Immune Based Evolutionary Algorithm for Determining the Optimal Sequence of Multiple Disinfection Operations

Yi-Chih Hsieh\textsuperscript{a}, Pei-Ju Lee\textsuperscript{b}, and Peng-Sheng You\textsuperscript{c,*}

\textsuperscript{a}Department of Industrial Management, National Formosa University
Huwei, Yunlin 632, Taiwan
\textsuperscript{b}Department of Information Management, National Chung Cheng University
Chia-Yi 621, Taiwan
\textsuperscript{c}Department of Business Administration, National ChiaYi University
Chia-Yi 600, Taiwan

(Submitted Oct. 31, 2016; Revised Dec. 16, 2017; Accepted Jan. 13, 2018)

Abstract

This paper presents a new multiple disinfection operation problem (MDOP) in which several buildings have to be sprayed with various disinfectants. The MDOP seeks to minimize the total cost of disinfection operations for all buildings. The problem is different from the typical vehicle routing problem since: (a) each building has to receive multiple spray applications of disinfectants; (b) the final spray application of disinfectant in each building is fixed; and (c) for safety, the time interval between two consecutive spray applications of disinfectants for each building must meet or exceed a specified minimum. The MDOP problem is NP-hard and difficult to solve directly. In this paper, we firstly develop an efficient encoding of spray operations to simultaneously determine the optimal sequence of buildings and their respective treatments with spray disinfectants. Secondly, we adopt immune algorithm to solve the presented MDOP. Finally, as a demonstration of our method, we solve the problem for a campus case to determine the optimal disinfection strategy and routes assuming both single and multiple vehicle scenarios. Numerical results of immune algorithm are discussed and compared with those of genetic algorithm and PSO to show the effectiveness of the adopted algorithm.

Keywords: Disinfection operation, Immune algorithm, Optimization

\*Corresponding author. Fax: + 886-5-2732934.
E-mail address:psyuu@mail.ncyu.edu.tw (P-S You).
1. Introduction

Taiwan is located in a subtropical zone with a long hot and humid season, therefore preventing the infestation of buildings by pests (e.g., flies, fleas, cockroaches, ants, mosquitoes, mice, gnats, etc.) is an important environmental sanitation and disinfection issue. There are four main disinfection methods for buildings:

1. Spray method: Using high pressure approach to spray liquid disinfectants on the area or path of pests.
2. Fumigation method: Heating the disinfectants to generate smoke in the area or path of pests.
3. Enticement method: Putting baits in the area or path of pests.
4. Decomposition method: Tossing disinfectants for decomposition in the area or path of pests.

For simplicity, throughout this paper we use the term “spray” to represent all of the above disinfection methods.

In this paper, we investigate the new multiple disinfection operation problem (MDOP), in which we assume that: (a) each building has to receive multiple sprays of disinfectants in a specific sequence to be effective at preventing infestation by various insects and bacteria; (b) the final disinfectant of spray in some buildings is fixed; (c) for safety, the minimum time interval between two consecutive sprays of disinfectants for each building must be met. The MDOP seeks to minimize the total cost of disinfection operations for all buildings, where the total cost consists of the routing cost of vehicles and both the working and idle costs of workers.

Note that:

1. The MDOP generalizes the typical Traveling Salesman Problem (TSP).
   In a TSP, one has to visit every node of a network once with the objective of minimizing the total travel time [1-3]. Hence, the considered MDOP generalizes the typical TSP if there is only one disinfection operation required for each building, and only the finish time of the disinfection operation for all buildings is considered in the objective.

2. The MDOP generalizes the typical Vehicle Routing Problem (VRP).
   In a VRP, one has to deliver products once to some specified nodes of a network by using multiple vehicles with the goal of minimizing the total vehicle routing time [4-6]. Hence, the considered MDOP generalizes the typical VRP if the buildings of the MDOP have to receive only one application of disinfectant spray and only the total finish time of the disinfection operation is considered.

3. The MDOP generalizes the typical Periodic Vehicle Routing Problem (PVRP).
   In a PVRP, one has to periodically delivery products to some specified nodes for many times with multiple vehicles with the goal of minimizing the total vehicle
routing time [7-9]. Hence, the considered MDOP generalizes the typical PVRP if: (i) the time interval between two consecutive sprays of disinfectants for each building is set to zero; (ii) there is no final spray of disinfectants for any building; and (iii) only the total completion time of the disinfection operation for all buildings is considered.

(4) The MDOP differs from the typical PVRP with time windows (PVRP-TW).
In a PVRP-TW, the vehicle has to periodically delivery product to the specified nodes within the given time windows [10-12]. However, in the considered MDOP, one has to spray various disinfectants for buildings and the time interval between two consecutive spray applications of disinfectants for each building must meet or exceed a specified minimum rather than time windows. Additionally, final spray application of disinfectant in each building is fixed for the MDOP.

(5) The MDOP differs from the typical hole-making problem in manufacturing.
In a hole-making problem, a hole requires various tools to drill and each tool is used to drill for some of holes [13-16]. Moreover, the sequence of tools used for a hole is fixed but no constraint for the time interval of use of tools for a hole. However, in the considered MDOP, the time interval between two consecutive spray applications of disinfectants for each building must meet or exceed a specified minimum and there is no priority for the spray application of disinfectant expect for the final spray.

Since the newly presented MDOP generalizes TSP, VRP, and PVRP, it is more difficult than these three specific routing problems. TSP, VRP and PVRP are all NP-hard problems [17], hence the considered MDOP is also NP-hard. Note that, for the MDOP, one has to determine the sequence of disinfection operations and disinfectants for the buildings with the following constraints: (i) each building’s final disinfectant should be used last for that building; (ii) the time interval between two consecutive sprays of disinfectants for a given building must meet or exceed a given time minimum; and (iii) the total cost (including routing, working, and idle costs) is minimized.

The purposes of this paper are multiple.
(1) A new MDOP is presented and an efficient spray operations encoding is presented to simultaneously determine both the sequence of buildings and the order of spray disinfectants for each building.

(2) An efficient spray operations encoding is proposed and embedded in immune algorithm (IA) to solve the considered MDOP.

(3) A campus case is solved for the optimal disinfection strategy assuming both single and multiple vehicle routes. Numerical results of IA are reported and compared with those of genetic algorithm (GA) and particle swarm optimization (PSO) to show the effectiveness of the adopted IA.
This paper is organized as follows. In Section 2, we present notations and assumptions of the MDOP. Section 3 presents the new efficient spray operations encoding to simultaneously determine both the sequence of buildings to spray and the order of spray operations for each building. Two simple examples are illustrated in this section. In Section 4, we describe the main steps of the three adopted heuristic algorithms (IA, GA, and PSO). Section 5 shows and discusses the numerical results of a campus case study. Finally, conclusions and future research are summarized in Section 6.

2. The new multiple disinfection operations problem (MDOP)

Next, we present the notations and assumptions for the MDOP.

2.1. Notations

\( I \) the number of buildings requiring multiple disinfection operations.
\( i \) the index for buildings, \( i=0, 1, 2, \ldots, I \), where \( i=0 \) denotes the depot.
\( J \) the number of types of disinfectants.
\( j \) the index for the types of disinfectants, \( j=1, 2, \ldots, J \).
\( n_i \) the number of types of disinfectant used for building \( i, n_i \geq 1, i=1, 2, \ldots, I \).
\( N = n_1 + n_2 + \ldots + n_I \) is the total number of disinfection operations for all buildings.
\( t_{ij} \) the spray time of disinfectant \( j \) in building \( i \).
\( q_{ij} \) the required quantity of disinfectant \( j \) for building \( i \).
\( d_{ii'} \) the traveling time from building \( i \) to building \( i', i \neq i', i, i'=0, 1, 2, \ldots, I \).
\( Q \) the disinfectant carrying capacity for each vehicle.
\( w \) the number of workers in a vehicle.
\( L \) the minimum time interval between two consecutive sprays of disinfectants for the same building.
\( \alpha \) the unit cost of traveling a unit distance (meter) for a vehicle.
\( \beta \) the cost of hiring a worker for an hour.
\( \gamma \) the penalty parameter of idle time for a worker.

2.2. Assumptions

(1) There are \( I \) buildings requiring multiple spray applications of disinfectants, and there are \( J \) types of disinfectants used to spray.

(2) Assume that building \( i \) requires \( n_i \) disinfection operations with disinfectants of types \( j_{i,1}, j_{i,2}, \ldots, j_{i,m} \in J, i=1, 2, \ldots, I \), and the spray time of disinfectant type \( j_{i,k} \) is \( t_{ik}, k=1, 2, \ldots, n_i \). \( N = n_1 + n_2 + \ldots + n_I \) is the total number of disinfectant treatments for all buildings.
The types and quantities of disinfectants for each building are given in advance,
and the quantity of disinfectants for a building is proportional to its area.
Assume that $q_{ij}$ is the required quantity of disinfectant $j$ for building $i$ and $d_{ii'}$ is
the travel time from building $i$ to building $i'$, $i \neq i'$, $i, i' \in \{1,2,\ldots,I\}$.

For some buildings, there is a designated final disinfectant that must be used in
the final spray application.

For safety, the time interval between two consecutive sprays of disinfectants for
each building has to meet or exceed a given minimum period of time $L$.

There are multiple identical vehicles available to carry disinfectants and workers,
and each vehicle’s capacity for disinfectants, $Q$, is limited. Each vehicle carries
various disinfectants to buildings to spray and returns back to the depot to refill
when the disinfectants are of insufficient quantity for the next spray operation.

Each vehicle can carry $w$ workers, where $w \geq 1$, and work efficiency is identical
for all workers. The cost of an hour of labor is $\beta$.

Two policies of workplace are considered here.

Policy 1: Worker(s) can be idle (i.e., wait) in front of a building as required until
the constraint of maintaining a minimum time interval between two
consecutive disinfectant sprays is satisfied.

Policy 2: Worker(s) cannot be idle (i.e., no wait) in front of a building if the
constraint of maintaining a minimum time interval between two
consecutive sprays of disinfectants is not satisfied. For Policy 2, the
penalty of idle time of workers is added into the objective function.
Moreover, we assume that the total idle time of workers, where $\gamma$ is the penalty parameter.

The objective of the MDOP is to minimize the total cost of the disinfection
operation, including: (i) the total routing cost of vehicles, (ii) the total working
cost of workers, and (iii) the total idle cost of workers. Note that:

- total routing cost $= \alpha \times$ the total routing length, where $\alpha$ is the unit cost of one unit of
length (m) for a vehicle.
- total working cost $= \beta \times w \times$ total working time (hr) $= \beta \times w \times$ (total routing time + total
idle time + total working time), where total routing time $= \text{total routing length (m)} \times 0.002$. Note that we assume that 0.002 (hr/m)
for each vehicle.
- total idle cost $= \gamma \times$ total idle time (hr) of workers, where $\gamma$ is the penalty parameter
of one hour for each worker.

2.3. An example

Consider an MDOP example with five buildings and four disinfectants, i.e., $I=5$ and
$J=4$. The corresponding required disinfectants and quantities for each building are
shown in Table 1. For example, Building 3 requires three disinfectants, namely, A, C and D, where D is the final disinfectant used in the disinfection operation for this building. Thus, in this example, the total number of disinfection operations for all buildings is \( N = 3 + 3 + 3 + 2 + 2 = 13 \). Suppose that one vehicle is available and \( Q = 20 \), \( t_{ij} = 1.0 \), \( d_{ii} = 0.5 \), \( L = 2 \) for all \( i, j, i' \). The following information details two disinfection operations, where Disinfection operation 1 is infeasible (since the final disinfectant for Buildings 3 and 4 should be D), and Disinfection operation 2 is feasible.

**Disinfection operation 1 (infeasible):**

<table>
<thead>
<tr>
<th>Index</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building (i):</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Disinfectant (j):</td>
<td>A</td>
<td>C</td>
<td>C</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>B</td>
<td>D</td>
<td>D</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>Quantity ( q_{ij} ):</td>
<td>10</td>
<td>5</td>
<td>3</td>
<td>8</td>
<td>5</td>
<td>4</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>13</td>
<td>10</td>
<td>13</td>
<td>6</td>
</tr>
</tbody>
</table>

**Disinfection operation 2 (feasible):**

<table>
<thead>
<tr>
<th>Index</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building (i):</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Disinfectant (j):</td>
<td>A</td>
<td>C</td>
<td>C</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>B</td>
<td>D</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>Quantity ( q_{ij} ):</td>
<td>10</td>
<td>5</td>
<td>3</td>
<td>8</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>7</td>
<td>13</td>
<td>13</td>
<td>10</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Accumulated ( q_{ij} ):</td>
<td>10</td>
<td>15</td>
<td>18</td>
<td>8</td>
<td>13</td>
<td>19</td>
<td>8</td>
<td>15</td>
<td>(13)</td>
<td>(13)</td>
<td>(10)</td>
<td>17</td>
<td>(4)</td>
</tr>
</tbody>
</table>

Disinfection operation 2 also indicates that the vehicle has to refill its disinfectant supply 6 separate times. The total routing time = \( 0.5 + (0.5 + 0.5 + 0.5) + 0.5 + (0.5 + 0.5 + 0.5 + 0.5 + 0.5 + 0.5 + 0.5 + 0.5 + 0.5 + 0.5) + 0.5 = 10.5 \) and the total working time of the worker = total routing time + total working time + total idle time = \( (10.5) + (13) + (2) = 27.5 \). A total idle time of 2 hours occurs between disinfection 4 (Building 2 and Disinfectant B) and disinfection 5 (Building 2 and Disinfectant C).

3. The new encoding scheme for MDOP

In this section, we present an efficient encoding to convert any permutation of 1\( \sim N \), where \( N \) is the total number of disinfection operations for buildings, into a feasible one. Thus, this novel encoding scheme can enhance the effectiveness and efficiency of the adopted algorithm (i.e., IA) for solving MDOP.

3.1. Encoding example for a single vehicle

The following encoding scheme will convert any infeasible sequence of disinfection operations into a feasible one. Its main steps for cases involving a single vehicle are as follows:
Step 1. Generate a $4 \times N$ matrix $M$, where Row 1=$(1,2,\ldots,N)$ is an index row, Row 2 is a random permutation of $\{1,2,\ldots,N\}$, and Rows 3 and 4 are the index of buildings and their required disinfectants, respectively.

Step 2. Find the given final disinfectant for each building in Rows 3 and 4. If the final disinfectant violates the order (i.e., it is not used as the final disinfectant), then swap it with the current final disinfectant in the matrix $M$. Repeat this step until all final disinfectants of all buildings are used as the final disinfectants.

Step 3. Based on the final matrix $M$ in Step 2, find the refill points of the vehicle with vehicle capacity $Q$.

Step 4. Compute the idle time of worker(s) for each disinfection operation based on $L$, the time interval between two consecutive disinfection operations for the same building.

Consider the example in Table 1 again. In this example, Building 3 requires three disinfectants, namely A, C and D, where Disinfectant D is the final disinfectant for this building. Suppose that one vehicle is available and $Q=20$, $t_{ij}=1.0$, $d_{ij}=0.5$, $L=2$ for all $i, j, i'$.

Next we show the swap process in Step 2 to convert any infeasible sequence of disinfection operations into a feasible one for a single vehicle. The swap process of this example is also illustrated step-by-step in Figure 1. Since the total number of disinfection operations in Table 1 is $N=3+3+3+2+2=13$, any permutation of $\{1, 2,\ldots,13\}$ can be converted to represent a feasible disinfection operation for the MDOP.

Following the main steps of the new encoding in Section 3.1 and Figure 1, we have:

Step 1. Generate a $4 \times 13$ matrix $M$, where Row 1 is the index row $(1,2,\ldots,13)$, Row 2 is a random permutation of $(1,2,\ldots,13)$, Row 3 is the index of building, and Row 4 is the index of the disinfectant for each building. Suppose that the random permutation of 1 to 13 in Row 2 is: $P=4-3-8-5-6-9-2-13-11-12-1-10-7$. Since $P(1)=4$, it indicates the first disinfection operation is Disinfectant A in Building 2 (i.e., find the column of index=4). Next $P(2)=3$, indicating the second disinfection operation is Disinfectant C in Building 1 (i.e., find the column of index=3). Then, we populate the matrix $M$ shown in Step 1 of Figure 1.

Step 2. There are three final disinfectants which are not used as the final disinfection operations for buildings of matrix $M$, namely, Building 3 (using Disinfectant A now), Building 4 (using Disinfectant B now) and Building 5 (using Disinfectant B now). Thus, we swap these three pairs with those of their given final disinfectants, that is, swap (Building 3, Disinfectant D) with (Building 3, Disinfectant A), (Building 5, Disinfectant D) with (Building 5, Disinfectant B), and (Building 4, Disinfectant D) with (Building 4, Disinfectant B). These swaps are shown in Step 2 of Figure 1.
Step 3. Insert 0 to indicate when a disinfectant product refill is required for the vehicle. For example, the total quantity for the first three disinfection operations is $10+5+3=18$. Since the next quantity is 8 (Building 2, Disinfectant B) and adding this disinfection operation will violate the capacity of vehicle ($Q=20$), we insert 0 after the first three disinfection operations. Similarly, we insert 0 for all refills throughout the matrix.

Step 4. In this step, we check the constraint of two hours ($L=2$) for the minimum time interval between two consecutive spray operations for a given building. As shown in Step 4 of Figure 1, there is an idle time of 2 hours for the worker in between applications of Disinfectants B and C in Building 2.

From Figure 1, we have converted an infeasible sequence of disinfection operations (in Step 1) into a feasible one (in Step 4). Using this feasible sequence, we can compute the total routing time of the vehicle and the total working and idle times of the workers to determine the objective value of MDOP. More clearly, we may obtain the assignment of the disinfection operation for the vehicle in Step 2. In Step 3, based upon the assignment and the constraint of carrying capacity for the vehicle, we can decide whether go to the next building or go to refill (i.e., insert 0 between buildings in Figure 1). Finally, based upon the constraint of minimal time interval between two consecutive spray applications of disinfectants for each building, we can obtain the entering time of worker to a building. Therefore, the idle time of the worker for each vehicle can be computed as Step 4 of Figure 1.

---------------------------
Figure 1 goes here
---------------------------

3.2. Encoding example for multiple vehicles

The main steps of encoding scheme for multiple vehicles are as follows.

Step 1. The same as that for a single vehicle as described in Section 3.1.

Step 2. The same as that for a single vehicle as described in Section 3.1.

Step 3. Assign the disinfection operation following Rows 3 and 4 to the vehicle with the earliest current finish time. If multiple vehicles have the same current finish time, then arbitrarily assign the disinfection operation to one of those vehicles. Repeat this step until all disinfection operations are assigned to vehicles.

Step 4. Compute the idle time of the worker(s) for the vehicles based on $L$.

Consider the example in Table 1 again with $Q=20$, $t_{ij}=1.0$, $d_{ii'}=0.5$, and $L=2$ for all $i$, $j$, $i'$. For convenience, we suppose that there are two vehicles available for this example. Our main procedure for converting an infeasible random permutation of disinfection operations into a feasible one is illustrated step-by-step in Figure 2.
Suppose that the random permutation of 1 to 13 is: \( P=4-3-8-5-6-9-2-13-11-12-1-10-7. \) In Figure 2, Steps 1 and 2 are the same as those of Figure 1. Following the steps of the scheme which are also shown in Figure 2, we have the followings.

Step 3-1. The initial finish time for Vehicles 1 and 2 is zero, so we arbitrarily assign the 1st operation to Vehicle 1 and compute its start and finish times as \( V_1=(0.5,1.5). \) Note that we assume \( d_{ij}=0.5 \) and \( t_{ij}=1.0. \)

Step 3-2. Assign the 2nd operation into the vehicle with the earlier finish time. That is, we assign the 2nd operation (Building 1, Disinfectant C) into Vehicle 2 and compute its start and finish times as \( V_2=(0.5,1.5). \)

Step 3-3. Assign the 3rd operation into the vehicle with the earlier finish time. Since \( \min \{ V_1(2), V_2(2) \}=\min \{ 1.5, 1.5 \}=1.5, \) the finish time is identical for Vehicles 1 and 2, and we may arbitrarily select one, say Vehicle 1. Thus, we assign the 3rd operation (Building 3, Disinfectant C) into Vehicle 1 and compute its corresponding start and finish times as \( V_1=(2.0,3.0). \)

Step 3-4. Assign the 4th operation into the vehicle with the earlier finish time. Since \( \min \{ V_1(2), V_2(2) \}=\min \{ 3.0, 1.5 \}=1.5, \) Vehicle 2 has the earlier finish time, and we assign the 4th operation (Building 2, Disinfectant B) into Vehicle 2 and compute its start and finish times as \( V_2=(3.5,4.5). \) Note that \( V_2(1)=1.5+2=3.5, \) since for Building 2 the previous finish time is 1.5 (see Disinfectant A, Step 3-1). For safety reasons, we have to add 2 hours (=\( L= \) minimum time interval for two consecutive operations in the same building) to compute the start time. Thus, the finish time of the 4th operation in Vehicle 2 is \( V_2(2)=V_2(1)+1.0=4.5. \)

Step 3-5. Assign the 5th operation into the vehicle with the earlier finish time. Since \( \min \{ V_1(2), V_2(2) \}=\min \{ 3.0, 4.5 \}=3.0, \) Vehicle 1 has the earlier finish time, we assign the 5th operation (Building 2, Disinfectant C) into Vehicle 1 and compute its start and finish times as \( V_1=(6.5,7.5). \) Note that the previous finish time of Building 2 (Disinfectant B in Step 3-4) is \( V_1(2)=4.5, \) so the 5th operation can start at \( 4.5+2(=L)=6.5 \) which implies that the idle time of the worker(s) is 6.5-(3.0+0.5)=3.0. Thus the finish time of the 5th operation in Vehicle 1 is \( V_1(2)=V_1(1)+1.0=7.5. \)

Step 3-6. Assign the 6th operation into the vehicle with the earlier finish time. Since \( \min \{ V_1(1), V_2(1) \}=\min \{ 7.5, 4.5 \}=4.5, \) Vehicle 2 has the earlier finish time, we assign the 6th operation (Building 3, Disinfectant A) into Vehicle 2 and compute its start and finish times as \( V_2=(5,6). \) Note that the previous finish time of Building 3 (Disinfectant C in Step 3-3) is \( V_1(2)=3.0, \) so the 6th operation can start at \( \max \{ 3.0+2(=L), 4.5+0.5 \}=5.0 \) which implies that no idle time for the worker(s). Thus the finish time of the 5th operation in
Vehicle 2 is $V2(2)=V2(1)+1.0=6.0$.

Step 3-7. Assign the 7th operation into the vehicle with the earlier finish time. Since $\min \{V1(2),V2(2)\}=\min \{7.5, 6.0\}=6.0$, Vehicle 2 has the earlier finish time, we assign the 7th operation (Building 1, Disinfectant B) into Vehicle 2 and compute its start and finish times as $V2=(7,8)$. Note that Vehicle 2 has to refill the disinfectant due to the capacity limit of vehicle ($Q=20$) before insert the 7th operation, and we insert 0 into the Vehicle 2. The start time of the 7th operation is $V2(1)=\text{finish time of the 6th operation} + \text{the travel time from Building A to depot} + \text{the travel time from depot to Building B} = 6.0+0.5+0.5=7.0$. The previous finish time of Building 1 (Disinfectant C in Step 3-2) is 1.5, so the 7th operation can start at $\max \{1.5+2(=L), 7.0\}=7.0$ which implies that no idle time for the worker(s). Thus the finish time of the 7th operation in Vehicle 2 is $V2(2)=V2(1)+1.0=8.0$.

By repeating this process until all buildings are treated, we create the steps shown in Figure 2. Note that, in Figure 2, the handle of constraints, i.e., (i) carrying capacity for each vehicle, and (ii) the time interval between two consecutive spray applications of disinfectants for each building must meet or exceed a specified minimum, are similar to those of single vehicle in Section 3.1.

4. Immune algorithm, genetic algorithm and particle swarm optimization

As mentioned in Section 1, MDOP is an NP-hard optimization problem. In the past decades, there have several evolutionary artificial intelligence algorithms been proposed to solve various types of optimization problems, including Genetic algorithm (GA), Particle swarm optimization (PSO), Tabu search (TS), Simulated annealing algorithm (SA), Ant colony optimization (ACO), Artificial bee colony algorithm (ABC), Immune algorithm (IA) etc. Additionally, several new algorithms inspired by animals, nature and society have also been proposed to solve various optimization problems, e.g., Whale optimization algorithm (WOA), Grey wolf optimizer algorithm (GWO), Virus colony search algorithm (VCS), Heat transfer search algorithm (HTS), Electromagnetic field optimization algorithm (EFO), and Teaching-learning-based optimization algorithm (TLBO), etc. We refer to [18] for the brief survey of various new evolutionary artificial intelligence algorithms.

Though there are several new evolutionary artificial intelligence algorithms proposed, GA and PSO might be the most well-known and popular algorithms in the literature due to their numerous successful applications, e.g., using GA to solve the
multi-objective reliability growth planning problem [19], using PSO and GA to solve the multi-objective control chart problem [20]. Note that in [19, 20] new versions of GA and PSO were developed to solve different multi-objective optimization problems. Additionally, IA, which is similar to GA, has attracted much attention because its memory mechanisms can provide more varieties in population and its several successful applications, e.g., using IA to solve a multi-objective ergonomic product classification problem [21]. Since the encoding of chromosome of IA and GA are based on 0 and 1, both algorithms are more suitable for discrete optimization problems. The original encoding of PSO is based on real number which is suitable for continuous optimization problems. However, the real number encoding of PSO can be easily converted into binary encoding (BPSO, binary particle swarm optimization) which implies that it is also suitable for discrete optimization problems.

In this paper, we focus on the main purpose of presenting a new MDOP and solve it by IA practically rather than comparing its effectiveness with several developed algorithms. Therefore, in this paper, we adopt IA to solve the new presented MDOP and compare its numerical results with those of GA and PSO to analyze the effectiveness of IA. Next, we briefly describe the main steps of IA, GA and PSO.

4.1. Immune algorithm (IA)

IA is very similar to GA. The main difference is that IA has to update the so-called memory set of solutions. We refer to the reference papers in [22-25] for the introduction of the immune system. Next, we briefly describe the main steps of IA as follows.

Step 1. Randomly generate a population of strings as the initial solutions.
Step 2. Compute the objective value, i.e., total cost, for each individual in the population.
Step 3. Based upon the objective value, choose the best $g$ individuals from the population.
Step 4. Clone these $g$ individuals chosen in Step 3 by using the genetic operators of crossover and mutation [26].
Step 5. Compute the new objective values for the individuals in Step 4. Update the memory set of strings, that is, replace the inferior individuals with the superior individuals in the memory set. Note that, in this step, individuals will be deleted if their structures are too similar to those in the memory set.
Step 6. Check the stopping criterion. If stop, then go to the next step, otherwise go to Step 2.
Step 7. Stop the algorithm and report the optimal or near optimal solution(s) from the memory set.
4.2. Genetic algorithm (GA)

GA is a well-known evolutionary method proposed by John Holland (1975). GA randomly generates a population of strings and the best string in the population will approach to an optimal solution with the use of evolutionary operators, e.g., crossover, mutation and reproduction. We refer to [26] for the introduction of GA and its mechanisms. The main steps of GA are summarized as follows.

Step 1. Randomly generate a population of strings as the initial solutions.
Step 2. Compute the objective value, i.e., total cost, for each individual in the population.
Step 3. Based upon the objective value, choose the best \( g \) individuals from the population.
Step 4. Clone these \( g \) individuals chosen in Step 3 by using the genetic operators of crossover and mutation. Compute the objective values of the new individuals.
Step 5. Check the stopping criterion. If stop, then go to the next step, otherwise go to Step 2.
Step 6. Stop the algorithm and report the optimal or near optimal solution(s) from the memory set.

4.3. Particle swarm optimization (PSO)

PSO is a well-known optimization method proposed by Kennedy and Eberhart in 1995 [27]. PSO randomly generates a population of particles and the particles in the population will move to an optimal solution with the update of \( pbest \) (particle best) and \( gbest \) (global best) through the so-called velocity and position of particles. We refer to the references in [28-29] for the introduction of PSO and its mechanisms. The main steps of PSO are summarized as follows.

Step 1. Initialize population, velocity and position of particles.
Step 2. Evaluation the objective values for particles.
Step 3. Find the \( pbest \) (particle best) for each particle.
Step 4. Find the \( gbest \) (global best) for all particles in populations.
Step 5. Update the velocity and position of each particle by using Eqs. (1) and (2) [28-29].

\[
V_{i}^{t+1} = wV_{i}^{t} + C_{1} \times rand_{1}(0) \times (X_{i}^{pbest} - X_{i}^{t}) + C_{2} \times rand_{2}(0) \times (X^{gbest} - X_{i}^{t}) \quad (1)
\]

\[
X_{i}^{t+1} = X_{i}^{t} + V_{i}^{t+1} \quad (2)
\]

Step 6. If stopping is indicated, then proceed to Step 7.
Step 7. Stop the algorithm and report the optimal or near optimal solution(s).
5. Numerical results and discussions

5.1. The instance of NFU

In this section, we present the campus case of MDOP at National Formosa University (NFU), Taiwan. Figure 3 illustrates the network of NFU main campus in Yunlin, Taiwan, and there are eighteen major buildings (node 1 to node 18) requiring the multiple disinfection operations. The depot of refill is located at node 0 and the corresponding distances of buildings are shown in Figure 3.

Since these buildings are different in purpose of use, e.g., class rooms, offices, restaurant, laboratories etc. Therefore, they require different disinfectants in disinfection operations. For example, the mechanic engineering building needs to prevent the biting of electric wires by mouse, the classrooms require the disinfection operations to prevent the mosquito etc, while the restaurant requires multiple disinfection operations to prevent the mouse, mosquito and bacteria etc. The required types, quantities, and spray time of various disinfectants for each building are estimated and listed in Table 2. Note that, for some buildings, the final disinfectants are required. For example, the final disinfectant for Building 1 is Disinfectant F and the final disinfectant for Building 13 is disinfectant D. Therefore, there are six possible sequences of disinfection operation of disinfectants for Building 1, namely, (A,B,H,F), (A,H,B,F), (B,A,H,F), (B,H,A,F), (H,A,B,F) and (H,B,A,F), respectively, and there are two possible sequences of disinfection operation of disinfectants for Building 13, namely, (B, C, D), (C, B, D), respectively. In this test instance, we set the capacity of vehicle is $Q=1000$, and the minimal interval time of two consecutive disinfection operations is $L=2$ (hours).

5.2. The parameters and strategies

In this paper, we adopt three algorithms, namely, IA, GA and PSO, to solve the campus case of MDOP. To find the appropriate crossover rate and mutation rate for IA and GA, we executed 100 experiments for various combinations of crossover rate and mutation rate, namely, (0.32, 0.02), (0.32, 0.05), (0.32, 0.08), (0.48, 0.02), (0.48, 0.05), (0.48, 0.08), (0.96, 0.02), (0.96, 0.05), (0.96, 0.08). Our preliminary numerical results show that crossover rate=0.96 and mutation rate=0.05 are appropriate for our experiments. In addition, to find the appropriate parameter values for $C_1$ and $C_2$ in
PSO, we also executed 100 experiments for various combinations of $C_1$ and $C_2$, namely, (1.49449, 1.49449), (2.0, 2.0), (3.1417, 3.1417), (5.1417, 5.1417), (5.1417, 3.1417) which were suggested in the literature. Our preliminary numerical results for the tests show that $(C_1, C_2)$ = (2.0, 2.0) are appropriate for our experiments. Moreover, based upon our preliminary tests, the parameters for IA and GA are set as: population = 200, affinity = 0.25, crossover = 0.96, mutation = 0.05, maximum generations = 500, maximum no. of reproduction of each chromosome = 7. For PSO, parameters are set as: population = 500, maximum generations = 1000, inertia weight $w$ = 0.2. Our programs are coded in MATLAB R2008b and all results are computed by Intel-Pentium IV 4 CPU 3.0GHz PC.

In this paper, we test various strategies for the MDOP, namely:

Strategy 1: 1 vehicle with 1 worker.
Strategy 2: 1 vehicle with 2 workers.
Strategy 3: 1 vehicle with 3 workers.
Strategy 1-1: 2 vehicles with 2 workers, i.e., one worker for each vehicle.
Strategy 1-2: 2 vehicles with 3 workers, i.e., one worker in a vehicle and two workers in another vehicle.
Strategy 2-2: 2 vehicles with 4 workers, i.e., two workers for each vehicle.
Strategy 2-3: 2 vehicles with 5 workers, i.e., two workers in a vehicle and three workers in another vehicle.
Strategy 3-3: 2 vehicles with 6 workers, i.e., three workers for each vehicle.

Note that we assume that the work efficiency is identical for all workers. Therefore, if a disinfection operation requires 90 minutes for a building with Strategy 1, then it reduces to 30 minutes when Strategy 3 is adopted. In addition, to test more experiments, we set $\alpha$ = 1, 5 and 10 for a unit distance (m), respectively. For all cases, we set $\beta$ = 500 and $\gamma$ = 0, 10000/60(min) = 166.67 (hr).

5.3. Numerical results and discussions

For each strategy, we experiment 100 times for IA, GA and PSO, and report the best solutions. Numerical results are summarized in Tables 3-6 and Figure 4. Note that there are 48 sub-instances solved for each algorithm in the experiments ($\alpha$ = 1, 5, 10, eight strategies, idle/no idle for worker(s)). From Tables 3-6 and Figure 4, we observe that:

(1) For IA approach, the best strategy for $\alpha$ = 1, 5, and 10 is Strategy 1 with objective values of 49786.42, 50327.02, 49924.12 when idle time of workers is not allowed, and 50301.52, 50001.35, 51052.02 when idle time of workers is allowed. That is, Strategy 1 (one vehicle with one worker) is the best one. For GA and PSO, it shows the similar result.
(2) IA is superior to GA, except for the case of Strategy 3 (one vehicle with 3 workers) when $\alpha=1$ and no idle time of workers. For example, for the case of Strategy 3 with $\alpha=1$ and no idle time of workers, the objective value GA is 51893.85 which better than 52148.25 obtained by GA.

(3) IA is superior to PSO and GA is superior to PSO for all cases of test problems. For example, for Strategy 1-1 with $\alpha=1$ and no idle time of workers, the objective value of PSO is 59362.03, while it is 53306.80 for GA and it is 52348.53 for IA. Similar results for the other cases.

(4) Figure 4 summarizes the numerical results of Table 3 to Table 5, and it can be used to select the best strategy for universities and disinfection companies according their budget or makespan (completion time). For example,

(i) If the budget of disinfection is 55000, idle time is not allowed and $\alpha=1$, then there are 5 feasible strategies, namely,

- Strategy 1: budget used=49786.42 and makespan=53.77 (hrs),
- Strategy 2: budget used=50884.02 and makespan=27.37 (hrs),
- Strategy 3: budget used=51893.85 and makespan=18.62 (hrs),
- Strategy 1-1: budget used=52348.53 and makespan=26.96 (hrs),
- Strategy 1-2: budget used=54095.58 and makespan=18.23 (hrs),

This further indicates that Strategy 1-2 is the best one with minimal makespan 18.23 (hrs) if budget is 55000.

(ii) If the makespan of disinfection is set to 15 (hrs), idle time is not allowed and $\alpha=1$, then there are 3 feasible strategies, namely,

- Strategy 2-2: budget used=55091.43 and makespan=13.77 (hrs),
- Strategy 2-3: budget used=56988.54 and makespan=11.21 (hrs),
- Strategy 3-3: budget used=59110.50 and makespan=9.45 (hrs),

This further indicates that Strategy 2-2 is the best one with minimal budget 55091.43 if the makespan of disinfection is limited to 15 (hrs).

(5) Table 6 reports the comparison of results among IA, GA and PSO. It shows that, in the objective value, IA outperforms GA from 1.74% to 4.75% and outperforms PSO from 9.39% to 18.67% for various combinations of $\alpha$ and idle/no idle for worker(s). To further analyze the performance of IA, GA, and PSO algorithms, based upon the 100 experiments, we use the following statistical hypothesis to test whether there is significant difference among these three algorithms.
\[ H_0: V(A)=V(B) \]
\[ H_1: V(A)\neq V(B) \]

where \( V(A) \) denotes the average objective value by using algorithm A, \( A=IA, GA, \) or PSO. The p-values of the statistical hypothesis show that:

(i) Except for one sub-instance (no idle, \( \alpha=1, \) strategy 3-3) with p-value of 0.082, IA outperforms GA for the other sub-instances.
(ii) IA outperforms PSO for all 48 sub-instances (with p-value < 0.05).
(iii) GA outperforms PSO for all 48 sub-instances (with p-value < 0.05).

These results of statistical hypothesis imply that IA outperforms GA, and GA outperforms PSO for solving the MDOP.

The above numerical results are based upon a practical instance at NFU (Taiwan). Currently, Strategy 1 is adopted at NFU, i.e., one vehicle with one worker. In the past, the worker scheduled all spray operations according to the order of disinfectants A, B, C, H, D, E, F, G, respectively. Additionally, for the same disinfectant, the nearest rule was used to schedule the order of buildings. For example, there are ten buildings requiring the spray operation of disinfectants A, and the spray order of these buildings adopted is: 9→14→15→16→10→3→2→1→4→5, since Building 9 is closest to depot (node 0 in Figure 3) and then Building 14 is closest to Building 9, Building 15 is closest to Building 14 and so on. The objective value for this typical schedule is $58628.75 (\alpha=10, \) no idle) which further implies that there is an improvement of 17.44% by IA (objective value = $49924.12), 15.58% by GA (objective value = 50724.82), and 4.00% by PSO (objective value = 56375.62).

6. Conclusions

In this paper:

(1) We have proposed and investigated the MDOP, in which several buildings have to be sprayed with multiple disinfectants. In addition, there are some disinfectants designated for use as the final disinfectants.

(2) We have developed an efficient encoding scheme of spray operations to convert any infeasible sequence of disinfection operations into a feasible one, and it can simultaneously determine the sequence of buildings and their disinfectant spray operations.

(3) We have compared the numerical results of IA, GA, and PSO with that of the typical schedule adopted at NFU, and it shows that there is an improvement of 17.44% by IA, 15.58% by GA, and 10.75% by PSO, respectively.

(4) We have applied IA, GA, and PSO for solving the MDOP using various strategies. Numerical results have shown that IA outperforms GA from 1.74% to 4.75%, except for one sub-instance of test problem, and IA is superior to PSO from 9.39% to 18.67% for all sub-instances of test problem.
(5) We have provided numerical results of strategies using various numbers of vehicles and workers. As shown in the discussions, the best strategy can be easily derived based upon the numerical results when the budget or makespan of the disinfection operation is given. Therefore, the numerical results of this paper could be useful for disinfection companies or universities in scheduling their optimal disinfection operations based upon their budgets or total completion time (makespan) targets.

In the future, one may use the other evolutionary artificial intelligence algorithms to solve the presented MDOPs and compare their effectiveness. Additionally, one may consider the other variants of MDOP. For example, there are 5 disinfection operations A, B, C, D, E for Building 1, and the first and last disinfection operations of disinfectants for this building must be fixed as A and E, respectively.

Acknowledgement

We thank Mr. Z.L Deng for the collection of partial numerical results of experiments. This research was supported by National Science Council, Taiwan, under Grant No. NSC 100-2221-E-150-041-MY3.

References


Yi-Chih Hsieh received his Ph.D. degree (1995) in Industrial Engineering from The University of Iowa, USA, and his current research interests include optimization, operations research, and applications of programming and artificial intelligence algorithms. He is now a professor at the Department of Industrial Management, National Formosa University, Taiwan.

Pei-Ju Lee received a Ph.D. degree (2015) in Information Science from University of Pittsburgh, USA. Her research interests include data fusion, data mining, human-robot interaction, and artificial intelligence algorithms. She is now an assistant professor at Department of Information Management, National Chung Cheng University, Taiwan.

Peng-Sheng You received a Ph.D. degree (1997) in Management Science and Engineering from University of Tsukuba, Japan, and his current research interests include inventory management, supply chain management and artificial intelligence algorithms. He is now a professor at the Department of Business Administration, National Chiayi University, Taiwan.
Table 1. The corresponding disinfection data for the five buildings in the example.

<table>
<thead>
<tr>
<th>Building (i)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disinfectant (j)</td>
<td>A,B,C</td>
<td>A,B,C</td>
<td>A,C,D*</td>
<td>B,D*</td>
<td>B,D*</td>
</tr>
<tr>
<td>Quantity (q_{ij})</td>
<td>10,8,5</td>
<td>10,8,5</td>
<td>6,3,4</td>
<td>13,7</td>
<td>13,7</td>
</tr>
<tr>
<td>Operation time(t_{ij})</td>
<td>1,1,1</td>
<td>1,1,1</td>
<td>1,1,1</td>
<td>1,1,1</td>
<td>1,1,1</td>
</tr>
</tbody>
</table>

*: The final disinfectant should be used in the disinfection operation.
Table 2. The data of required disinfectants for buildings 1-18.

<table>
<thead>
<tr>
<th>Building (i)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disinfectant (j)</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>G*</td>
</tr>
<tr>
<td></td>
<td>F*</td>
<td>F*</td>
<td>H</td>
<td>G*</td>
<td>H</td>
<td>D*</td>
<td>D*</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quantity (q_{ij})</td>
<td>504.0</td>
<td>304.5</td>
<td>554.4</td>
<td>469.2</td>
<td>590.0</td>
<td>388.8</td>
<td>284.0</td>
<td>336.0</td>
<td>96.6</td>
</tr>
<tr>
<td></td>
<td>504.0</td>
<td>304.5</td>
<td>554.4</td>
<td>469.2</td>
<td>590.0</td>
<td>388.8</td>
<td>284.0</td>
<td>112.0</td>
<td>96.6</td>
</tr>
<tr>
<td></td>
<td>168.0</td>
<td>101.5</td>
<td>277.2</td>
<td>156.4</td>
<td>295.0</td>
<td>388.8</td>
<td>284.0</td>
<td>168.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>252.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation time (t_{ij})</td>
<td>94.00</td>
<td>70.75</td>
<td>108.40</td>
<td>88.20</td>
<td>100.33</td>
<td>64.80</td>
<td>57.33</td>
<td>76.00</td>
<td>36.10</td>
</tr>
<tr>
<td></td>
<td>94.00</td>
<td>70.75</td>
<td>108.40</td>
<td>88.20</td>
<td>100.33</td>
<td>64.80</td>
<td>57.33</td>
<td>50.66</td>
<td>36.10</td>
</tr>
<tr>
<td></td>
<td>62.66</td>
<td>47.16</td>
<td>72.26</td>
<td>58.80</td>
<td>66.66</td>
<td>64.80</td>
<td>57.33</td>
<td>50.66</td>
<td></td>
</tr>
<tr>
<td></td>
<td>62.66</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building (i)</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>Disinfectant (j)</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>C</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>G*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F*</td>
<td>D*</td>
<td>D*</td>
<td>D*</td>
<td>E*</td>
<td>E*</td>
<td>E*</td>
<td>G*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>H</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quantity (q_{ij})</td>
<td>210.0</td>
<td>144.0</td>
<td>120.0</td>
<td>96.0</td>
<td>198.0</td>
<td>312.0</td>
<td>320.0</td>
<td>25.2</td>
<td>124.8</td>
</tr>
<tr>
<td></td>
<td>210.0</td>
<td>144.0</td>
<td>120.0</td>
<td>96.0</td>
<td>198.0</td>
<td>312.0</td>
<td>320.0</td>
<td>8.4</td>
<td>41.6</td>
</tr>
<tr>
<td></td>
<td>70.0</td>
<td>144.0</td>
<td>120.0</td>
<td>96.0</td>
<td>66.0</td>
<td>104.0</td>
<td>160.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>72.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation time (t_{ij})</td>
<td>65.00</td>
<td>44.00</td>
<td>38.00</td>
<td>32.00</td>
<td>43.00</td>
<td>72.00</td>
<td>73.33</td>
<td>24.20</td>
<td>40.80</td>
</tr>
<tr>
<td></td>
<td>65.00</td>
<td>44.00</td>
<td>38.00</td>
<td>32.00</td>
<td>43.00</td>
<td>72.00</td>
<td>73.33</td>
<td>16.13</td>
<td>27.20</td>
</tr>
<tr>
<td></td>
<td>43.33</td>
<td>44.00</td>
<td>38.00</td>
<td>32.00</td>
<td>28.66</td>
<td>48.00</td>
<td>48.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>29.33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) *: the final disinfectant for the building.
(b) A=Insecticides, B=Antiseptic, C=Synergists, D=Repellent, E=Rodenticides, F=Repellent, G=Insect Growth Regulator, H=Rodenticides.
(c) Operation time=operation time for a worker.
Table 3. Numerical results of IA for various strategies.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Stategy</th>
<th>α</th>
<th>Idle</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>1-1</th>
<th>1-2</th>
<th>2-2</th>
<th>2-3</th>
<th>3-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N</td>
<td>49786.42</td>
<td>50884.02</td>
<td>52148.25</td>
<td>52348.53</td>
<td>54095.58</td>
<td>55091.43</td>
<td>56988.54</td>
<td>59110.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>50301.52</td>
<td>50525.22</td>
<td>51618.25</td>
<td>52704.07</td>
<td>53479.35</td>
<td>53983.53</td>
<td>56451.75</td>
<td>56557.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>N</td>
<td>50327.02</td>
<td>50977.62</td>
<td>51347.95</td>
<td>52774.27</td>
<td>53385.68</td>
<td>53525.43</td>
<td>56712.00</td>
<td>57276.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>50001.35</td>
<td>50707.13</td>
<td>51406.25</td>
<td>52833.43</td>
<td>54310.98</td>
<td>54913.80</td>
<td>56801.33</td>
<td>57583.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>N</td>
<td>49924.12</td>
<td>51388.42</td>
<td>51570.55</td>
<td>52638.80</td>
<td>53478.33</td>
<td>53757.73</td>
<td>55572.08</td>
<td>57126.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>51052.02</td>
<td>51076.12</td>
<td>51855.15</td>
<td>53360.70</td>
<td>53490.35</td>
<td>55325.00</td>
<td>57791.92</td>
<td>58134.60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: N indicates that idle time of workers is not allowed.
Y indicates that idle time of workers is allowed.
<table>
<thead>
<tr>
<th>Strategy α</th>
<th>Idle</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>1-1</th>
<th>1-2</th>
<th>2-2</th>
<th>2-3</th>
<th>3-3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objective value ($)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>N</td>
<td>50495.32</td>
<td>51762.82</td>
<td>51893.85</td>
<td>5306.80</td>
<td>5389.80</td>
<td>55495.53</td>
<td>59018.04</td>
<td>60452.90</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>50811.52</td>
<td>52012.42</td>
<td>52604.05</td>
<td>54173.40</td>
<td>55498.60</td>
<td>55949.93</td>
<td>57996.58</td>
<td>58117.30</td>
</tr>
<tr>
<td>5</td>
<td>N</td>
<td>51030.82</td>
<td>51289.62</td>
<td>52095.25</td>
<td>53668.47</td>
<td>55480.40</td>
<td>56001.50</td>
<td>57507.25</td>
<td>59711.90</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>50667.38</td>
<td>51606.82</td>
<td>52710.05</td>
<td>53578.67</td>
<td>56347.68</td>
<td>56864.97</td>
<td>59092.21</td>
<td>60028.20</td>
</tr>
<tr>
<td>10</td>
<td>N</td>
<td>50724.82</td>
<td>51768.02</td>
<td>52031.65</td>
<td>53293.30</td>
<td>54590.65</td>
<td>54701.47</td>
<td>57733.33</td>
<td>58846.00</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>51154.98</td>
<td>51776.17</td>
<td>52530.25</td>
<td>54925.07</td>
<td>55613.45</td>
<td>60159.37</td>
<td>62867.96</td>
<td>64341.20</td>
</tr>
<tr>
<td><strong>Makespan (hrs)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>53.81</td>
<td>27.41</td>
<td>18.65</td>
<td>26.98</td>
<td>18.32</td>
<td>13.78</td>
<td>11.33</td>
<td>9.61</td>
</tr>
<tr>
<td>5</td>
<td>N</td>
<td>53.82</td>
<td>27.38</td>
<td>18.63</td>
<td>26.97</td>
<td>18.32</td>
<td>13.81</td>
<td>11.29</td>
<td>9.52</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>54.22</td>
<td>27.40</td>
<td>18.65</td>
<td>27.69</td>
<td>19.86</td>
<td>14.83</td>
<td>11.90</td>
<td>10.74</td>
</tr>
<tr>
<td>10</td>
<td>N</td>
<td>53.81</td>
<td>27.40</td>
<td>18.63</td>
<td>27.04</td>
<td>18.39</td>
<td>13.91</td>
<td>11.23</td>
<td>9.49</td>
</tr>
<tr>
<td></td>
<td>Y</td>
<td>55.94</td>
<td>27.89</td>
<td>19.08</td>
<td>30.06</td>
<td>19.01</td>
<td>17.57</td>
<td>15.19</td>
<td>13.01</td>
</tr>
</tbody>
</table>

Note: N indicates that idle time of workers is not allowed.
Y indicates that idle time of workers is allowed.
**Table 5.** Numerical results of PSO for various strategies.

<table>
<thead>
<tr>
<th>Stategy</th>
<th>a</th>
<th>Objective value ($)</th>
<th>Makespan (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Idle 1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>N</td>
<td>56192.02</td>
<td>58496.82</td>
</tr>
<tr>
<td></td>
<td>y</td>
<td>54376.42</td>
<td>58678.82</td>
</tr>
<tr>
<td>5</td>
<td>N</td>
<td>55784.02</td>
<td>58496.82</td>
</tr>
<tr>
<td></td>
<td>y</td>
<td>52977.43</td>
<td>54794.42</td>
</tr>
<tr>
<td>10</td>
<td>N</td>
<td>56375.62</td>
<td>60566.42</td>
</tr>
<tr>
<td></td>
<td>y</td>
<td>52937.65</td>
<td>54720.12</td>
</tr>
</tbody>
</table>

Note: N indicates that idle time of workers is not allowed. Y indicates that idle time of workers is allowed.
Table 6. Comparison of objective values for three algorithms for various strategies.

<table>
<thead>
<tr>
<th>α</th>
<th>Idle</th>
<th>Algorithm</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>1-1</th>
<th>1-2</th>
<th>2-2</th>
<th>2-3</th>
<th>3-3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>IA</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.49%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.06%</td>
</tr>
<tr>
<td></td>
<td>GA</td>
<td>1.42%</td>
<td>1.73%</td>
<td>0.00%</td>
<td>1.83%</td>
<td>2.39%</td>
<td>0.73%</td>
<td>3.56%</td>
<td>2.27%</td>
<td>1.74%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PSO</td>
<td>12.87%</td>
<td>14.96%</td>
<td>19.80%</td>
<td>13.40%</td>
<td>16.90%</td>
<td>17.17%</td>
<td>22.84%</td>
<td>28.12%</td>
<td>18.26%</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>IA</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td></td>
<td>GA</td>
<td>1.01%</td>
<td>2.94%</td>
<td>1.91%</td>
<td>2.79%</td>
<td>3.78%</td>
<td>3.64%</td>
<td>2.74%</td>
<td>2.76%</td>
<td>2.70%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PSO</td>
<td>8.10%</td>
<td>16.14%</td>
<td>18.53%</td>
<td>8.84%</td>
<td>15.09%</td>
<td>15.76%</td>
<td>13.83%</td>
<td>18.27%</td>
<td>14.32%</td>
<td></td>
</tr>
</tbody>
</table>

Note: N indicates that idle time of workers is not allowed.
Y indicates that idle time of workers is allowed.

\((A-B)/B\%\), A=objective value of A, A=IA, GA, PSO, B=the best objective value among IA, GA, PSO.
Figure 1. The example of the encoding procedure for disinfection operation with single vehicle.
Step 1 is the same as that of single vehicle

Step 2 is the same as that of single vehicle

Building = (2 1 3 2 2 3 1 5 4 5 1 4 3)
Operation = (A C C B C A B B D A D D)

Step 3-1 Vehicle 1 building = (2) (start, finish)
Vehicle 1 operation = (A)
(0.5,1,5)
Vehicle 2 building = ( )
Vehicle 2 operation = ( )

Step 3-2 Vehicle 1 building = (2)
Vehicle 1 operation = (A)
(0.5,1,5)
Vehicle 2 building = (1)
Vehicle 2 operation = (C)
(0.5,1,5)

Step 3-3 Vehicle 1 building = (2 3)
Vehicle 1 operation = (A C)
(0.5,1,5) (2,3)
Vehicle 2 building = (1 Idle=1.5 2)
Vehicle 2 operation = (C B)
(0.5,1,5) (3,5,4,5)

Step 3-4 Vehicle 1 building = (2 3)
Vehicle 1 operation = (A C)
(0.5,1,5) (2,3)
Vehicle 2 building = (1 Idle=1.5 2)
Vehicle 2 operation = (C B)
(0.5,1,5) (3,5,4,5)

Step 3-5 Vehicle 1 building = (2 3 Idle=3 2)
Vehicle 1 operation = (A C C)
(0.5,1,5) (2,3) (6,5,7,5)
Vehicle 2 building = (1 Idle=1.5 2)
Vehicle 2 operation = (C B A)
(0.5,1,5) (3,5,4,5) (5,6)

Step 3-6 Vehicle 1 building = (2 3 Idle=3 2)
Vehicle 1 operation = (A C C)
(0.5,1,5) (2,3) (6,5,7,5)
Vehicle 2 building = (1 Idle=1.5 2)
Vehicle 2 operation = (C B A)
(0.5,1,5) (3,5,4,5) (5,6) (7,8)

Step 3-7 Vehicle 1 building = (2 3 Idle=3 2)
Vehicle 1 operation = (A C C)
(0.5,1,5) (2,3) (6,5,7,5)
Vehicle 2 building = (1 Idle=1.5 2)
Vehicle 2 operation = (C B A A)
(0.5,1,5) (3,5,4,5) (5,6) (7,8)

Step 3-13 Vehicle 1 building = (2 3 Idle=3 2)
Vehicle 1 operation = (A C C B D D)
(0.5,1,5) (2,3) (6,5,7,5) (8,5,9.5) (11,5,12,5) (13,5,14,5)
Vehicle 2 building = (1 Idle=1.5 2)
Vehicle 2 operation = (C B A A)
(0.5,1,5) (3,5,4,5) (5,6) (7,8) (9,10) (11,12) (12,5,13,5)

Figure 2. The example of the encoding procedure for disinfection operation with two
Figure 3. The network of eighteen buildings (nodes 1-18) and the depot (node 0).
Figure 4. Numerical results of strategies vs total cost and makespan for various approaches.