Age-Dependent Inventory Routing Problem Model for Medical Waste Collection

Ridho Syahrial Ibrahim, Ahmad Rusdiansyah
Department of Industrial and Systems Engineering
Institut Teknologi Sepuluh Nopember
Surabaya, 60111, Indonesia
ridho.101891@gmail.com, arusdian@ie.its.ac.id

Abstract

The growth of human population results more and more medical waste generated by healthcare activities. Typically, if the disposal of the medical waste is done by a medical waste disposal company, a medical waste vehicle visits the healthcare to collect the waste periodically. To minimize the cost, healthcare facilities tend to prefer a low frequency of visits, i.e., until the inventory level reaches the maximum of its capacity, or the age of the waste is at nearly maximum allowance. If some of all healthcare facilities request a visit at a same time, this preference could make some problems for the medical waste disposal company, such as overcapacity or delayed visits to other healthcare facilities because of limited number of available vehicles. In this paper, we integrate Vendor-Managed Inventory (VMI) concept into an inventory routing model to make an optimized medical waste vehicle schedules and routes, whereas the medical waste disposal company has flexibilities to decide the visit schedule and the number of medical waste bags to be carried, as long there is no overcapacity problem and no medical waste aged more than allowed in all healthcare facilities. From the numerical experiments, it shows that by forcing the medical waste disposal company to pick up all medical waste in the inventory for every visit, i.e., reduce flexibility, there is a probability that overcapacity may occurs at the waste disposal facility. Additionally, the total cost is may increased when the flexibility is reduced.

Keywords
Medical Waste, Inventory Routing Problem, Vendor-Managed Inventory, Mixed Integer Linear Programming

1. Introduction
Along with the increasing number of human population in the world, the number of healthcare facilities is also increased (Mete and Serin, 2019), resulting more medical waste generated by the healthcare facilities and spread in more locations. The medical waste produced by healthcare facilities is classified as waste that is hazardous to human health and environment (Chaerul et al., 2008). So, it is very important for healthcare facilities to have a good medical waste management system. The management system includes, but not limited to, waste collection, storage, and transportation process. According to the recommendation of World Health Organization (WHO), medical waste produced by healthcare facilities should be stored in a temporary storage. In Indonesia, the maximum duration of storing the waste is regulated in Peraturan Menteri Kesehatan No. 7 Tahun 2019 Tentang Kesehatan Lingkungan Rumah Sakit (2019). For instance, the maximum duration of storing an infectious waste is 7 days if the storage temperature is between 2- and 8-degree Celsius.

The waste disposal process can be done in-house by the healthcare facility or by using a medical waste disposal service company. If the waste disposal is managed by a medical waste disposal company, healthcare facilities tend to prefer a low frequency of visits, i.e., until the inventory level reaches the maximum of its capacity, or the age of the waste is at nearly maximum allowance, where for every visit, the vehicle must pick up all the medical waste in the inventory or storage. If some or all healthcare facilities request a visit at a same period, this preference could result some problems, such as overcapacity in medical waste disposal facility or a late visit to healthcare facilities that is caused by no more available medial waste vehicle. These problems could be avoided if there is a coordination between the healthcare facilities and the waste disposal company by giving flexibilities to the medical waste disposal company the visit schedule and quantities of medical waste bags to be picked up. Also, this cooperation can result a better utilization

of vehicle capacity, that can lead to a lower total cost. In a context of supply chain, this kind of coordination is known as Vendor-Managed Inventory (VMI).
Therefore, in this research we integrate VMI concept into an inventory routing model to make an optimized medical waste vehicle schedules and routes.

2. Literature Review

2.1 Vendor-Managed Inventory

Vendor-Managed Inventory, or also known as supplier-managed inventory, is a form of coordination in a supply chain which aim to minimize the supply chain cost, where the supplier, usually a manufacturer or reseller, has a responsibility to decide a replenishment policy in the organization that consumes its goods or services (Waller and Johnson, n.d.). The replenishment policy involves the replenishment schedule and the replenishment size. A research by Rusdiansyah and Tsao (2005) in a vending-machine supply chain showed that a huge saving in operational cost is obtained by making the replenishment schedule flexible. Speranza et al. (n.d.) developed a vendor-managed inventory routing problem where it showed that by giving flexibilities in both replenishment schedule and replenishment size, more substantial saving is generated compared to if only flexibility in replenishment schedule is given.

2.2 Related Studies

There are previous researches regarding the optimization of medical waste transportation problem. Gu and Baran (2017) used Travelling Salesman Problem (TSP) model to solve the problem. The objectives of the research are to minimize the distance traveled by the waste vehicle and its average speed.

Hachicha et al. (2014) modeled a real-world problem using Capacitated Vehicle Routing Problem (CVRP) to minimize the distance traveled by vehicles in a medical waste transportation system in Tunisia. A CVRP model was also used by Mete and Serin (2019) to decide the location of medical waste disposal. In that research, there were 167 medical waste producers and 5 candidates of medical waste disposal location. The model was run by using those 5 locations as a depot, then the location of waste disposal was decided by comparing the result and chose the most optimum one. Ahlaqqach et al. (2020) presented a Hazmat Heterogeneous Fleet Vehicle Routing Problem (HHFVRP) where medical waste collected from several healthcare facilities was centralized in a central warehouse which acts as a depot before being delivered to several medical waste disposal facilities. The objective of the model is to minimize the total cost and risk in the transportation process.

Ghannadpour et al. (2021) developed a Healthcare Waste Collection Vehicle Routing Problem (HWCVRP) model to minimize the transportation cost of the medical waste, social risk, and fuel consumption of the medical waste vehicle. In this research, vehicles departed from a depot to healthcare facilities to pick up medical waste. The vehicle then continued the trip by visiting waste disposal facility to unload them before went back to the depot.
A Periodic Load-dependent Vehicle Routing Problem (PLVRP) considering transportation and storage risk was developed by Taslimi et al. (2020). The results showed that if only storage risk is considered, the frequency of vehicle visits will be increased, in other words there should not be any medical waste are stored in the healthcare's inventory. On the contrary, if only transportation risk is considered, then vehicles will visit the healthcare as late as possible to reduce the risk of medical waste accident happened during the transportation.

The stochasticity of medical waste produced by healthcare facilities is considered in the Periodic Vehicle Routing Problem (PVRP) model by Alshraideh and Abu Qdais (2017). The model developed is implemented to a real-life problem that involves 19 hospitals and a medical waste disposal facility. The model results a better solution than existing condition, with a difference of distance travelled per week needed is 102 km.

A flexibility for the waste collector to decide the visit schedule to several pharmacies is integrated into the Stochastic Collector Managed Inventory Routing Problem (SCMIRP) model developed by Nolz et al (2011). The Age-dependent Medical Waste Inventory Routing Problem (AMWIRP) model developed in this research is more "relaxed", where the medical waste disposal company has flexibilities to decide the visit schedule to each healthcare facility and the number of medical waste bags picked up. The model developed also considers age of the waste, where there is a policy for maximum of age of the waste stored in the inventory.

3. Problem Description and Notation

The Age-dependent Medical Waste Inventory Routing Problem (AMWIRP) is defined on a graph $\mathcal{G} = (\mathcal{N}', \mathcal{A})$. Where $\mathcal{N}'$ and $\mathcal{A}$ are set of nodes including depot, and set of arcs, respectively. More precisely, $\mathcal{N}' = \mathcal{N}_K \cup \mathcal{N}_{PL}$, where $\mathcal{N}_K$ represents a set of healthcare facilities and $\mathcal{N}_{PL}$ represents a set of waste disposal facilities including depot. Let us also define $\mathcal{N}$ as a set of all nodes excluding depot. This problem can be considered as a dynamic problem, so a set of discrete planning horizon $\mathcal{T} = \{1,2, \dots, T\}$ is considered, where $\mathcal{T}' = \{0\} \cup \mathcal{T}$.

In each period $t \in \mathcal{T}$, every node $i \in \mathcal{N}'$ has an inventory level of waste aged $w \in \mathcal{W}'$ period, I_{itw}, and an inventory capacity of U_i. The inventory level of each node $i \in \mathcal{N}_K$ is increased along a number of waste bags produced, d_{it}, in each period. The maximum duration of storing the waste bag in each healthcare's inventory is B period. If node $i \in \mathcal{N}_K$ is visited by the medical waste vehicle, waste bags aged w period, q_{itw}, will be loaded into the vehicle. In the same period, the medical waste vehicle can continue to visit other unvisited healthcare facilities or visit unvisited waste disposal facilities to unload the medical waste bag. In each period $t \in \mathcal{T}$, each node $i \in \mathcal{N}_{PL}$ disposes a number of waste bags aged w period, e_{itw} that can not exceed its disposal capacity, d_{it}. And finally, a traveling cost c_{ij} is charged if a vehicle traverses from node $i \in \mathcal{N}'$ to node $j \in \mathcal{N}'$.

In this problem there is a collaboration between the healthcare facilities and the waste disposal company. The healthcare facilities give their inventory level information and flexibilities to the waste disposal company regarding the visit schedule and the number of waste bag picked up by vehicles. So, some decisions must be made by the waste disposal company involves:

1. When to visit each healthcare facility and each medical waste disposal facility?
2. How many medical waste bags are picked up for every visit to each healthcare facility? And how many medical waste bags are delivered to each waste disposal facility?
3. How is the route of the medical waste vehicle?

4. Mathematical Model

The model we developed is based on the Inventory Routing Problem with Pickups and Deliveries (IRP-PD) by Archetti et al. (2018). The notations used in the model is shown in table 1.

Table 1. Notations

Sets	
$\mathcal{N}_K$	Set of all healthcare facilities
$\mathcal{N}_{PL}$	Set of medical waste disposal facilities, including depot
$\mathcal{N}'$	Set of all nodes, including depot, $\mathcal{N}' = \mathcal{N}_K \cup \mathcal{N}_{PL}$, $\mathcal{N}' = \{0,1,2, \dots, N\}$
$\mathcal{N}$	Set of all nodes, excluding depot, $\mathcal{N} = \{1,2, \dots, N\}$
$\mathcal{A}$	Set of arcs (i, j) where $i, j \in \mathcal{N}'$
$\mathcal{T}$	Set of time-periods, $\mathcal{T} = \{1,2, \dots, T\}$, $t \in \mathcal{T}$
$\mathcal{T}'$	Set of time-periods, including period 0, $\mathcal{T}' = \mathcal{T} \cup 0$
$\mathcal{W}$	Set of waste age-period $\mathcal{W} = \{1,2, \dots, W\}$, $w \in \mathcal{W}$
$\mathcal{W}'$	Set of waste age-period, including period 0 $\mathcal{W}' = \mathcal{W} \cup 0$
Parameter	
d_{it}	If $i \in \mathcal{N}_K$: Number of medical waste bags produced in period If $i \in \mathcal{N}_{PL}$: Maximum capacity of waste disposal
U_i	Maximum capacity of inventory at node i
c_{ij}	Cost of traversing from node i to node j
m	Number of available vehicles
CAP	Vehicle capacity
I_{i0w}	Inventory level of medical waste bag aged $w \in \mathcal{W}'$ period at node i in period 0
Variable	
q_{itw}	If $i \in \mathcal{N}_K$: Number of medical waste bag picked up in period t If $i \in \mathcal{N}_{PL}$: Number of medical waste bag delivered in period t
y_{it}	Binary variable that takes value of 1 if node $i, i \neq 0$ is visited at period t,; 0 otherwise

y_{0t}	Number of vehicles used at period t
I_{itw}	Inventory level of medical waste bag aged $w \in \mathcal{W}'$ period at node i in period 0
x_{ijt}	Binary variable that takes value of 1 if arc $(i,j) \in \mathcal{A}$ is assigned to a vehicle at period t; 0 otherwise
l_{ijtw}	Number of medical waste bags aged $w \in \mathcal{W}'$ period in a vehicle when traversing arc $(i,j) \in \mathcal{A}$
e_{itw}	Number of medical waste bags age $w \in \mathcal{W}'$ period disposed at node $i \in \mathcal{N}_{PL}$ in period t

4.1 Objective Function

The objective of the AMWIRP model made is to minimize the total cost which only consist of travelling cost. It can be written mathematically as (1).

$$minimize \sum_{(i,j)\in\mathcal{A}} \sum_{t\in\mathcal{T}} c_{ij} x_{ijt} \qquad (1)$$

4.2 Integrality and Binary Constraints

The medical waste produced by healthcare facilities is contained in a plastic bag. Thus, the medical waste stored in the inventory I_{itw}, picked up at node $i \in \mathcal{N}_K$ or delivered to node $i \in \mathcal{N}_{PL}$, q_{itw}, and in-transit medical waste l_{ijtw} are discrete. Mathematically, it can be written as (2), (3), and (4).

$$q_{itw} \in \mathbb{Z} \qquad \forall i \in \mathcal{N}', t \in \mathcal{T}', w \in \mathcal{W}' \qquad (2)$$

$$l_{ijtw} \in \mathbb{Z} \qquad \forall (i,j) \in \mathcal{A}, t \in \mathcal{T}, w \in \mathcal{W}' \qquad (3)$$

$$I_{itw} \in \mathbb{Z} \qquad \forall i \in \mathcal{N}', t \in \mathcal{T}', w \in \mathcal{W}' \qquad (4)$$

If node $i \in \mathcal{N}$ is visited by a vehicle in period $t \in \mathcal{T}$, then y_{it} is equal to 1, otherwise 0. If an arc $(i,j) \in \mathcal{A}$ is traversed by a vehicle, then x_{ijt} is equal to 1, otherwise 0. These binary constraints can be written as (5) and (6).

$$y_{it} \in \{0,1\} \qquad \forall i \in \mathcal{N}, t \in \mathcal{T} \qquad (5)$$

$$x_{ijt} \in \{0,1\} \qquad \forall (i,j) \in \mathcal{A}, t \in \mathcal{T} \qquad (6)$$

4.3 Routing Constraints

The number of vehicles used in period $t \in \mathcal{T}$ is equal to the number of arcs traversed by vehicles directly from depot. It can be written mathematically as (7).

$$\sum_{j\in\mathcal{N}} x_{0jt} - y_{0t} = 0 \qquad \forall t \in \mathcal{T} \qquad (7)$$

Constraint (8) enforces that if a node $i \in \mathcal{N}$ is visited at period $t \in \mathcal{T}$, then there must be an arc traversed to that node. This constraint also enforces that the maximum number of visit to every node except depot is once in each period.

$$\sum_{j\in\mathcal{N}'} x_{jit} - y_{it} = 0 \qquad \forall i \in \mathcal{N}, t \in \mathcal{T} \qquad (8)$$

The number of vehicles exiting from node $i \in \mathcal{N}'$ is equal to the number of vehicles arrived at that node. This flow reservation constraint can be written mathematically by (9).

$$\sum_{j\in\mathcal{N}'} x_{jit} - \sum_{j\in\mathcal{N}'} x_{ijt} = 0 \qquad \forall i \in \mathcal{N}', t \in \mathcal{T} \qquad (9)$$

To eliminate subtour, constraint (10) is needed. This subtour elimination constraint is written as (10).

$$\sum_{i\in\mathcal{S}} \sum_{j\in\mathcal{S}} x_{ijt} \leq \sum_{i\in\mathcal{S}} y_{it} - y_{mt} \qquad \forall \mathcal{S} \subseteq \mathcal{N}, m \in \mathcal{S}, t \in \mathcal{T} \qquad (10)$$

4.3 Inventory Constraints

At node $i \in \mathcal{N}_K$ in period $t \in \mathcal{T}$, the number of waste bags aged 0 period in the inventory, I_{it0}, is defined as the difference between the number of waste bags produced at that period and waste bags aged 0 period picked up by a vehicle. It can be written mathematically as (11).

$$I_{it0} - d_{it} + q_{it0} = 0 \qquad \forall i \in \mathcal{N}_K, t \in \mathcal{T} \qquad (11)$$

At node $i \in \mathcal{N}_K$ in period $t \in \mathcal{T}$, the inventory level of waste aged w period, where $w \neq 0$, is defined as the inventory level of waste aged $w-1$ at period $t-1$ minus the number of waste bags aged w period picked up by a vehicle. It can be written mathematically as (12).

$$I_{itw} - I_{i,t-1,w-1} + q_{itw} = 0 \qquad \forall i \in \mathcal{N}_K, t \in \mathcal{T}, w \in \mathcal{W} \qquad (12)$$

The total inventory level at node $i \in \mathcal{N}_K$ in period $t \in \mathcal{T}$ must not exceed its maximum capacity. It can be written mathematically as (13).

$$\sum_{w \in \mathcal{W}'} I_{itw} \leq U_i \qquad \forall i \in \mathcal{N}_K, t \in \mathcal{T} \qquad (13)$$

At node $i \in \mathcal{N}_K$ in each period $t \in \mathcal{T}$, it is not allowed to have a waste bag aged more than $A \in \mathcal{W}_{\mathcal{A}}$ period. Mathematically, it can be written as (14).

$$\sum_{w \notin \mathcal{W}_{\mathcal{A}}} I_{itw} = 0 \qquad \forall i \in \mathcal{N}_K, t \in \mathcal{T} \qquad (14)$$

In each period $t \in \mathcal{T}$, the inventory level of waste bag aged 0 period at node $i \in \mathcal{N}_{PL}$ is defined as the number of waste bags aged 0 period delivered at that node minus the number of waste bags aged 0 period disposed in that period. It can be written mathematically as (15).

$$I_{it0} - q_{it0} + e_{it0} = 0 \qquad \forall i \in \mathcal{N}_{PL}, t \in \mathcal{T} \qquad (15)$$

At node $i \in \mathcal{N}_{PL}$ in period $t \in \mathcal{T}$, the inventory level of waste aged w period, where $w \neq 0$, is defined as the inventory level of waste aged $w-1$ at period $t-1$ plus the number of waste bags aged w period delivered minus the number of waste bags aged w period disposed. It can be written mathematically as (16).

$$I_{itw} - q_{itw} - I_{i,t-1,w-1} + e_{itw} = 0 \qquad \forall i \in \mathcal{N}_{PL}, t \in \mathcal{T}, w \in \mathcal{W} \qquad (16)$$

The number of waste bags unloaded at node $i \in \mathcal{N}_{PL}$ plus the total inventory level at previous period should not exceed its inventory capacity. This constraint can be written as (17)

$$\sum_{w \in \mathcal{W}'} I_{i,t-1,w} + \sum_{w \in \mathcal{W}'} q_{itw} \leq U_i \qquad \forall i \in \mathcal{N}_{PL}, t \in \mathcal{T} \qquad (17)$$

The number of waste bags stored in the inventory must be equal or larger than 0 in every node $i \in \mathcal{N}'$. It can be written as (18).

$$\sum_{w \in \mathcal{W}'} I_{itw} \geq 0 \qquad \forall i \in \mathcal{N}', t \in \mathcal{T} \qquad (18)$$

4.4 Load-Related Constraints

The number of waste bags picked up and delivered must not be a negative value. It can be written mathematically as (19).

$$\sum_{w \in \mathcal{W}'} q_{itw} \geq 0 \qquad \forall i \in \mathcal{N}', t \in \mathcal{T} \qquad (19)$$

The number of waste bags picked up and delivered must not exceed the vehicle's capacity. It can be written as (20).

$$\sum_{w \in \mathcal{W}'} q_{itw} \leq CAPy_{it} \qquad \forall i \in \mathcal{N}', t \in \mathcal{T} \qquad (20)$$

The number of waste bags aged w period in a vehicle after a visit to node $i \in \mathcal{N}_K$ is equal to the number of its load before the visit plus the number of waste bags age w period picked up at that node. Mathematically, it can be written as (21).

$$\sum_{j \in \mathcal{N}'} l_{jitw} + q_{itw} - \sum_{j \in \mathcal{N}'} l_{ijtw} = 0 \qquad \forall i \in \mathcal{N}_K, t \in \mathcal{T}, w \in \mathcal{W}' \qquad (21)$$

The number of waste bags aged w period in a vehicle after a visit to node $i \in \mathcal{N}_{PL}$ is equal to the number of its load before the visit plus the number of waste bags age w period delivered at that node. Mathematically, it can be written as (22).

$$\sum_{j \in \mathcal{N}'} l_{jitw} - q_{itw} - \sum_{j \in \mathcal{N}'} l_{ijtw} = 0 \qquad \forall i \in \mathcal{N}_{PL}, t \in \mathcal{T}, w \in \mathcal{W}' \qquad (22)$$

The total load of a vehicle when traversing arc $(i, j) \in \mathcal{A}$ must not exceed its capacity. It can be written as (23).

$$\sum_{w \in \mathcal{W}'} l_{ijtw} \leq CAPx_{ijt} \qquad \forall (i, j) \in \mathcal{A}, t \in \mathcal{T} \qquad (23)$$

The total load of a vehicle when traversing arc $(i, j) \in \mathcal{A}$ must be equal or larger than 0. It is written as (24).

$$\sum_{w \in \mathcal{W}'} l_{ijtw} \geq 0 \qquad \forall (i, j) \in \mathcal{A}, t \in \mathcal{T} \qquad (24)$$

In each period $t \in \mathcal{T}$, all vehicles depart from the depot without load. It can be written mathematically as (25).

$$\sum_{w \in \mathcal{W}'} l_{0jtw} = 0 \qquad \forall j \in \mathcal{N}, t \in \mathcal{T} \qquad (25)$$

4.5 Other Constraints

The total number of waste bags disposed at node $i \in \mathcal{N}_{PL}$ in period $t \in \mathcal{T}$ should not exceed its maximum disposal capacity. It can be written mathematically as (26).

$$\sum_{w \in \mathcal{W}'} e_{itw} \leq d_{it} \qquad \forall i \in \mathcal{N}_{PL}, t \in \mathcal{T} \qquad (26)$$

The number of vehicles used each period should not exceed the number of available vehicles. It can be written as (27).

$$y_{it} \leq y_{t0} \leq m \qquad \forall i \in \mathcal{N}, t \in \mathcal{T} \qquad (27)$$

4.5 Model for Partial Flexibility Scenario

In this scenario, all healthcare facilities only give a flexibility to the waste disposal company regarding the visit schedule. In other words, if a healthcare facility is visited, all medical waste bags stored in their inventory must be picked up by the vehicle. So, these following constraints must be added to the model.

$$y_{it} d_{it} - q_{it0} = 0 \qquad \forall i \in \mathcal{N}_K, t \in \mathcal{T} \qquad (28)$$

$$y_{it} I_{i,t-1,w-1} - q_{itw} = 0 \qquad \forall i \in \mathcal{N}_K, t \in \mathcal{T}, w \in \mathcal{W} \qquad (29)$$

That policy, i.e., reducing flexibility, can result an overcapacity at waste disposal facility. So, constraint (17) should be removed from the model. Instead, we introduce a new variable f_{it}, which is the number of excess waste bags in the inventory at node $i \in \mathcal{N}_{PL}$ in period $t \in \mathcal{T}$. So, constraint (30) must be added to the model.

$$\sum_{w \in \mathcal{W}'} I_{i,t-1,w} + \sum_{w \in \mathcal{W}'} q_{itw} \leq U_i + f_{it} \qquad \forall i \in \mathcal{N}_{PL}, t \in \mathcal{T} \qquad (30)$$

Please note constraint (30) is valid only when the depot is able to perform a waste disposal. If the waste disposal fully performed by other parties or in other locations, i.e., $\mathcal{N}_{PL} = \{0\} \cup \mathcal{N}_{PLWD}$, then these following constraints should be used instead of (30).

$$\sum_{w \in \mathcal{W}'} I_{0,t-1,w} + \sum_{w \in \mathcal{W}'} q_{0tw} = 0 \qquad \forall t \in \mathcal{T} \qquad (31)$$

$$\sum_{w\in\mathcal{W}'} I_{i,t-1,w} + \sum_{w\in\mathcal{W}'} q_{itw} \le U_i + f_{it} \qquad \forall i \in \mathcal{N}_{PLWD}, t \in \mathcal{T} \qquad (32)$$

There is a penalty M for every single excess of waste bag at node $i \in \mathcal{N}_{PL}$. So the objective function of the model is written as (33).

$$Minimize \sum_{(i,j)\in\mathcal{A}} \sum_{t\in\mathcal{T}} c_{ij}x_{ijt} + \sum_{i\in\mathcal{N}_{PL}} \sum_{t\in\mathcal{T}} f_{it}M \qquad (33)$$

5. Numerical Experiments

In this section, we will use the model to solve a medical waste transportation problem. The model will be run on a dummy instance using exact method through *Lingo* software.

5.1 Instance

The instance used consists of a single depot, where the medical waste disposal facility is located, and six healthcare facilities. The distance between each facilities/nodes is symmetrical, shown in table 2, and visualized in figure 1.

Table 2. Distance between nodes

	c_{ij}						
from \ to	**0**	**1**	**2**	**3**	**4**	**5**	**6**
0	0	36	5	36	16	21	22
1	36	0	31	50	27	48	22
2	5	31	0	34	15	21	17
3	36	50	34	0	48	19	28
4	16	27	15	48	0	36	25
5	21	48	21	19	36	0	27
6	22	22	17	28	25	27	0

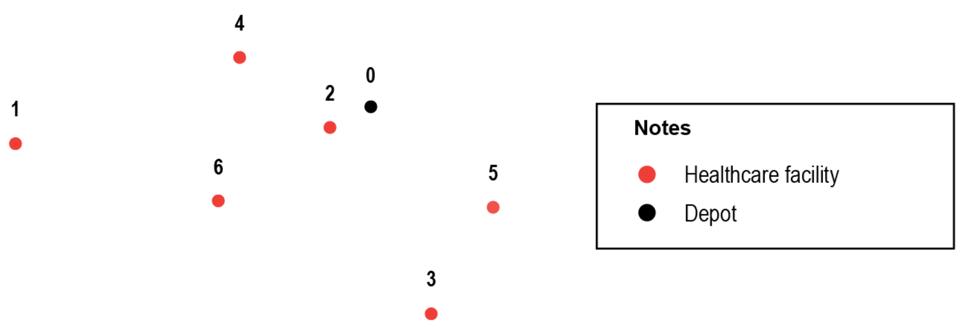

Figure 1. Visualization of the instance

In this problem, the planning horizon is 4 periods. The maximum period for a medical waste bag to be stored in the inventory is 3 periods at the end of each period. For simplification, the medical waste produced in each medical waste is assumed to be constant over time ($d_{i1} = d_{i2} = \cdots = d_{it}$). Six homogeneous waste vehicles are available for each period, with a load capacity of 446 of medical waste bags. The values of each parameter in each node, including the inventory level at the beginning of the planning horizon are shown in table 3.

Table 3. Parameter values at each node

Node i	d_{it}	U_i	I_{i0w}			
			$w = 1$	2	3	4
0	133	400	0	0	0	0
1	39	156	11	9	14	17
2	85	170	55	0	21	64
3	68	204	67	43	63	47
4	89	267	78	64	77	20
5	119	238	11	70	56	50
6	46	138	26	15	9	14

5.1 Optimization Result: Full Flexibility Scenario

In this scenario, the medical waste disposal company is given both flexibilities, the visit schedule and the number of medical waste bag picked up. The optimization result shows that the optimum total cost of 221 is obtained by using 2 medical waste vehicles at period 1, which the route of vehicle 1 is 0-5-3-6-2-0 and the route of vehicle 2 is 0-1-4-0. Both vehicles return to depot with fully loaded condition, 446 of medical waste bags in each vehicle. In period 2, one vehicle is needed to visit node 3, 4, and 6, respectively. In period 3, a visit needed to node 2 to pick up 7 medical waste bags age 4 periods. There is no visit needed in period 4. The detailed values of q_{itw} and inventory level at each node are shown in table 4.

Table 4. Full Flexibility: Number of medical waste bags picked up/ delivered and inventory level at each node

Period t	*Node i*	q_{itw}					I_{itw}					$\sum_{w>4} I_{itw}$
		w=0	1	2	3	4	0	1	2	3	4	
1	**0**	232	106	96	215	243	-	-	-	203	243	-
	1	3	24	37	22	33	36	-	-	-	-	-
	2	26	-	-	38	20	59	11	7	-	-	-
	3	68	45	-	63	11	-	-	-	-	-	-
	4	89	29	58	88	63	-	-	-	-	-	-
	5	-	1	-	2	74	119	21	28	28	-	-
	6	46	7	1	2	42	-	-	-	-	-	-
2	**0**	119	119	21	28	28	88	119	21	28	231	243
	1	-	-	-	-	-	39	36	-	-	-	-
	2	-	-	-	-	-	85	59	11	7	-	-
	3	-	-	-	-	-	68	-	-	-	-	-
	4	-	-	-	-	-	89	-	-	-	-	-
	5	119	119	21	28	28	-	-	-	-	-	-
	6	-	-	-	-	-	46	-	-	-	-	-
3	**0**	85	59	-	11	7	85	147	119	32	35	243
	1	-	-	-	-	-	39	39	36	-	-	-
	2	85	59	-	11	7	-	26	59	-	-	-
	3	-	-	-	-	-	68	68	-	-	-	-
	4	-	-	-	-	-	89	89	-	-	-	-
	5	-	-	-	-	-	119	-	-	-	-	-
	6	-	-	-	-	-	46	46	-	-	-	-
4	**0**	-	-	-	-	-	-	85	147	119	32	35
	1	-	-	-	-	-	39	39	39	36	-	-
	2	-	-	-	-	-	85	-	26	59	-	-
	3	-	-	-	-	-	68	68	68	-	-	-
	4	-	-	-	-	-	89	89	89	-	-	-
	5	-	-	-	-	-	119	119	-	-	-	-
	6	-	-	-	-	-	46	46	46	-	-	-

5.2 Optimization Result: Partial Flexibility Scenario

In this scenario, the medical waste disposal company must pick up all medical waste bags stored in the inventory of visited node, but the flexibility regarding the visit schedule decision is remain. The penalty cost for each excess medical waste bag at the depot is 1. The optimization results shows that the minimum of total cost is obtained by using 3 vehicles at period 1, which the route of each vehicle is 0-4-0, 0-1-6-3-0, and 0-2-5-0, respectively. There is no visit needed at period 2. In period 3, a vehicle is needed to visit node 2 and 5 to avoid overcapacity happens at both nodes. And no visit needed at period 4. The detailed values of q_{itw} and inventory level at each node are shown in table 5.

Table 5. Partial Flexibility: Number of medical waste bags picked up/ delivered and inventory level at each node

Period t	Node i	q_{itw}					I_{itw}					$\sum_{w>4} I_{itw}$
		w=0	1	2	3	4	0	1	2	3	4	
1	0	446	138	131	243	243	271	110	131	-	243	-
	1	39	24	37	22	33	-	-	-	-	-	-
	2	85	11	7	38	20	-	-	-	-	-	-
	3	68	45	-	63	11	-	-	-	-	-	-
	4	89	29	58	88	63	-	-	-	-	-	-
	5	119	22	28	30	74	-	-	-	-	-	-
	6	46	7	1	2	42	-	-	-	-	-	-
2	0	-	-	-	-	-	-	-	110	131	-	243
	1	-	-	-	-	-	39	-	-	-	-	-
	2	-	-	-	-	-	85	-	-	-	-	-
	3	-	-	-	-	-	68	-	-	-	-	-
	4	-	-	-	-	-	89	-	-	-	-	-
	5	-	-	-	-	-	119	-	-	-	-	-
	6	-	-	-	-	-	46	-	-	-	-	-
3	0	204	204	-	-	-	-	-	-	110	131	243
	1	-	-	-	-	-	39	39	-	-	-	-
	2	85	85	-	-	-	-	-	-	-	-	-
	3	-	-	-	-	-	68	68	-	-	-	-
	4	-	-	-	-	-	89	89	-	-	-	-
	5	119	119	-	-	-	-	-	-	-	-	-
	6	-	-	-	-	-	46	46	-	-	-	-
4	0	-	-	-	-	-	-	-	-	-	110	131
	1	-	-	-	-	-	39	39	39	-	-	-
	2	-	-	-	-	-	85	-	-	-	-	-
	3	-	-	-	-	-	68	68	68	-	-	-
	4	-	-	-	-	-	89	89	89	-	-	-
	5	-	-	-	-	-	119	-	-	-	-	-
	6	-	-	-	-	-	46	46	46	-	-	-

Table 5 shows that there is an excess inventory of medical waste bags at the depot as much as 309. The optimum total cost for this scenario is 557, which consist 309 of penalty cost and 248 of transportation cost. Even by ignoring the penalty cost, the transportation cost for this scenario is still larger compared to the full flexibility scenario. Also, the maximum number of vehicles needed for a period is 1 more than the full flexibility scenario.

6. Conclusion

In this research we developed an inventory routing model for a medical waste transportation problem considering the age of the waste. We also integrated Vendor-Managed Inventory concept into the model, where the medical waste disposal company has flexibilities in terms of visit schedule and number of medical waste bags picked up. From the numerical experiments, it shows that by giving both flexibilities, overcapacity problem at healthcare facilities and medical waste disposal facility could be avoided. If the flexibities are reduced by forcing the medical waste disposal company to pick up all medical waste in the inventory for every visit, there is a probability that overcapacity problem may occurs at the waste disposal facility. Additionally, the total cost is may increased when the flexibility is reduced.

A suggested refinement on our model is to consider time windows, or stochasticity of medical waste produced by healthcare facility. Future work can also consider risk factor such as storage risk and transportation risk.

References

Ahlaqqach, M., Benhra, J., Mouatassim, S., and Lamrani, S., Multi-objective Optimization of Heterogeneous Vehicles Routing in the Case of Medical Waste Using Genetic Algorithm, *Communications in Computer and Information Science*, 1207 CCIS, 256–269, 2020.

Alshraideh, H., and Abu Qdais, H., Stochastic modeling and optimization of medical waste collection in Northern Jordan. *Journal of Material Cycles and Waste Management*, 19(2), 2017.3

Archetti, C., Christiansen, M., and Grazia Speranza, M., Inventory routing with pickups and deliveries. *European Journal of Operational Research*, 268(1), 314–324, 2018.

Chaerul, M., Tanaka, M., and Shekdar, A. V., A system dynamics approach for hospital waste management. *Waste Management*, *28*(2), 442–449, 2008.

Ghannadpour, S. F., Zandieh, F., and Esmaeili, F., Optimizing triple bottom-line objectives for sustainable health-care waste collection and routing by a self-adaptive evolutionary algorithm: A case study from tehran province in Iran. *Journal of Cleaner Production*, *287*, 125010, 2021.

Gu, J., and Baran, E., Optimizing Medical Waste Collection in Eskişehir by Using Multi-Objective Mathematical Model. In *Gazi University Journal of Science Part A: Engineering and Innovation* (Vol. 4, Issue 4), 2017.

Hachicha, W., Mellouli, M., Khemakhem, M., and Chabchoub, H., Routing system for infectious healthcare-waste transportation in Tunisia: A case study. *Environmental Engineering and Management Journal*, *13*(1), 21–28, 2014.

Peraturan Menteri Kesehatan No. 7 Tahun 2019 Tentang Kesehatan Lingkungan Rumah Sakit, 110, 2019.

Mete, S., and Serin, F., Optimization of medical waste routing problem: The case of TRB1 region in Turkey. *International Journal of Optimization and Control: Theories and Applications*, *9*(2), 197–207, 2019

Nolz, P. C., Absi, N., and Feillet, D., Optimization of infectious medical waste collection using RFID. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *6971 LNCS*, 86–100, 2011.

Rusdiansyah, A., and Tsao, D. B., An integrated model of the periodic delivery problems for vending-machine supply chains. *Journal of Food Engineering*, *70*(3), 421–434, 2005.

Speranza, M. G., Archetti, C., Bertazzi, L., Laporte, G., and Speranza, M. G., *A Branch-and-Cut Algorithm for a Vendor-Managed Inventory-Routing Problem A Branch-and-Cut Algorithm for a Vendor Managed Inventory Routing Problem*, (n.d.).

Taslimi, M., Batta, R., and Kwon, C., Medical waste collection considering transportation and storage risk. *Computers and Operations Research*, *120*, 104966, 2020.

Waller, M., and Johnson, M. E., *VENDOR-MANAGED INVENTORY IN THE RETAIL SUPPLY CHAIN Reprinted with permission of Journal of Business Logistics*, (n.d.).

Biography

Ridho S. Ibrahim is a master student of Logistics and Supply Chain Management in the Department of Industrial and Systems Engineering at the Institut Teknologi Sepuluh Nopember. He earned his Diploma in Industrial Electrical Engineering at Politeknik Elektronika Negeri Surabaya before completed his Bachelor of Engineering in Electrical Engineering at the Institut Teknologi Sepuluh Nopember.

Ahmad Rusdiansyah received his B.Eng. in Industrial Engineering from Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia in 1992, the M.Eng. in Industrial Engineering from Dalhousie University, Halifax NS, Canada in 1999 and the Dr.Eng. in Industrial Engineering and Management from Tokyo Institute of Technology, Tokyo, Japan in 2005. He also holds CSCP and CLTD certificates of APICS. He is currently head of the Transportation and Distribution Logistics (TDLog) Research Group. His research interests include transportation and distribution systems modelling.