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ORIGINAL ARTICLE

Stochastic modeling and optimization of medical waste collection in Northern Jordan

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Abstract Jordan has witnessed a rapid increase in healthcare facilities during the last two decades. As a consequence, the amount of generated medical waste have been increased rapidly and a proper management system is indeed needed to eliminate the environmental and health hazards resulted from such waste. An approved medical waste treatment facility is the incinerator located at the northern region of Jordan which serves the four northern governorates. Two trucks are used to pickup waste from the hospitals in these governorates to be treated at the incinerator. In this paper, a route scheduling model is proposed to minimize the total travel distance which in turn minimizes transportation cost and reduces emissions. The proposed model takes into account the capacity of trucks, number of visits per week, timing between visits along with the service level required by the hospitals. An optimal routing schedule was found and verified. Compared to current routing schedule, a saving of 102 km per week was achieved.

Keywords Hazardous · Optimization · Stochastic · Scheduling · Waste

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Introduction

During the last two decades Jordan has witnessed a rapid development in healthcare services which is accompanied with increased numbers of healthcare facilities (i.e. hospitals and medical centers). This increase in the number of healthcare institutions implied an increase in the number of patients who receive the healthcare services and consequently reflected on the amount of the medical waste generated from these facilities. Hence, a proper management system is required, so as to minimize the health and environmental risks associated with such hazardous wastes [5, 6].

Abu Qdais et al. [1] conducted a survey to characterize the medical waste generated at the Jordanian hospitals. Hospitals from public, private and educational categories were considered. The average waste generation rates ranged from 0.29 to 1.36 kg/bed/day, while in terms of patient numbers it was found to be from 0.36 to 0.87 kg/patient/day.

The increase in the amounts and types of medical waste has resulted in issuance of Medical Waste Regulation (Regulation No. 1 for the year 2001) that aimed at regulating the management processes of such hazardous waste. One of the main issues in the regulation was the treatment of the medical waste using incinerators. An approved incinerator to deal with the medical waste in northern Jordan, is the one located at Jordan University of Science and Technology (JUST) campus. This incinerator has been approved by both the Ministry of Health and the Ministry of Environment to deal with all medical waste generated by the healthcare facilities in the four northern governorates of Jordan, namely Irbid, Al-Mafraq, Jarash, and Ajloun.

Several studies have considered the problem of waste collection. Some of these studies consider the waste collection problem in its deterministic characteristics and provide a near optimal routing schedule that minimizes collection cost and meets demand time windows. For example, Baptista et al. [2] studied the process of collecting recycling paper containers in Portugal. In their study a periodic Vehicle Routing Problem (VRP) with variable number of visits have been considered. Mourao and Almeida [8] illustrated a capacitated VRP for a refuse collection process. Lower bounding techniques along with heuristics were used to provide near optimal solutions to such waste collection problems. Shih and Chang [11] have developed a computer program for the collection of infectious hospital waste. In their paper, they proposed a two phase periodic VRP and the model is solved through integer programming techniques.

Other studies found in the literature have taken into account the stochastic behavior of the collection process. Examples of such studies include that of Mendoza et al. [3] and Rei et al. [10] were the VRP with stochastic demand is solved through proposed heuristics. Nolz et al. [9] considered the collection of infectious medical waste by formulating the problem as a collector-managed inventory routing problem and using the radio frequency identification (RFID) technology. A tabu search algorithm was developed to optimize the collection time and the corresponding vehicle routes. To validate their suggested routing approach, the authors have used real life data to generate routing schedules. For more on the VRP and recent solution algorithms we refer the readers to the book "Vehicle Routing: Problems, Methods, and Applications" by Toth and Vigo [13].

In summary, studies found in the literature have considered the problem of waste collection either as a deterministic problem or have taken the stochastisity of collected waste into account. Up to our knowledge, non of the existing studies have combined the stochastic demand issue with time window requirements. In this paper, we propose a modeling approach that combines both issues and we illustrate how this model can be solved through a real case study of medical waste collection in the northern part of Jordan.

The rest of the paper is organized as follows. Problem description is given in "Problem description" section. "Mathematical model" section presents the proposed mathematical model for solving the waste collection problem. Results and discussion are provided in "Results and discussion" section. Finally, concluding remarks are given in "Conclusion" section.

Problem description

An incinerator is located at Jordan University of Science and Technology campus. There are two pickup trucks that collect generated medical waste from nineteen hospitals located at the northern part of Jordan. A list of these hospitals and their respective capacity in terms of beds are

Table 1 List of hospitals from which the medical waste is collected along with their fitted waste generation distributions

Code	Hospital	Distribution			No. of beds
		Type	Mean	Variance	
H1	King Abullah University Hospital	LogNormal	0.2823	5.63	678
H2	Rahibat Alwardyah Hospital	LogNormal	0.3532	2.478	87
H3	Ibn Alnafees Hospital	LogNormal	0.4203	2.825	103
H4	Alnajah Hospital	LogNormal	0.7019	1.443	15
H5	Algawasmi Speciality Hospital	LogNormal	0.3879	1.664	28
H6	Catholic Hospital	LogNormal	0.9179	2.127	18
H7	Irbid Islamic Hospital	LogNormal	0.5273	1.622	30
H8	Mafraq Public Hospital	LogNormal	0.2542	3.877	70
H9	Ramtha Public Hospital	LogNormal	0.3743	3.945	110
H10	Aleeman Hospital	LogNormal	0.2966	4.35	130
H11	Prince Rahmah Hospital	LogNormal	0.2996	5.134	210
H12	Prince Basmah Hospital	LogNormal	0.2348	5.127	202
H13	Prince Rayah Hospital	LogNormal	0.3477	3.827	94
H14	Alyarmouk Hospital	LogNormal	0.2443	3.791	67
H15	JUST Health Center	LogNormal	0.6869	2.709	–
H16	Women and Pediatrics Hospital	LogNormal	0.5267	3.186	112
H17	Jarash Public Hospital	LogNormal	0.187	4.579	159
H18	Moaath Bin Jabal Hospital	LogNormal	0.2322	3.449	75
H19	Abo Obaidah Hospital	LogNormal	0.2379	3.594	60

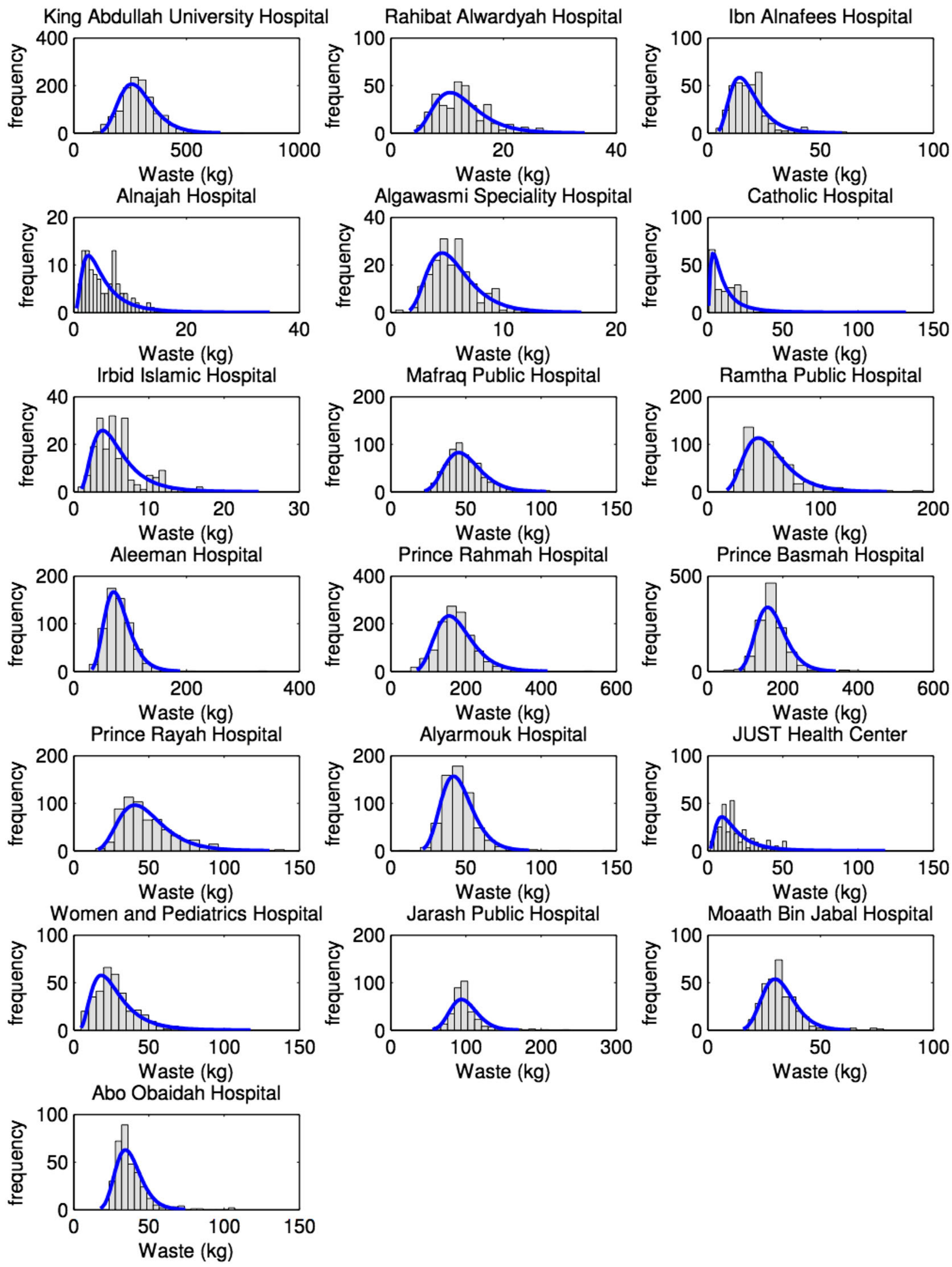

Fig. 1 Histograms of collected daily medical waste for the 19 hospitals considered along with a probability density *curve* showing the fitted distribution

shown in Table 1. On a daily basis, each collection truck starts its trip from the incinerator, collects medical waste from the listed hospitals on its scheduled route, then drives back to the incinerator. Each of these two trucks has a capacity of 1500 kg of collected medical waste. Historical data of the generated waste from these hospitals is available since January, 2010. Figure 1 shows frequency histograms for the daily collected medical waste for all of the nineteen hospitals. Figure 1 also shows the probability density curve for the fitted distribution on top of the histograms providing a visual check of how well the proposed distributions fit the data. Parameters of the fitted

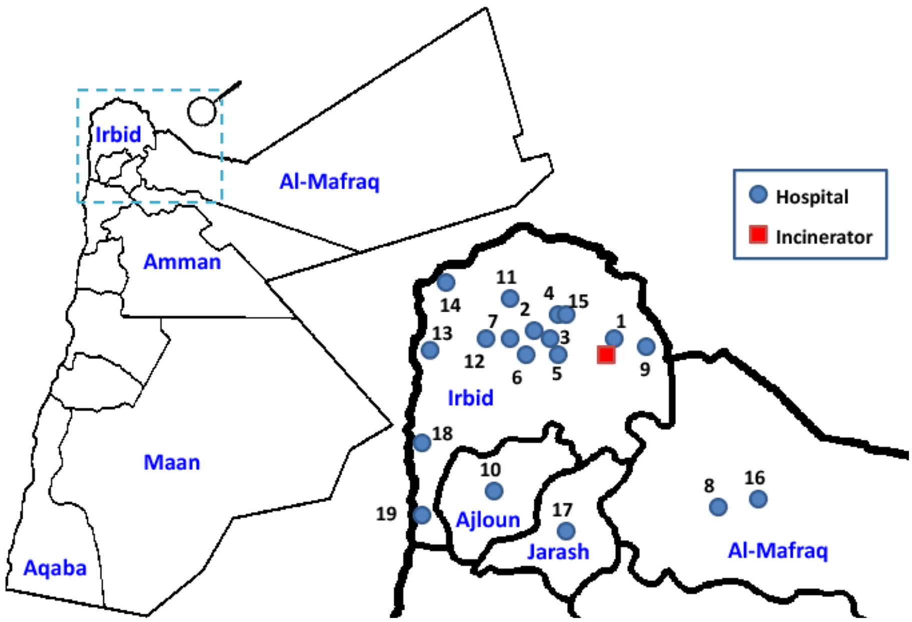

Fig. 2 Jordan map and location of hospitals in the four Northern governorates with respect to the incinerator

distributions are given in Table 1. Relative locations of hospitals and the incinerator are shown in Fig. 2, while Table 2 provide travel distances from the incinerator to each of the hospitals along with the travel distance between hospitals.

Current waste collection schedule as shown in Table 3 is based on an add-hoc procedure of collecting waste from nearby hospitals to meet contract requirements with the Ministry of Health that public hospital must be visited every 2 days at maximum since no waste storage areas are available. Current collection schedule does not take into account neither the amount of generated waste at each hospital nor the capacity of collection trucks. Given the current situation, it is required to minimize the total travel distance of collection trucks while providing an acceptable level of service for hospitals in terms of waste pickup. Minimizing travel distance will in turn minimizes travel cost and will also reduces gas emissions to the environment.

Mathematical model

In this section, the problem of medical waste collection described in "Problem description" section will be formulated mathematically. Assume the following index sets:

$i =$ The set of pickup trucks: $i \in \{1, 2\}$

$j =$ The set of hospitals: $j \in \{1, 2, \ldots, 19\}$

$k =$ Days of the week: $k \in \{1, 2, \ldots, 7\}$

and let x_{ijk} be a binary variable that equals 1 if truck i visits hospital j at day k of the week and 0 otherwise. Then the problem can be modeled as:

$$\text{Minimize} \quad T_{\cos t} = \sum_{i,k} D(x_{ijk}) \tag{1}$$

Subject to:

$$p\left(\sum_{j} W(x_{ijk}) \le C_i\right) \ge \alpha \tag{2}$$

$$\sum_{i} \left(x_{ijk} + x_{ij(k+1)} + x_{ij(k+2)}\right) \ge 1 \tag{3}$$

$$\sum_{i,j,k=7} x_{ijk} = 0 \tag{4}$$

$$x_{ijk} \in \{0, 1\}$$

where α is a constant that takes a value between 0 and 1, C_i is the capacity of truck i, $W(x_{ijk})$ is a function of the decision variable x_{ijk} that represents the accumulated medical waste and $D(x_{ijk})$ is the minimum travel distance for the given set of hospitals by x_{ijk}.

The first constraint given by Eq. (2) in the model restricts the accumulation of waste at hospitals and assures that the collected waste by each truck at each day is less than the truck capacity at a probability level α. This constraint sets a service level for the hospitals visited that must be meet. The service level is expressed as the probability of picking up accumulated waste when the truck arrives given as α. Higher values for α imply higher service level with α of 0.9–0.95 present an acceptable service level. Equation (3) constrains the visits to hospitals to be 2 days apart at maximum. The third and last constraint in Eq. (4) states that Friday is a holiday and no hospitals will be visited.

The objective function given by Eq. (1) is the sum of the travel distance $D(x_{ijk})$ for each truck for each day. Finding

Table 2 Travel distances between incinerator and hospitals and between hospitals (km)

From/to	Incinerator	King Abullah University Hospital	Rahibat Alwardyah Hospital	Ibn Alnafees Hospital	Alnajah Hospital	Algawasmi Speciality Hospital	Catholic Hospital	Irbid Islamic Hospital	Mafraq Military Hospital	Ramtha Military Hospital
Incinerator	0	3	16	17	19	17	18	18	35	14
King Abullah University Hospital		0	13	14	16	14	15	15	32	11
Rahibat Alwardyah Hospital			0	2	3	2	3	3	48	16
Ibn Alnafees Hospital				0	2	1	2	2	47	15
Alnajah Hospital					0	2	3	3	48	16
Algawasmi Speciality Hospital						0	1	1	47	15
Catholic Hospital							0	1	48	16
Irbid Islamic Hospital								0	48	16
Mafraq Military Hospital									0	39
Ramtha Military Hospital										0
Aleeman Hospital										
Prince Rahmah Hospital										
Prince Basmah Hospital										
Prince Rayah Hospital										
Alyarmouk Hospital										
JUST Health Center										
Women and Pediatrics Hospital										
Jarash Military Hospital										
Moaath Bin Jabal Hospital										
Abo Obaidah Hospital										

Table 2 continued

From/to	Aleeman Hospital	Prince Rahmah Hospital	Prince Basmah Hospital	Prince Rayah Hospital	Alyarmouk Hospital	JUST Health Center	Women and Pediatrics Hospital	Jarash Military Hospital	Moaath Bin Jabal Hospital	Abo Obaidah Hospital
Incinerator	25	18	23	43	30	17	40	31	40	65
King Abullah University Hospital	22	15	20	40	27	16	37	28	37	62
Rahibat Alwardyah Hospital	34	5	6	26	17	2	54	39	20	42
Ibn Alnafees Hospital	33	4	5	25	16	1	53	38	19	41
Alnajah Hospital	32	1	6	24	17	2	54	37	19	41
Algawasmi Speciality Hospital	33	4	5	25	16	1	53	38	19	41
Catholic Hospital	32	2	2	24	17	2	54	37	19	41
Irbid Islamic Hospital	32	2	2	24	17	2	54	37	19	41
Mafraq Military Hospital	65	48	48	65	57	47	7	53	66	88
Ramtha Military Hospital	51	18	19	42	26	20	41	39	39	61
Aleeman Hospital	0	34	36	30	48	33	69	23	54	76
Prince Rahmah Hospital		0	6	25	13	6	55	42	19	41
Prince Basmah Hospital			0	24	12	5	56	41	19	41
Prince Rayah Hospital				0	35	24	86	45	6	24
Alyarmouk Hospital					0	15	66	52	37	58
JUST Health Center						0	53	38	20	42
Women and Pediatrics Hospital							0	59	73	94
Jarash Military Hospital								0	50	71
Moaath Bin Jabal Hospital									0	26
Abo Obaidah Hospital										0

Table 3 Current waste collection schedule along with the travel distance for each route

Truck	Day	King Abullah University Hospital H1	Rahibat Alwardyah Hospital H2	Ibn Alnafees Hospital H3	Alnajah Hospital H4	Algawasmi Speciality Hospital H5	Catholic Hospital H6	Irbid Islamic Hospital H7	Mafraq Military Hospital H8	Ramtha Military Hospital H9
1	1	10	2	1	4	7	6	8		
1	2	4							1	3
1	3	10	2	1	4	7	6	8		
1	4	4							1	3
1	5	10	2	1	4	7	6	8		
1	6	4							1	3
1	7									
2	1									
2	2									
2	3									
2	4									
2	5									
2	6									
2	7									
Visits per week		6	3	3	3	3	3	3	3	3

Truck	Day	Aleeman Hospital H10	Prince Rahmah Hospital H11	Prince Basmah Hospital H12	Prince Rayah Hospital H13	Alyarmouk Hospital H14	JUST Health Center H15	Women and Pediatrics Hospital H16	Jarash Military Hospital H17	Moaath Bin Jabal Hospital H18	Abo Obaidah Hospital H19	Travel distance
1	1		3	5			9					56
1	2							2				96
1	3		3	5			9					56
1	4							2				96
1	5		3	5			9					56
1	6							2				96
1	7											
2	1				4	1				2	3	160
2	2	2	3	4					1			117
2	3				4	1				2	3	160
2	4	2	3	4					1			117
2	5				4	1				2	3	160
2	6	2	3	4					1			117
2	7											
Visits per week		3	6	6	3	3	3	3	3	3	3	1287

Numbers in this table represent the order in which hospitals are visited

Table 4 Optimal waste collection schedule along with the travel distance for each optimal route

Truck	Day	King Abullah University Hospital H1	Rahibat Alwardyah Hospital H2	Ibn Alnafees Hospital H3	Alnajah Hospital H4	Algawasmi Speciality Hospital H5	Catholic Hospital H6	Irbid Islamic Hospital H7	Mafraq Military Hospital H8	Ramtha Military Hospital H9
1	1	8	7	1	6	2	4	3	10	
1	2	6								1
1	3									
1	4									
1	5	1							2	
1	6		9	7		6	3	5		
1	7									
2	1									
2	2									
2	3	6	5	4	3	2		1	7	
2	4	1					2			4
2	5				2					
2	6	1								2
2	7									
Visits per week		6	3	3	3	3	3	3	3	3

Truck	Day	Aleeman Hospital H10	Prince Rahmah Hospital H11	Prince Basmah Hospital H12	Prince Rayah Hospital H13	Alyarmouk Hospital H14	JUST Health Center H15	Women and Pediatrics Hospital H16	Jarash Military Hospital H17	Moaath Bin Jabal Hospital H18	Abo Obaidah Hospital H19	Travel distance
1	1						5	9				119
1	2	4				2			3			140
1	3		1	5	3		6			2	4	130
1	4	1							2			79
1	5							3				82
1	6	1	4				8		2			110
1	7											0
2	1		5	1	3					2	4	131
2	2											0
2	3							8				117
2	4					3						75
2	5		1	6	4					3	5	132
2	6					3						70
2	7											0
Visits per week		3	4	3	3	3	3	3	3	3	3	1185

Numbers in this table represent the order in which hospitals are being visited

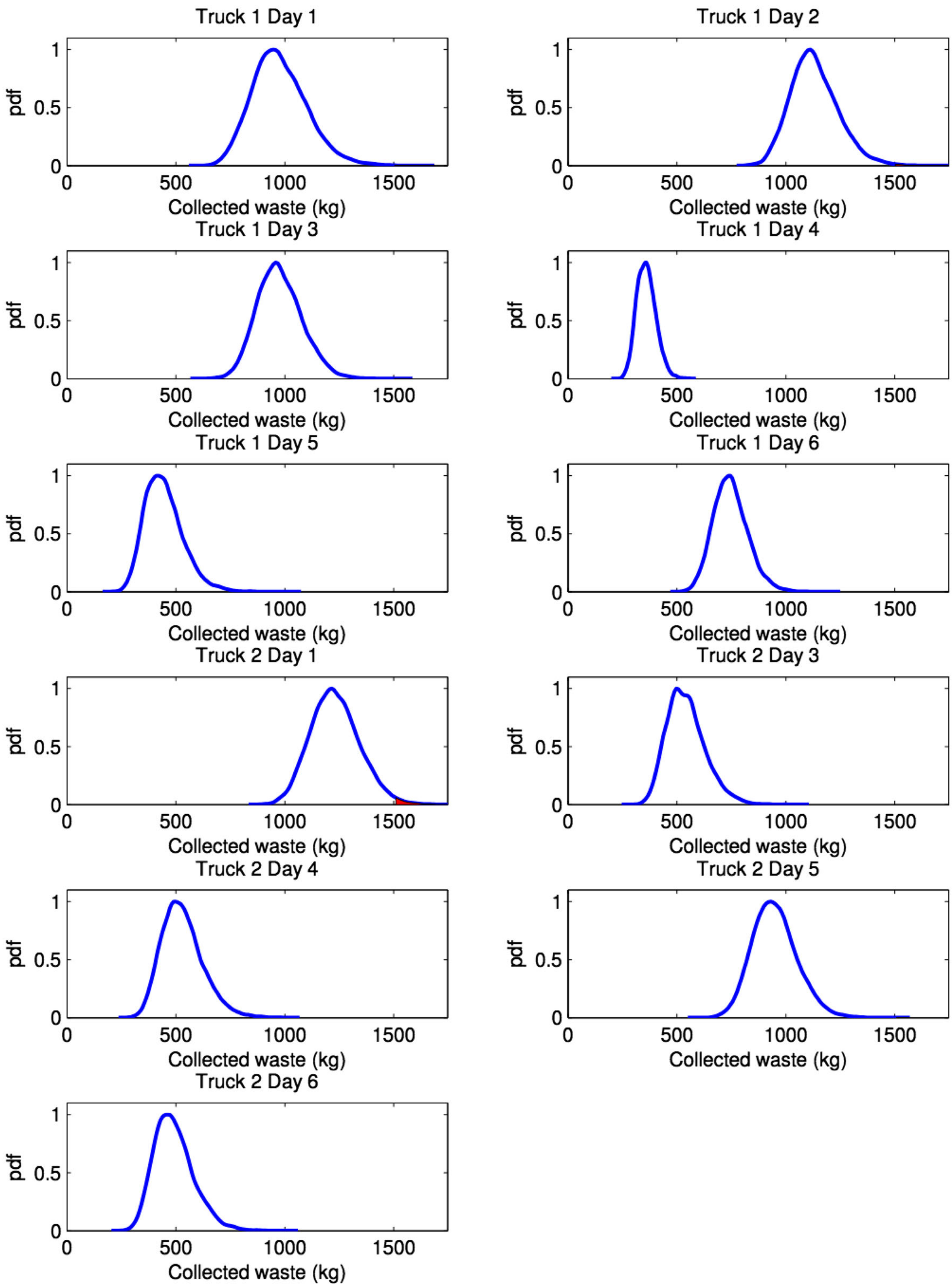

Fig. 3 Probability distribution of daily collected waste for each truck. *Shaded areas* represent the probability of daily picked up waste being greater than the truck capacity

$D(x_{ijk})$ for a given x_{ijk} values is in itself an optimization problem. Fortunately, this is a well studied problem in operations research known as the travel salesman problem (TSP) [4, 12, 14].

Results and discussion

The model described in "Mathematical model" section has been programmed as a set of Matlab m-files. Matlab version 7.11 (R2010b) was used. The objective function for our model is discrete and hence, the genetic algorithm (GA) optimization routine implemented in Matlab was used to optimize for the proposed model. Genetic algorithm parameters were set as follows. Each chromosome consisted of 266 binary genes (combination of $i = 2$ trucks, $j = 19$ hospitals, and $k = 7$ days) representing x_{ijk} values. Population size was set to 60 chromosomes and the number of generations was set at 150 generations. Permutation of new population was restricted such that each new chromosome must satisfy the model constraints given in Eqs. (3) and (4). Following Matlab's GA routine, permutations were done gene wise to generate new chromosomes. As for stopping criteria, stall generations was set at 40 generations with a tolerance of 0.0001. That is, if the average improvement in the objective function value over 40 generations is less than the tolerance provided, the algorithm stops. As indicated by Eq. (1), optimization is done in two steps. In the first step, the algorithm proposes a new set of values for x_{ijk}. While in the second step, suggested visits for each truck and day combinations are fed into a TSP optimization routine to find the best routing schedule for hospitals to be visited and then the total cost is calculated over the 14 combinations of trucks and days. The used TSP optimization routine is based also on the use of GA algorithm and is publicly available [7]. To validate permuted chromosomes for constraint (2), collected waste was simulated 100,000 times and the probability that the collected waste exceeds truck capacity was obtained. The service level α was set at 0.95.

The found optimal schedule for collection trucks is shown in Table 4. At a first glance it can be noted that for day 2, truck 2 has not been scheduled to collect waste saving a day for truck service and maintenance. The total travel distance for the optimal schedule is 1185 km, a saving of 102 km in travel distance was achieved. We note here that each of the nineteen hospitals considered is visited at least three times per week according to the proposed schedule. This is important since most hospitals have limited storage capacity for medical waste and hence, the found optimal schedule solves their storage problem and meets contract requirements.

Fitted distributions of daily collected waste for both trucks are shown in Fig. 3 with probability of collected waste exceeding truck capacity shown as shaded area. A summary of the fitted distributions in Fig. 3 including the average and the probability that the collected waste exceeds truck capacity are given in Table 5. For the two trucks the achieved service level is at least 98 %.

We shall note that the problem considered in here is a medium sized optimization problem with 266 decision variables and four constraints. For larger sized problems, using the GA approach might not be the best and other optimization heuristics might be employed. For more information on heuristics used for solving transportation problems, readers are suggested to have a look at *Vehicle Routing: Problems, Methods, and Applications* by Toth and Vigo [13].

Conclusions

In this paper, we consider a stochastic medical waste collection problem. We show how the stochasticity of collected waste can be implemented in the model as a probability constraint representing the service level

Table 5 Average collected medical waste for the optimal schedule along with the probability that the collected waste exceeds truck capacity

Truck	Day	Average collected waste (kg)	P (collected waste $\leq$ capacity)
1	1	976.72	0.9995
1	2	1131.5	0.9974
1	3	976	0.9999
1	4	359.89	1
1	5	445.25	1
1	6	746.67	1
2	1	1230.95	0.9869
2	3	542.82	1
2	4	530.24	1
2	5	949.12	0.9999
2	6	491.59	1

Table 6 Average collected waste following the proposed schedule

Truck	Day	Average collected waste (kg)
1	1	950.07
1	2	1095.45
1	3	1011.27
1	4	439.82
1	5	576.55
1	6	712.23
2	1	1402.76
2	3	597.36
2	4	501.09
2	5	889.35
2	6	471.28

provided by the waste collector. The service level was set at 95 % and the optimal solution was obtained through the use of Genetic algorithm optimization routine in Matlab. Compared with the current routing schedule, the proposed model provides a less costly routing schedule with 1185 km of travel distance at a saving of 102 km per week. The obtained routing schedule has been verified for 4 weeks and the actual performance was similar to that found by our model. Average collected waste for the 4 weeks based on the proposed schedule is shown in Table 6.

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