HCWTCs. If there are no data for HCW quantities, then usually the quantity of generated HCW can be calculated in two ways. The first one is based on the number of hospital beds and their occupancy, and the second one, which is used in this paper, is based on the average quantity of waste generated per capita and the number of residents of 17 Belgrade municipalities. The following notation was used in order to formulate a mathematical model:

Sets:

$I = \{1,\dots, |I|\}$ - set of candidate locations for HCWCCs;

$J = \{1,\dots, |J|\}$ - set of demand centers;

$K = \{1,\dots, |K|\}$ - set of candidate locations for HCWTCs;

Parameters:

p – an estimated fraction of HCW that can be sent to the HCWTCs;

f_i – fixed costs for an HCWCCs at location $i \in I$;

f_k – fixed costs for a HCWTCs at a location $I \in I$;

b_i - capacity (tonnes) of HCWCCs established at location $i \in I$;

d_j - tonnes of HCW generated in demand center $j \in J$

h_k - capacity (tonnes) of HCWTCs $k \in K$

c_{ij} - transportation cost per tonne of HCW from demand center $j \in J$ to HCWCCs $i \in I$

a_{ik} - transportation cost per tonne of HCW from HCWCCs $i \in I$ to HCWTCs $k \in K$

Decision variables:

y_i - binary variable taking the value of 1 if a HCWCCs is located at location i, and 0 otherwise

s_{ij} - tonnes of HCW transported from the demand center $j \in J$ to the HCWTCs located at $i \in I$

w_{ik} - tonnes of HCW transported from the HCWCCs located at $i \in I$ to the HCWTCs located at $k \in K$

z_k - binary variable taking the value of 1 if an HCWTCs is located at location $k \in K$, and 0 otherwise

The mathematical formulation of the problem is:

$$\text{Min} \sum_i f_i y_i + \sum_k f_k z_k + \sum_i \sum_j c_{ij} s_{ij} + \sum_i \sum_k a_{ik} w_{ik} \tag{1}$$

$$\sum_{j \epsilon J} s_{ij} \leq b_i y_i, \forall i \epsilon I \tag{2}$$

$$\sum_{i \epsilon I} w_{ik} \leq h_k z_k, \ \forall k \epsilon K \tag{3}$$

$$\sum_{i \epsilon I} w_{ik} = p \sum_{j \epsilon J} s_{ij}, \ \forall i \epsilon I \tag{4}$$

$$\sum_{i \epsilon I} s_{ij} = d_j, \forall j \epsilon J \tag{5}$$

$$y_i \in \{0,1\}, \forall i \epsilon I \tag{6}$$

$$s_{ij} \in \{0,1\}, \forall i \epsilon I, \forall j \epsilon J \tag{7}$$

$$w_{ik} \in \{0,1\}, \forall i \epsilon I, \forall k \epsilon K \tag{8}$$

$$z_k \in \{0,1\}, \forall k \epsilon K \tag{9}$$

The objective function (1) minimizes the total costs of the system. Constraint sets (2) and (3) are capacity constraints for HCWCCs and HCWTCs, respectively. Constraint set (4) ensures that an estimated fraction of HCW is transported from HCWCCs to HCWTCs for further treatment. Constraint set (5) ensures that all generated HCW quantities are collected from HCW generators. Finally, constraint sets (6), (7), (8) and (9) define the nature of the variables.

3. NUMERICAL RESULTS

The model has been tested on a case study of the city of Belgrade and its 17 municipalities as HCW generators (Table 1). Fixed costs for HCWCCs are 500 €/day while fixed costs for HCWTCs are 1000 €/day. Capacities for HCWCCs and HCWTCs are sufficient and set to 10000 kg/day. In order to test the proposed model, the parameter *p* has three values (0.4, 0.8 and 1).

Table 1. Quantities of generated HCW

	Generators	HCW quantity (kg)	Potential locations for HCWCCs and HCWTCs
1	Zemun	2501.72	HCWCC
2	Novi Beograd	2463.98	
3	Stari grad	553.03	
4	Palilula	2072.16	HCWCC
5	Savski venac	450.17	HCWCC
6	Vračar	661.45	
7	Zvezdara	1956.16	HCWCC
8	Voždovac	1851.64	
9	Čukarica	2048.32	HCWCC (2 locations)
10	Surcin	528.01	HCWTC/HCWCC
11	Rakovica	1380.82	
12	Obrenovac	831.32	
13	Grocka	990.73	HCWTC/ HCWCC
14	Barajevo	310.96	HCWCC

	Generators	HCW quantity (kg)	Potential locations for HCWCCs and HCWTCs
15	Sopot	230.16	HCWCC
16	Mladenovac	602.84	HCWCC
17	Lazarevac	661.00	HCWTC

The model has been solved using the software tool LPSolve IDE 5.5.2.5. Results of the model testing for given input data are presented in table 2. The allocation of HCW generators to opened HCWCCs is given in table 3.

Table 2. Results of model testing

p=0.4			p=0.8			p=1		
Objective function value	Opened HCWTTc	Opened HCWCCs	Objective function value	Opened HCWTTc	Opened HCWCCs	Objective function value	Opened HCWTTc	Opened HCWCCs
145407.30 €	Surčin	Zemun	222347.40 €	Surčin	Surčin	257087.5€	Surčin	Surčin
		Čukarica1			Čukarica1		Grocka	Zvezdara
		Čukarica2			Čukarica2			Grocka
	Grocka	Mladenovac		Grocka	Zvezdara		Lazarevac	Sopot
		Zvezdara			Grocka			
		Grocka						

Table 3. Allocation of HCW generators to HCWCCs

	p=0.4	p=0.8	p=1
HCW generators	HCWCCs		
Zemun	Zemun	Surčin	Surčin
Novi Beograd	Zemun	Surčin	Surčin
Stari grad	Zvezdara	Zvezdara	Zvezdara
Palilula	Zvezdara	Zvezdara	Zvezdara
Savski venac	Zvezdara	Zvezdara	Zvezdara
Vračar	Zvezdara	Zvezdara	Zvezdara
Zvezdara	Zvezdara	Zvezdara	Zvezdara
Voždovac	Zvezdara	Zvezdara	Zvezdara
Čukarica	Čukarica1	Čukarica1	Surčin
Surcin	Zemun	Surčin	Surčin
Rakovica	Čukarica1	Čukarica1	Zvezdara
Obrenovac	Čukarica2	Čukarica2	Surčin
Grocka	Grocka	Grocka	Grocka
Barajevo	Čukarica2	Čukarica2	Sopot
Sopot	Mladenovac	Grocka	Sopot
Mladenovac	Mladenovac	Grocka	Sopot
Lazarevac	Čukarica2	Čukarica2	Sopot

As can be seen from the results, for p=0.4 two HCWTCs and six HCWCCs are opened, while for p=0.8, two HCWTCs and five HCWCCs are opened. Although the number of opened facilities in scenario 2 is smaller than in scenario 1, the total costs of the system are higher. Namely, quantities of transported HCW on the network differ due to different values of parameter *p*, so the objective function value is higher for p=0.8. In case when p=1, when all generated HCW quantities are transported from HCWCCs to HCWTCs, the number of opened HCWCCs is smaller but all three locations for HCWTCs are opened. In this scenario, HCW isn't treated in HCWCCs, meaning that HCWCCs serve only as collection points for HCW. Also, since the fixed costs of opening HCWTCs are higher than HCWCCs, total system costs are the largest for all observed scenarios. It can be concluded that input parameters, especially generated HCW quantities and fixed costs of opening facilities, play a significant role in model testing, hence considerable attention must be given to their definition.

3. CONCLUSION

Health-care waste management has become very important, from an economic, environmental and protection point of view for all involved actors in health-care management. In this paper, an approach for designing a logistics network for the HCW was tested on a real-scale example for the city of Belgrade. Test results showed that the model is dependent on the input parameters, especially fixed costs of opening facilities as well as generated HCW quantities. Future directions of model development may include HCWCCs and HCWTCs capacity constraints, different approaches for determining HCW generated quantities, but most importantly treating the uncertainties present in obtaining input data for modeling, etc.

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