Medical waste management during coronavirus disease 2019 pandemic at the city level

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Abstract

Coronavirus disease 2019 brings about the economic damage and loss of life. Thus, demand of personal protective equipment continues to increase, consequently an increase in infectious equipment pollution. Most of these wastes threaten the environment and increase the spread of diseases. This paper provides a research hypothesis whether effective medical waste management would prevent the possible impacts of coronavirus disease 2019-related waste issues on environment at the city level. To confirm this hypothesis, installation of waste treatment centre is addressed. Then, by incorporating uncertain waste generation amounts utilizing Jimenez method, a pickup routing is addressed to decide the pickup routes between the waste treatment centre and residential area. This study is first to assign the optimistic, realistic and pessimistic scenarios of the uncertain waste generation using time series analysis method and waste generation formulation. Also, L-type matrix is used to define, assess and prioritize the environmental and operational risks on waste generation formulation and to provide risk reaction strategies. Practicality of these approaches is illustrated in the case of Turkey. The computational results reveal the effectiveness of the integrated method, which ensures practical and theoretical insights controlling the waste generation to prevent virus propagation for health authorities.

Keyword Epidemic outbreaks · Medical waste · Risk approach · Uncertain environment · Waste generation

Introduction

Coronavirus disease 2019 (COVID-19) has spread across the globe; thus, mortality rates have been increased (WHO, 2020). COVID-19 also brings about the change in waste generation and composition, disposal and waste management on waste process (Van Fan et al. 2020). Waste management sector consisting of waste production, waste treatment and disposal and challenges to the industry (Haque et al. 2020) is also affected. Personal protective equipment (PPE) is a good option for protecting medical workers and public against COVID-19 (Cook 2020) because COVID-19 has unknown characteristics and the solution is time-consuming and costly. Protective materials can be divided into two groups: protective materials (gowns, gloves, medical mask

and face shield) used by health care professionals dealing with direct care of patients and medical masks for people who experience respiratory symptoms. The most critical issues confronting people are the alarming shortage and wastage of PPE. Medical equipment such as mask, glove and other tools should be available for all people in the epidemic outbreaks. Shortage of medical supplies can boost the death rate and cause the severe losses of the human lives (Govindan et al. 2020). An increasing demand for medical equipment (Kargar et al. 2020) is directly linked with the medical waste. The use of PPEs increases both the amount and density of the medical waste (Singh et al. 2020a, b). The pandemic management involves the fulfilment of preparation before disaster or after disaster to mitigate the negative impacts. Medical wastes produced during the COVID-19 have gained increasing attention (Yang et al. 2020). PPE, mask, glove and face shield bring about the huge contribution to waste amount (Ilyas et al. 2020). The coronavirus also remains on materials for days (Nzediegwu and Chang 2020). Therefore, an optimal management of PPE is important to control the outbreak. Infectious personal protective equipment (IPPE) should be organized with the measures linked

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with collection, treatment and burial to mitigate all risks (Korkut 2018). Medical waste such as contaminated mask and glove, called as hazardous waste, should be separated from the domestic waste (Zambrano-Monserrate et al. 2020). Since huge demand for protective material is predicted to boost suddenly in Turkey, medical waste will increase suddenly. Eco-friendly alternatives to enhance effective waste management system can ensure a sustainable world (Fadare and Okoffo 2020). The contribution of this paper is the demonstration of effective waste management system including location and routing decisions in IPPE management under uncertain environment. In addition, although three scenarios of the fuzzy parameters are allocated based on the historical data in the Jimenez method, Holt–Winters (HW) model and waste generation (WG) formulation is used to assign these scenarios, which is the scientific novelty in the presented paper. For WG formulation, most influential risks on IPPE waste generation are evaluated to provide risk reaction strategies. Also, in the second stage, both the mathematical modelling approach and the heuristics developed are used to compare the results. As far as we know, this presented study is first to provide the integrated IPPE waste treatment centre (WTC) location and pickup routing problem (PRP) considering prediction of uncertain waste amount. The main aims of the presented study are determination of the WTC location, solving pickup routing problem regarding uncertain waste amount, forecasting the uncertain WG, and determination of the most influential risks on IPPE waste generation, to provide risk reaction strategies utilizing the WG outcomes.

COVID-19 effects based on waste management are studied by various researchers (Penteado and Castro 2021). In this section, preliminary works related to this paper are presented to show the research gaps. Up to date, some studies related to the novel coronavirus are conducted, but generally in the medical subjects. Infectious medical waste for the COVID-19 pandemic was studied by Yu et al. (2020) and Kargar et al. (2020). However, many papers have been carried out related to the reverse logistics problems, but for a pandemic outbreak, to our knowledge, no papers have provided a framework related to IPPE waste management. Yu et al. (2020) presented mathematical modelling in a reverse logistics for medical waste in the COVID-19 pandemic. They decided some optimum locations and transportation planning. Budak and Ustundag (2017) addressed mixed integer modelling to decide some location decisions aiming at minimum cost. Their study covered the pickup, distribution and disposition of medical waste. Liu et al. (2020) used a heuristic to determine the waste storage placement. Also, transportation modelling for medical waste between hospital and storage placements was developed with the ant colony–tabu hybrid algorithms. Mantzaras and Voundrias (2017) addressed a model that decides the waste treatment

locations, waste volume, distribution vehicles and vehicle routes. They used two software applications to solve this problem and observe that major share of the cost is related to the treatment installation cost. Nolz et al. (2014) presented a mathematical formulation for the stochastic IRP considering pickup of medical waste, mitigation of medical risk, etc. Heuristic solutions were also provided for methods on real-world study. Chauhan and Singh (2016) provided health care waste disposal location problem utilizing multi-criteria decision-making (MCDM) methods. Yazdani et al. (2020) and Gergin et al. (2019) addressed a waste disposal location problem using a new best–worst method and a clustering algorithm, respectively.

Medical waste research is mainly carried out using MCDM methods. Decision on the optimal waste treatment methods was grouped under MCDM problems by Zavadskas et al. (2016) and Iglesias et al. (2008). Liu et al. (2013) presented a MCDM method including fuzzy approach to assess medical waste disposal techniques. They considered various options such as incineration and steam sterilization. Liu et al. (2015) provided a MCDM method to choose the health care waste treatment options. Dursun et al. (2011) developed a MCDM method based on fuzzy logic to select the medical waste treatment options. Mishra et al. (2020) addressed a MCDM problem of health care waste disposal methods utilizing evaluation based on distance from average solution (EDAS). Steam sterilization was selected as the optimal medical waste disposal technique. Ju et al. (2020) also presented a selection problem of medical waste disposal method using multi-granular linguistic distribution assessments (LDA). They obtained the steam sterilization as the most optimal medical waste disposal technique. Xiao (2018) developed a new MCDM tool to assess the optimal treatment technology for the health care waste. D numbers were used to deal with human judgement due to the various uncertainties. Steam sterilization was provided as the optimal technology to handle this waste. Makajic-Nikolic et al. (2016) developed a fault tree analysis (FTA) to evaluate the risks evaluation of health care waste. The highest scored failures were determined, and measures to prevent the failures are provided in medical waste management.

Preliminary papers are provided to reveal the gaps in the literature. Up to date, some studies related to the novel coronavirus are conducted, but generally in the medicine area. As far as we know, considering theoretical view, this study is first to present the integrated IPPE waste management decisions considering uncertain WG. Regarding practical gap, a real-world case is addressed to demonstrate the developed model at the city level.

This work was conducted in 2020, in the University of Munzur, Tunceli, Turkey.

Materials and methods

Efficient waste management is one of the main milestones of sustainable world. In recent years, sustainability and ecological concerns regarding waste issues have shown a substantial increase due to global warming, epidemic disasters, and natural disasters. Thus, waste-based methods are hot research topics for both practitioners and researchers. Waste solutions incorporating minimization and prevention issues are popular in the waste management area. To make these decisions scientific sound, integrated solution approaches should be carried out. Thus, a combined problem including location and PRP regarding uncertain WG is proposed in this paper. Figure 1 depicts a representation of two stages of presented problem. In the first stage, location problem regarding demand-weighted distances and installation costs is solved. In the second stage, routes are decided between the installed WTC and residential areas. In this stage, picked-up waste amounts are uncertain. Thus, Jimenez method is carried out in the second stage. This method uses optimistic, realistic and pessimistic scenarios. For these scenarios, two methods are used to predict the WG.

Amount of IPPE waste has significantly increased during the COVID-19 (Rhee 2020). More than 240 tons of medical waste (mask, gloves) is observed per day (Adyel 2020). The type of PPE wastes can include glove, medical mask, goggle, shield, gown, respirator and apron (WHO 2020). The major share related to the type of wastes is mainly observed as

masks since the widely used PPE is face masks (Dargaville et al. 2020). Medical waste amount between 2009 and 2019 is represented in Table 1 that provides an increasing pattern of the medical waste amount until 2015. In 2015, the high value is obtained, and then a decreasing pattern is observed. This year is expected as high value due to the outbreak.

To investigate the impacts of the environment and operation risks on WG formulation for medical facilities and residential area, environmental risks including high infection rate, increasing population, mortality rate, recovery rate, PPE costs and insufficient budget for waste measures, and operational

Table 1 Medical waste amount between 2009 and 2019 (Tunceli Province 2019 Environmental Status Report)

Year	Time period (t)	Medical waste amount (tonne)
2009	1	29,4
2010	2	28,02
2011	3	24,9
2012	4	42,54
2013	5	43,22
2014	6	74,52
2015	7	248,396
2016	8	52,85
2017	9	52,654
2018	10	54,778
2019	11	61,015

Fig. 1 A representation of the proposed problem

risks including low recyclability rate of PPE, high disposal costs, high maintenance costs, lack of waste workers and lack of control in waste WTCs are defined. Thus, optimal risk reaction strategies can be defined and the effects of high-level risks on WG are provided.

The basic assumptions are outlined as follows:

- Each route between the WTC and the main WTC.
- Vehicle capacity could not exceed.
- Maximum distance constraint could not exceed.
- There are no initial waste quantities at the starting point.

Location problem

The first problem aims to find optimal WTC location based on the minimization of demand-weighted average distances between the hospital and the WTC, WTC and residential areas, and WTC installation costs. The notation of the mathematical modelling is presented in the following:

I, J and T define the residential area, candidate WTC nodes and time periods, respectively. d_{ij} is the distance between the WTC nodes and the residential area. M is the maximum travelled distance of the vehicles. C is the transportation cost per km, and B is the maximum budget to install the WTC. K_j is the installation cost of WTC j, and f is the operation costs of the WTC. The decision variable y_j will be 1 if a WTC is installed at point j, 0 otherwise. The decision variable x_{ij} will be 1 if the residential area at point i is assigned to WTC at point j.

Minimize

$$\sum_{j=1}^J y_j K_j + \sum_{j=1}^J \sum_{t=1}^T f y_j + \sum_{i=1}^I \sum_{j=1}^J C d_{ij} x_{ij} \quad (1)$$

The objective function (1) ensures to minimize the installation cost of WTC, operation costs of WTC and demand-weighted distances between the WTC and the residential area.

$$\sum_{j \in J} x_{ij} = 1 \quad i \in I \quad (2)$$

$$x_{ij} \leq y_j \quad i \in I, j \in J \quad (3)$$

$$\sum_i x_{ii} * f \leq B \quad (4)$$

$$x_{ij} * d_{ij} \leq M \quad i \in I, j \in J \quad (5)$$

$$y_j = (0, 1) \quad j \in J \quad (6)$$

$$x_{ij} = (0, 1) \quad i \in I, j \in J \quad (7)$$

Constraint (2) ensures that each area is allocated to a WTC. Constraint (3) ensures that area is assigned to itself if the node is assigned as a WTC. Constraint (4) ensures to decide the WTC location based on maximum budget. Constraint (5) ensures the distances between WTC and nodes regarding maximum distance constraints. Constraints (6) and (7) describe the range of the decision variables.

Pickup routing problem

The second problem is addressed to find the pickup routes between the WTC location and residential areas regarding uncertain waste amount. The notation of the mathematical modelling is presented in the following:

Indices

- i: Residential area.
- j: WTC.
- l: Waste pickup nodes.
- k: Vehicles.

Parameters

- c_{ij} : Generalized distances between nodes i and j.
- Q_k : Capacity of vehicle k.
- P_i : Waste amounts at node i.

Decision Variables

U_{ik} : upper waste limit of node i with vehicle k (unit)

$$X_{ijk} = \begin{cases} 1, & \text{if } k \text{ vehicle goes to node } j \text{ from node } i \\ 0, & \text{otherwise} \end{cases}$$

$$z_{ik} = \begin{cases} 1, & \text{if } k \text{ vehicle picks up from the node } i \\ 0, & \text{otherwise} \end{cases}$$

$$\min z = \sum_{k=1}^K \sum_{i=1}^I \sum_{j=1}^J c_{ij} * X_{ijk} \quad (8)$$

$$\sum_{j=1}^J X_{ijk} = \sum_{j=1}^J X_{jik} \quad i = 1, \dots, I; k = 1, \dots, K \quad (9)$$

$$\sum_{k=1}^K \sum_{j=0}^J X_{ljk} = 1 \quad l = 1, \dots, L \quad (10)$$

$$0 \leq U_{ij} \leq Q_k, i = 1, \dots, I; k = 1, \dots, K \quad (11)$$

$$U_{lk} \geq U_{ik} + p_l * z_{lk} - (1 - X_{ijk}) * Q_k, i = 0, \dots, I, l = 1, \dots, L; k = 1, \dots, K \quad (12)$$

$$\sum_{j=1}^J X_{ijk} \leq z_{lk}, i = 1, \dots, I; j = 0, \dots, J; k = 1, \dots, K \quad (13)$$

$$\sum_{i=1}^I T_{ilk} * p_l \leq Q_k, i = 0, \dots, I, l = 1, \dots, L; k = 1, \dots, K \quad (14)$$

$$X_{ijk}, z_{lk}, U_{ik} \geq 0, i = 0, \dots, I; j = 0, \dots, J; k = 1, \dots, K \quad (15)$$

The objective function (8) minimizes the total distances between the WTC and residential area. Constraint (9) ensures that vehicle ends the tour in the WTC. Constraint (10) presents that each pickup node is visited. Constraint (11) provides that the picked-up waste amounts could not exceed the vehicle capacity. Constraint (12) and Constraint (13) allow balancing the pickup amounts. Constraint (12) calculates the transported waste amount from the residential area. Constraint (13) ensures that the vehicle pickup waste if the vehicle travels between pickup nodes. Constraint (14) ensures that the vehicle capacity could not be exceeded. Constraint (15) provides that decision variables are greater than zero point.

Jimenez method

The method is developed for fuzzy model parameters, and objective values are ranked by a fuzzy ranking method (Jimenez et al. 2007). A novelty for the method is that coefficients are demonstrated with fuzzy numbers (Hatami-Marbini and Tavana 2011). Expected value (EV) is provided with the fuzzy numbers, and $c=c^r, c^q, c^s$ are predicted with optimistic, realistic and pessimistic scenario (Fathollahi-Fard et al. 2020).

$$EV(c) = \frac{c^r + 2c^q + c^s}{4}$$

The constraints (i.e. $a = a^r, a^q, a^s, b = b^r, b^q, b^s, a_i X \geq b_i, i = 1, 2, \dots, I$) are presented in the following: (α = feasibility level).

$$\left(\alpha \frac{a_i^r + a_i^q}{2} + (1 - \alpha) \frac{a_i^r + a_i^s}{2} \right) X \geq \left(\alpha \frac{b_i^r + b_i^q}{2} + (1 - \alpha) \frac{b_i^r + b_i^s}{2} \right)$$

$$\left(\left(1 - \frac{\alpha}{2} \right) \times \frac{a_i^s + a_i^q}{2} + \left(\frac{\alpha}{2} \right) \times \frac{a_i^r + a_i^q}{2} \right) X \geq \left(\left(1 - \frac{\alpha}{2} \right) \times \frac{b_i^s + b_i^q}{2} + \left(\frac{\alpha}{2} \right) \times \frac{b_i^r + b_i^q}{2} \right)$$

p_i^q Realistic option for waste amount on node i.
 p_i^s Pessimistic option for waste amount on node i

$$U_{lk} \geq U_{ik} + \left(\left(\frac{\alpha}{2} \right) \times \frac{p_l^s + p_l^q}{2} + \left(1 - \frac{\alpha}{2} \right) \times \frac{p_l^r + p_l^q}{2} \right) * z_{lk}$$

– ($i = 0, \dots, I, l = 1, \dots, L; k = 1, \dots, K$)
 $(1 - x) * Q_k$ (16)

$$\sum_{i=1}^I T_{ilk} * \left(\left(\frac{\alpha}{2} \right) \times \frac{p_l^s + p_l^q}{2} + \left(1 - \frac{\alpha}{2} \right) \times \frac{p_l^r + p_l^q}{2} \right)$$

($l = 1, \dots, L; k = 1, \dots, K$) $\leq Q_k$ (17)

Fuzzy parameters are included into Eqs. (12, 14). Feasibility degrees are presented with $M = (0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1)$ (Jimenez et al. 2007).

WG problem

PPE predictions using logical models are suggested by WHO (2020). Data utilized in the pandemic disasters could be predicted using forecasting techniques (Göçmen, 2020). In this stage, WG is obtained utilizing WG formulation and time series analysis. First, WG formulation is used to find the WG. Thus, the environmental risks and operational risks are considered to incorporate to the model depicted in Table 2. The risk management covers the risk definition, measurement, evaluation and control of prioritized risks. Probability and the effect are the main parameters of risk formulation. The measurement of the probability and effects is taken by quantitative and qualitative definitions utilizing historical data and risk reports. Risk scores are obtained multiplying effect and probability parameters to prioritize risks. Risk scores are calculated to determine the risk classes between A and E in the L-type (5X5) matrix depicted in Fig. 2. High and very high classes are represented with red colour; low classes that can be neglected to control actions are depicted with green colour.

The amount of generated waste is influenced by some parameters such as population, infection rate, mortality rate, disposal practice and recyclability. Probability and severity values are assigned considering the medical waste studies. In these studies, population, infection, mortality and recovery

Notation and formulation are described in the following:
 p_i^r Optimistic option for waste amount on node i.

ery rates are mainly incorporated into the risk management approaches.

Table 2 Risk scores and classes

	Risks	Probability	Severity	Class	Risk
Environmental risks	High infection rate	5	5	E	25
	Increasing population	5	4	E	20
	Mortality rate	4	4	D	16
	Recovery rate	4	4	D	16
	PPE costs	3	3	C	9
Operational risks	Low recyclability rate of PPE	5	3	E	15
	High disposal costs	3	3	C	9
	High maintenance costs	3	2	C	6
	Lack of waste workers	3	3	C	9
	Lack of control in waste WTCs	3	4	C	12
	Insufficient budget for waste measures	3	3	C	9

Fig. 2 5×5 Matrix (Peeters and Peng 2015)

Likelihood		Risk Index: Combination of Severity and Likelihood				
		Low	Medium	High	Very High	Very High
E		Low	Medium	High	Very High	Very High
D		Low	Low	Medium	High	Very High
C		Very Low	Low	Low	Medium	High
B		Very Low	Very Low	Low	Low	Medium
A		Very Low	Very Low	Very Low	Very Low	Low
		1	2	3	4	5 Severity
		"Red"		"Yellow"		"Green"

The main aims decided by the developed model are presented in the following:

- Determining the amount of generated waste for medical facilities
- Determining the amount of generated waste for residential area

A set of hospitals, in which main WTC is represented by point 0, serve patients for a planning horizon. Hospital is denoted with N , and time with T .

The notations are presented in the following. The motivation of this formulation is Kargar et al. (2020).

Indices:

t Period

Parameters:

Pop Population

I_t Infection rate in period t

P_t Patient rate in hospitals i in period t

R_t Recovery rate in period t

Rec_t Recyclability rate in period t

M_t Mortality rate in period t

Q_t Number of patients quarantined in period t

H_t Patient rate getting hospitalized in period t

W_t Waste amount in period t

$$WGH_t = ((Pop * I_t * P_t * H_t) + (1 - R_t - M_t - Rec_t)) * W_t \quad (18)$$

$$WGR_t = ((Pop * I_t * P_t * H_t) + (Q_t * (1 - R_t - Rec_t))) * W_t \quad (19)$$

Equations (1–2) are waste generation formulations that waste at each period is calculated by considering the parameters. The data including observed medical waste amount between 2009 and 2019 are also used to predict the 2020 value. Figure 3 shows the Holt–Winters model. S_t and T_t are level and additive trends. Smoothing symbols are α and

$$S_t = \alpha \left(\frac{X_t}{I_{t-s}} \right) + (1 - \alpha) (S_{t-1} + T_{t-1}) \quad (1)$$

$$T_t = \gamma (S_t - S_{t-1}) + (1 - \gamma) T_{t-1} \quad (2)$$

$$I_t = \delta \left(\frac{X_t}{S_t} \right) + (1 - \delta) I_{t-s} \quad (3)$$

$$\widehat{X}_{t+h} = (S_t + hT_t) I_{t-s+h} \quad (4)$$

Fig. 3 Holt–Winters model (Trull et al. 2020)

γ . I_t is the seasonal equation with smoothing value δ . X_t is the observed data, and $\widehat{X}_{t+h}$ formulation ensures to predict the h time.

Equation (1) provides the base level. Equation (2) and Eq. (3) illustrate the trends and seasonal factors, respectively. Equation (4) ensures to forecast the WG.

Solution method

Location and PRP are complex problems to solve the real case data (Archetti et al. 2007). In this presented study, general algebraic modelling system (GAMS) could solve the ten nodes in a reasonable time. This study utilizes the MIP and a heuristic to solve the location and PRP problems. PRP problem is more complex due to the uncertain WG values and multi-node. This stage is solved using the heuristics named simulated annealing (SA). The SA was firstly published by Metropolis et al. (1953). This study deals with the balanced distribution of atoms. The algorithm is advanced by Pincus in the 1970s. This intuitive approach mimics the physical annealing process. Physical annealing is the process that starts with the heating of metals and continues with their slow cooling to crystallize with minimum energy.

The simulation of annealing starts with a high temperature (T).

- Many solutions are generated among the neighbours (C) of the existing solution. Calculate the cost changes for each solution Delta C.
- Each solution is accepted or rejected based on the specified criteria. Delta C < 0 means that the current solution is accepted. Delta C is represented as $e^{-f(x_i) - f(x_i - 1)}$ by choosing the starting point x_i ($i = 0$). R, named random number is represented as $0 < r < 1$. Otherwise, the formulation $\exp(\text{Delta C}/T) > R$ is used to accept new solution.
- Determination of internal loop and external loop condition is carried out, in which internal loop is defined as the number of repetitions in each iteration and

```

Read node latitude and longitude
Calculate distance matrix
Calculate the savings matrix
Sort the savings matrix
While do nodes i and j of the maximum savings not processed
if node i or j not processed then
Determine Routei or Routej routes and modify
else merge Routei, Routej
end if
End while

```

Fig. 4 Pseudocode for PRP

external loop as stop criterion. Metropolis probability formulation is used when the solution in the current iteration is not better than the before. This formulation is defined in the following: Metropolis possibility = $e^{-(f(x_i) - f(x_{i-1})) / (k_b \cdot T)}$, *Boltzmann sabiti $k_b = 1,380,650,524.10 - 23$ J/K. x_i starting point ($i = 0$), $f(x_i)$ is calculated. $f(x_{i-1})$ is obtained with $x_i = x_{i-1}$.

- After each calculation step, the temperature is mitigated based on a specified function.
- The algorithm is finished when the expected iteration is obtained, or the temperature obtains the minimum value. SA parameters used are as follows:

I_{iter} , maximum iteration is 100; maximum inner iteration is 10; T_0 , initial temperature is 100; α , temperature damping rate is 0.98.

Simulated annealing is applied for the PRP. A modified savings is defined, and the pseudocode is depicted in Fig. 4. The node latitude and longitude values (mainly 39^0 , 39^0) are used.

Case study

To evaluate the developed model to control the pandemic supply chain, a real case is presented. The required data to conduct this study are obtained from Tunceli City located in Turkey. WTC is not available in this city, the pickup waste amounts are transported to the other city, named Bingöl in Turkey. In this problem, various candidate locations are considered as WTC. The waste in each residential area is transported to WTC. The total population of Tunceli is 84660. To calculate the waste included by WTC, a weight linked with the historical data of WG amount is assigned. Distances between residential area and WTC are measured using Google Maps. Table 3 demonstrates the distance matrix between the WTC and districts, represented as nodes in the paper.

Table 3 Distance matrix

	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8
Node 1	0	55,8	57,8	43,9	74,1	70,3	122	44,4
Node 2	55,8	0	42	80	111	80,8	66,7	49
Node 3	57,8	42	0	82,2	112	67,4	59,9	58,8
Node 4	43,9	80	82,2	0	55,2	94,7	146	68,8
Node 5	74,1	111	112	55,2	0	125	176	99,1
Node 6	70,3	80,8	67,4	94,7	125	0	98,6	93,8
Node 7	122	66,7	59,9	146	176	98,6	0	115
Node 8	44,4	49	58,8	68,8	99,1	93,8	115	0

Table 4 The location results

Distance	Number of WTC	Number of vehicles	Total cost (US dollars $\times 10^2$)
20	5	3–2–1	15,600–14,740–13,360
40	4	3–2–1	14,320–13,256–12,490
60	3	3–2–1	12,200–11,560–10,420
80	2	3–2–1	9980–8740–7890
100	1	3–2–1	6931–6024–5982

Table 5 Waste quantities for vehicles

Nodes/vehicles	Vehicle 1 (tonne)	Vehicle 2 (tonne)	Vehicle 3 (tonne)
Node 1		90,000	
Node 2	2300		
Node 3		1500	
Node 4	1200		
Node 5			1400
Node 6			1800
Node 7		400	
Node 8			232

Results and discussion

Computational analysis is provided for the utilization of the presented method. The MIP could solve the location problem a reasonable time. The heuristics are provided to solve the PRP. To handle the fuzzy parameters, Jimenez method is included to the PRP. Optimistic, realistic and pessimistic scenarios are obtained from the prediction method and WG formulation.

Location and PRP results

Developed mathematical models are tested on the case study. In addition, sensitivity analysis is provided for the model verification and to analyse the parameter changes. In this analysis, location results and total costs utilizing MIP solver are demonstrated in Table 4. Total cost is computed for each distance, number of vehicles and WTC. The results show that total cost increases with the number of vehicles and WTC. At the distance constraint for 20–100 km, changes on the total cost, number of WTC and vehicles are investigated. One WTC is required to cover all area within 100 km since the city is not enough large and installation of the second WTC is costly. 125–150 km restrictions are not more influential on the total cost.

In Table 5, routes and waste quantities for each node are obtained using MIP solver. The total waste obtained is

Fig. 5 Routes developed by SA code

shared to the nodes based on the population and density. The starting and end point of the routes is WTC. Routes are generated for the pickup process regarding capacity of the vehicles and the amount of the waste and presented in the following: Vehicle 1 follows the route as WTC–2–4–WTC, Vehicle 2 follows the route as WTC–1–3–7–WTC, and Vehicle 3 follows the route as WTC–6–8–5–WTC.

In SA, the same routes are generated. Figure 5 depicts that those three routes are formed regarding latitude and longitude. Comparing MIP solver, same routes are generated. Green line represents the first tour, while the second and third routes are represented by red and blue lines, respectively. Yellow symbol depicts the installed WTC.

Vehicle 1 follows this route: WTC–Node 2–Node 4–WTC

Vehicle 2 follows this route: WTC-Node 1-Node 3-Node 7-WTC

Vehicle 3 follows this route: WTC-Node 6-Node 8-Node 5-WTC.

Figure 6 demonstrates the routing cost for each iteration. The algorithm is finished when maximum iteration 100 is obtained. The results show that the routing cost is obtained as 422,200 US Dollars. MIP solver provides the same cost under the feasibility level 0.4 depicted in Table 3. With iteration 15, the routing cost is accepted as new solution.

Computational results including location and routing costs are provided in Table 6. Sensitivity analysis is also provided for the model verification and to evaluate the degree changes. The minimum total cost is obtained under the feasibility level 0.4.

WG results

In the WG formulation, high-level risks (15–20 scores) depicted in Table 7 are incorporated into the equations. High infection rate and population are the most influential factors on WG. In the presented paper, residential areas with high infection rate and population produces more waste.

WG rate in hospitals and residential area is about 1.2 kg per patient and day. The total population is 84660. Infection rate is considered 0.77 as low estimate. Recovery and recycling rate is only 3% for polypropylene PPE (Singh et al., 2020a,b). Mortality rate and recovery rate are %1.9 and %55.2, respectively. Thus, WG for hospital and for residential area is obtained as 39,521 and 40,131 ton, respectively.

Fig. 6 Cost solutions ($10^2 \times$ US Dollars) of iterations

Table 6 Objective function results

Feasibility levels α	0.4	0.5	0.6	0.7	0.8	0.9	1
Routing cost (US Dollars $\times 10^2$)	4222	4227	4545	4401	4368	4384	4384
Location cost (US Dollars $\times 10^2$)	2709	4334	4678	4980	5025	5213	5223

Total value nearly 79,652 ton is used to obtain the optimistic scenario.

Risk response strategies are carried out for the high-level risks. The European waste hierarchy presents six methods in the following:

Prevention: The most favourable option is prevention in the waste hierarchy. The WFD 2008 defines this term as measures to reduce the amount of waste (Gharfalkar et al. 2015).

Minimization: Minimization of waste brings about cost savings, challenging business areas (UNEP 2011).

Reuse: This term means that using waste in their original form with little repair.

Recycle: Recycle includes reprocessing waste to produce new material.

Recovery: Recovery defines the energy produced from waste.

Disposal: Disposal of infectious medical wastes is challenging that WHO states an environmentally friendly and low-cost method for infectious medical wastes (Birchard 2002).

Then, WG is generated by utilizing the Holt–Winters method. Table 8 demonstrates the predicted waste amount based on the base level, trend and seasonal factors to obtain the pessimistic scenario. This value is used for the pessimistic number in Jimenez method. Realistic scenario is considered as the average of the optimistic and pessimistic values, 89,242 ton.

In order to compare the performance of the prediction, the linear regression model is provided, and the linear regression equation is provided in the following formula:

$WG = 80,801 - 0.017 * \text{population} + 44.268 * \text{number of patients} + 1.708 * \text{number of beds} - 1.331 * \text{number of doctors} + 0.080 * \text{number of deaths}$. The linear regression results are demonstrated in Table 9. The result ensures a correlation which can predict the number of medical wastes as a function of city population, the number of patients, the

Table 7 High-level risks

Risk	Probability	Severity	Class	Risk
High infection rate	5	5	E	25
Increasing population	5	4	E	20
Mortality rate	4	4	D	16
Recovery rate	4	4	D	16
Low recyclability rate of PPE	5	3	E	15

Table 8 Prediction results of medical waste amount

Year	Time period (t)	Observed medical waste amount (tonne) (X_t)	Base level (S_0)	Trend (T_t)	Seasonal factor (I_t)	Predicted waste amount (tonne)
2009	1	29,4	–	–	0,942	–
2010	2	28,02	–	–	0,898	–
2011	3	24,9	–	–	0,798	–
2012	4	42,54	31,2	0,0	1,363	–
2013	5	43,22	31,2	0,0	1,163	42,540
2014	6	74,52	31,2	0,0	1,642	36,310
2015	7	248,396	31,2	0,0	4,378	51,270
2016	8	52,85	31,2	0,0	1,528	136,648
2017	9	52,654	31,2	0,0	1,425	47,695
2018	10	54,778	31,2	0,0	1,699	44,482
2019	11	61,015	31,2	0,0	3,166	53,024
2020	12	–	31,2	0,0	0,764	98,832

Table 9 Linear regression results

Model	Sum of squares	Df	Mean square	F	Sig	R ²
Regression	7731.109	5	1546.222	39.190	0,000	0.894

number of hospital beds, doctors and deaths (significance value $0.000 < 0.05$, $R^2 = 0.894$).

Conclusion

Increasing demand of PPE has been controlled all over the world. Thus, providing an IPPE management is necessity to deal with this problem. In this regard, PPE waste planning for a city supply chain problem is conducted considering WTC location and routing decisions. The presented model ensures both distribution and location decisions, and WG prediction utilizing both mathematical formulation and prediction method. In addition, a risk management approach is developed to handle the environmental and operational risk factors to decide the WG. The computational results on real case data illustrate that integrated waste management approach could be effective to prevent the waste and provide more healthy people and sustainable world. To summarize the paper, IPPE management under uncertain environment is addressed. Uncertain parameters are assigned considering optimistic, realistic and pessimistic scenarios of Jimenez method. HW model and WG formulation is also used to assign these scenarios. For WG formulation, risk factors on IPPE WG are examined.

In recent years, integrating health and sustainability applications have attracted considerable attention. Environment-based methods are of vital importance for the decision-makers to revise the traditional systems. Effective waste techniques are crucial to decide whether the decision-makers take into account the global world

requirements. Smart medical waste disposal applications are the backbone of the sustainable world. Since world population and illnesses dramatically increase, ecosystem balance must be ensured. To deal with these issues, waste management systems should be examined, measured and analysed. Using new technologies is required since large data are utilized. For future works, stochastic programming modelling is suggested for IPPE waste logistics. Moreover, incorporating traffic loads of obtained routes can ensure more realistic solution to the problem. The limitation of this paper is that SA method may not be applicable for more populated cities, 1 million above.

Decision-making methods are focal stage to solve some problems such as selection of waste treatment methods. These problems are more complex since methods have some similarities, e.g. recovery, recycling and reuse. Therefore, decision-makers can fail to determine the methods and obtain mistaken results. An automated computational system is required to achieve to detect the optimum method.

Managerial views for medical sector regarding computational results are listed as follows:

- Important issue to prevent the IPPE waste is an optimal prediction of waste amount. Hence, real data could provide decision-makers to define the waste levels.
- For large-scale networks, integrated waste management plans are required to develop the network. Installing waste centres, waste picking decisions and waste generation plans should be handled.

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