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FREIGHT MOBILITY RESEARCH INSTITUTE
College of Engineering & Computer Science
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DESIGN OF SUSTAINABLE URBAN ELECTRONIC GROCERY DISTRIBUTION NETWORK

Report

by

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DISCLAIMER

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EXECUTIVE SUMMARY

To meet the expectation of multi-modal distributions from customers for last-mile delivery, a sustainable two-echelon E-Grocery delivery system is studied, which is motivated by the adaption of autonomous delivery robot (ADRs), parcel lockers in E-Grocery distribution industry. We formulate the multi-modal last mile system as a two-echelon location-routing problem with mixed vehicles and mixed satellites (2E-LRP-MVMS). A multi-objective optimization model is developed to capture the characteristics of cost components and environmental impact. The goal of the 2E-LRP-MVMS is to determine the location facilities, to optimize the number of parcels delivered to two echelons and routes at each level, also to reduce costs caused by carbon emissions. A hybrid immune algorithm is proposed, and two improved steps, vaccination and immunization are introduced in the algorithm. This research contributes to the last-mile delivery network design domain by modeling the environmental and economic cost of E-Grocery distribution adopting mixed fleets and mixed satellites.

1.0 INTRODUCTION

Despite the fact that freight movements in the E-grocery industry have continually contributed to the economic growth of cities, and the expansion and continuous growth of the E-commerce market lead to a dramatic increase in E-grocery deliveries [1]. E-grocery is also deemed to have unsustainable impacts on the environment. Deliveries are now expected to go into customers that were never designed for freight traffic-creating congestion and emissions. The high number of deliveries, combined with the increasing demand for the speedy delivery and the unpredictability of customer orders, also results in multiple trips, which leads to more environmental pollution.

From the operators' perspectives, parcel locker services improve order fulfillment by minimizing vehicle trips that are commonly associated with cost-savings for the operators. Second, parcel locker services allow freight consolidation which reduces the travel distance that is generated to serve customers. This reduces demand for curbside parking, road congestions, and emissions [2][3].

However, some other customers still prefer to pick up the package at home. ADR, which is a new element of urban E-Grocery distribution way, has the potential regarding the last-mile delivery to customers to reduce the urban road traffic and emissions. However, it restricted to different conditions compared to conventional vehicles, for example, travel distance. Current researches suggest that air-based drones are good for rural and suburban areas for the last mile delivery, but not so ideal for urban centers, especially in a dense area, where ground and road-based robots will dominate. Driven by area density (for example, the last-mile cost increases greatly due to longer travel distances in rural areas) and consumer preferences, three consumer delivery multi transportation method—are likely to dominate E-Grocery delivery in the future for the last-mile delivery: drones, autonomous ground vehicles with parcel lockers and delivery robot (Fig. 1).

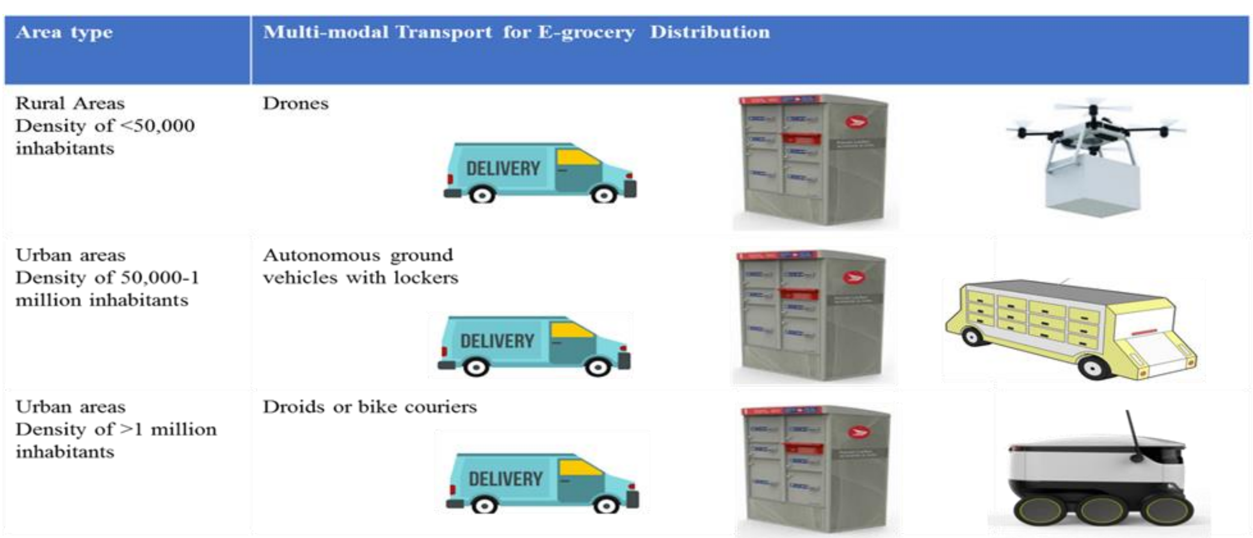


Figure 1. Multi-modal transport in E-grocery delivery network

How to coordinate these transportation ways to achieve a sustainable E-grocery delivery network is worthy of attention. In regular delivery, multiple parcels can be loaded onto a van and later be exchanged in a matter of seconds, while the parcels mounted on a robot would need to be filled individually. By now, delivery van performs the majority of urban logistics activities, because of the economies of scale brought by the large volume, which means low cost and high emissions delivered by van. Freight transport agency or E-grocery companies can make use of an advantage on a van, a robot, and a parcel locker to design a multi-modal delivery system in E-grocery distribution network, for example, the van have a much large-volume and low unit transportation cost, the robot has low emissions and suitable for high-traffic locations, also, if we take a locker into consideration, the requirement of time window for a locker is more flexible. Fig. 2 illustrates a two-echelon E-grocery delivery network. In the first echelon, a van starts from a depot, visits the assigned existing satellites, then returns the same depot, and in the second echelon, a customer can be served by both a delivery robot or a parcel locker, here we assume that these customers are flexible with the last-mile service. With the increase of the customer's demand, companies will decide if there is a need to open a new depot or a satellite to minimize the total operations costs and emission costs. In this paper, we formulate this problem as a 2E-LRP-MVMS, discussing the potential delivery van, robot, and parcel locker regarding the urban sustainable E-Grocery delivery network on a tactical-operation level.

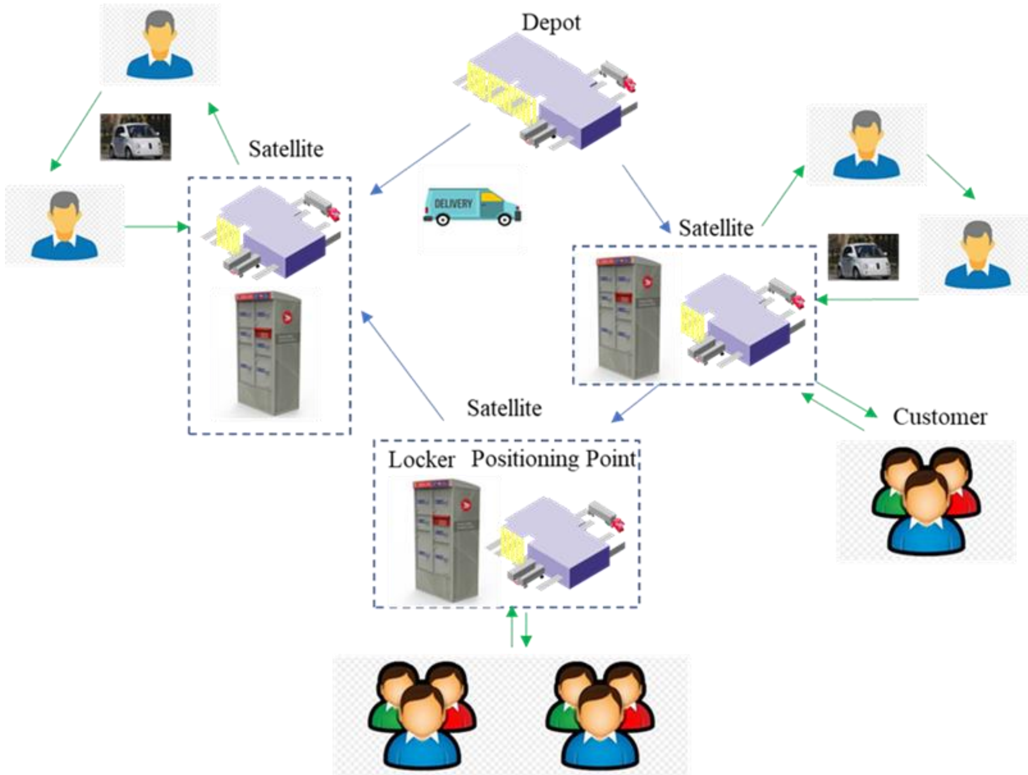


Figure 2. Two-echelon E-grocery delivery network

2.0 LITERATURE REVIEW

Many innovative concepts and technologies for people and freight transportation have recently been developed targeting the excessive traffic, pollutions, and transportation cost in large urban areas. For example, drone-based delivery systems are being initiated in distribution centers and online retailers such as Amazon prime air, Google wing projects, UPS truck-launched drone, Deutch Post DHL, and JingDong Drone Deliveries. Drones can reach their consumers faster than the traditional human-based delivery, but drone utilization has its drawbacks. Yao Liu et al. (2019) mentioned that the effect of energy consumption aroused by the payload weight during the flight should not be ignored [4].

Parcel lockers are currently being widely used. However, there are a limited number of researches attempt to develop a quantitative approach, and few articles that investigate issues related to our work are qualitative [5]. Yael Deutsch (2018) designed a parcel locker network as a solution to the Logistics Last Mile Problem, choosing the locations, optimal number, and sizes of parcel lockers [6]. In a practical situation, parcel lockers as a choice usually combined with other last-mile delivery approaches to meet the customer's requirement. Recently, a new kind of delivery robot was tested in the State of Arizona, which carry a certain weight of groceries can operate on sidewalks and crosswalks. However, a few pieces of research model the transportation and environmental cost of the robot. To the best of our knowledge, it is the first attempt to integrate vans, robots and parcel lockers into urban E-grocery distribution network. The related works of literature mainly focus on three aspects.

2.1 TWO-ECHELON LOCATION ROUTING PROBLEM (2E-LRP)

The LRP deals with the optimal location problem and the delivery routes designing problem, which simultaneously considers the facility location and routes assignment to vehicles. This classical LRP has been developed by considering additional real-life characteristics, one possible extension of this problem is by considering the capacity of the depot, which results in the capacited LRP. Another popular extension is considering Time Windows. 2E-LRP initially proposed by González-Feliu et.al. (2007), and it was also considered by Perboli et al. [7], Roberto Baldacci et al. [8], Santos et al. [9], Philippe Grangier et al. [10], and Lin Zhou et al. [11].

Mehmet Soysal (2015) presents a 2E-LRP that accounts for traveled distance, vehicle speed, vehicle type, load, and emissions [12]. However, most models mentioned use a unified satellite and assumes the unit handling cost is constant. Our study is the first attempt to model the different cost of satellites, which can act as a parcel locker or a positioning point of a robot to complete the last mile delivery.

2.2 MULTI-OBJECTIVE LOCATION ROUTING PROBLEM

One of the common characteristics of all the studies above is that the cost is the only optimized objective, without considering the external cost. Tavakkoli-Moghaddam, Makui, and Mazloomi (2010) developed an LRP with two-objectives. First is to minimize the sum of facility costs and transport costs. The second objective is to maximize the served customer demand [13]. K. Govindan (2014) proposed a two-echelon location–routing problem under the time-window constraints, which considered vehicle types, loads, environmental effects [14]. Another paper from

Martínez-Salazar et al. (2014) that proposed a two objective 2E-LRP with capacity constraints. The first objective is to minimize the sum of total costs, and the second is to minimize the difference between routes duration [15].

2.3 ALGORITHMS USED TO SOLVE THE 2E-LRP

The 2E-LRP is a generalization of the LRP, which is an NP-hard problem [16]-[18], because the two subproblems involved are shown to be NP-hard [19], and it is impossible to find the optimal solution in polynomial time. Feliu et al. (2008), Baldacci, Roberto (2019) used an exact branch-and-cut algorithm to solve a 2E-LRP [20][21]. As it is hard to solve the realistically sized instances to optimality by pure exact methods, the metaheuristics method is chosen in most cases [22]. For example, tabu search [23], constructive heuristics and applies variable neighborhood descents [24], multi-start iterated local search [25], a variable neighborhood search [26] [27].

In recent years, Artificial Immune Systems (AIS) has received a significant amount of interest from researchers and industrial sponsors. AIS is a highly parallel, evolved, and distributed adaptive system. The information processing abilities of AIS provide important aspects in the field of computation [28]. Manish Shukla (2013) presents an artificial immune system-based algorithm for vehicle routing problems, and the result showed that AIS performed better compared to Simulated Annealing and Genetic Algorithm [29]. Since our problem considers a parcel lockers, robots, and vans involved in the E-grocery distribution, new models and innovative methods are necessary to help better understand the benefits of the two-echelon delivery system.

The contributions of this paper that identifies differences between our research and related works are as follows:

- Firstly, a sustainable urban E-grocery distribution network is designed, integrating mixed fleets and mixed satellites. As far as we know, this is the first time that van, robot, and parcel locker are combined in an urban E-grocery network, which may shed light on the last-mile delivery operations.
- Secondly, presenting a novel two objective optimization model targeting a 2E-LRP-MVMS. To the best of our knowledge, no LRP literature has tackled multiple objectives in 2E-LRP-MVMS. This paper will develop a multi-objective model by considering emissions based on the single cost objective. Importing real-world assumptions for the parcel locker and robot, and each robot has a certain number of separate compartments is assumed.
- Thirdly, presenting a hybrid immune algorithm, and two improved steps, vaccination and immunization are introduced in the algorithm. The former is to improve fitness, while the latter is to prevent population degradation. This research aims to fill this gap by developing a new multi-objective 2E-LRP-MVMS formulation as well as the hybrid immune algorithm.

3.0 PROBLEM DESCRIPTION AND MATHEMATICAL FORMULATION

3.1 PROBLEM DESCRIPTION

The Two-echelon vehicle routing problem using a mixed vehicle and mixed satellite (2E-LRP-MVMS) is as illustrated in Fig. 3 (Here, a satellite can be a positioning point or a locker). Parcels delivery from depot to customers is managed by vehicle routing and distribution through satellites. We assume that each satellite can serve as a locker and positioning point at the same time. Parcels are dispatched from a depot to a satellite in the first echelon. At each active satellite, parcels are moved from a first-echelon vehicle to a second-echelon vehicle. Each vehicle starts from a second-echelon satellite, follows a prescribed route to serve designed customers, and returns to the same satellite when the robot is selected for the second-echelon route, or the customer walks or drives to a locker and return back if a locker is selected. Walking and driving are not considered in this problem. With the increase of the customer's demand, a new depot or a new satellite will be valued to add in the existing network, as the expansion of the network will directly affect the total costs and emissions.

In this work, the 2E-LRP-MVMS consists of:

(1) Make a decision on the locations of depots and satellites.

(2) Plan vehicle routes through depots and satellites in the first echelon.

(3) Assign the customers to a positioning point or a locker.

(4) Plan vehicle routes for the assigned customers in the second echelon.

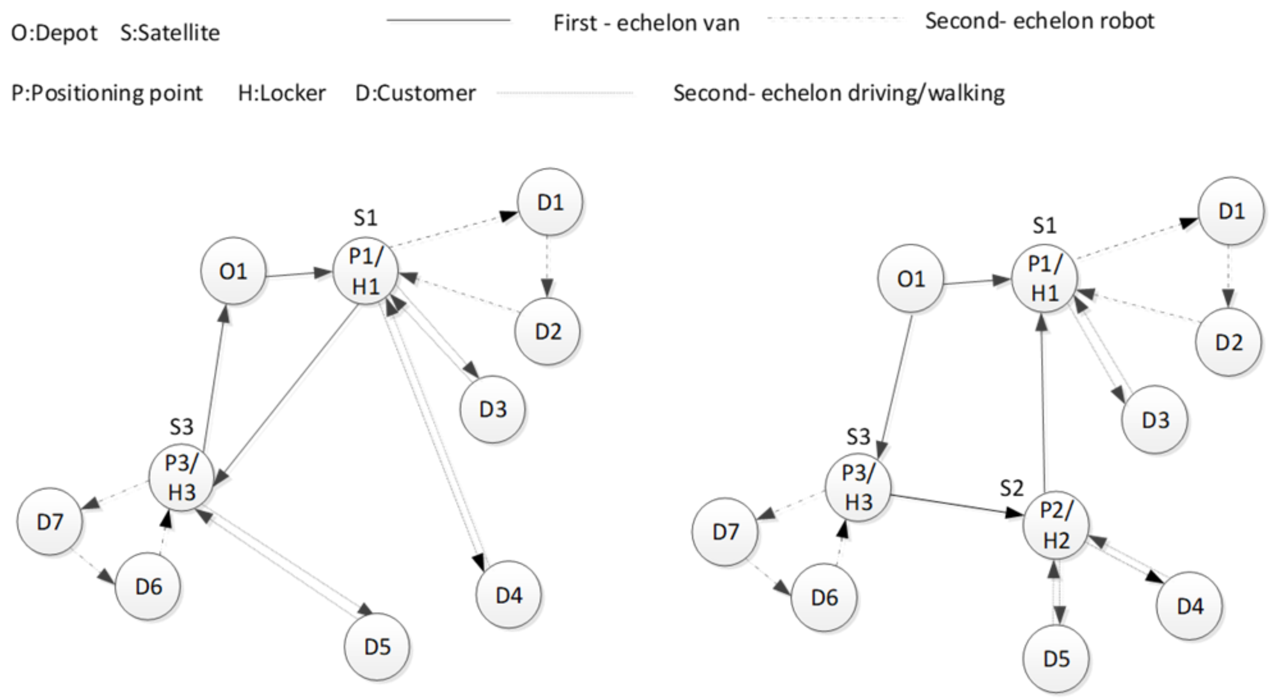


Figure 3. Two-echelon location routing network with mixed vehicles and mixed satellites

3.2 MATHEMATICAL FORMULATION

The *2E-LRP-MVMS* is firstly described as a network graph $W = (N, L)$, where N is the set of nodes, and L is the set of arcs. Here, there are four kinds of nodes: depots (O), customers (D), parcel lockers (H), and positioning points (P), where parcel lockers (H), and positioning points (P) are consisting of satellites (S). We have $N = O \cup D \cup H \cup P$, and further define that: $N_1 = \mathrm{O} \cup \mathrm{H} \cup P$, $N_2 = D \cup P$, and $N_3 = H \cup P$, Accordingly, two-echelon delivery routes can be distinguished: the first-echelon delivery route $(o,\ h) \cup (o, p)$, $o \in O$, $h \in H$, $p \in P$, and the second-echelon route $(h,\ d) \cup (p, d)$, $h \in H$, $p \in P$, $d \in D$.

The following notations and assumptions are used for formulating the proposed model:

- Each satellite can serve as a locker or a positioning point. If a locker is assigned to a customer, there will be no second-echelon delivery; if a positioning point is assigned to a customer, they may receive their packages by a robot.
- We assume that the depot, parcel locker, and positioning point have unlimited capacities.
- The orders are referred to as a homogenous package, therefore, the demand represents a certain number of homogenous packages.
- There is enough time to prepare a robot between two consecutive tours, including changing the battery.
- Each robot has a certain number of separate compartments.
- The first-echelon delivery must begin/end at the same open depot.
- The second-echelon delivery must begin/end at the same satellite.

Table 1. Model's Sets

N	Set of nodes
L	Set of arcs
O	Set of depots {1, …, i}
H	Set of parcel lockers {1, …, m}
P	Set of positioning points {1, …, m}
D	Set of customers {1, …, j}
N_1	Set of nodes consist of $\{O \cup H \cup P\}$
N_2	Set of nodes consist of $\{D \cup H \cup P\}$
N_3	Set of nodes consist of $\{H \cup P\}$
M_v	Set of Vehicles
Y	Set of the period time, $y \in Y$

Table 2. Model's Parameters

F_o	The opening cost of depot o, $o \in O$
F_{n_3}	The opening cost of a satellite n_3, $n_3 \in N_3$
F_{1v}	Fixed cost of each vehicle that is operated in the first - echelon for vehicles of type of v
F_{2v}	Fixed cost of each vehicle that is operated in the second - echelon for vehicles of type of v
W_o	Average handing cost at a depot o, $o \in O$
W_h	Average handing cost at a parcel locker h, $h \in H$
W_p	Average handing cost at a positioning point p, $p \in P$

Q_o	The handling capacity of depot o, $o \in O$
Q_h	The handling capacity of parcel locker h, $h \in H$
Q_p	The handling capacity of positioning point p, $p \in P$
O_{max}	Maximum desired number of depots
S_{max}	Maximum desired number of satellites
C_{ij}^{v}	Unit distribution cost between the node i and j using vehicle type v
τ_o	Environmental impacts of opening a depot, $o \in O$
τ_n	Environmental impacts of opening a satellite, $n \in N_3$
ω_o	Average environmental impacts for handling at a depot o, $o \in O$ in the time period $y \in$ Y
ω_h	Average environmental impacts for handling at a locker h, $h \in H$ in the time period $y \in Y$
ω_p	Average environmental impacts for handling at a positioning point p, $p \in P$ in the time period $y \in Y$
φ_{ij}^{v}	Unit Environmental impacts of transport between the node i and j, using vehicle type v
q_v	Capacity of vehicle type v, $v \in V$
q^{ADV}	Compartments number of a robot
x_{dy}	Demand from a customer d, $d \in D$ in the time period $y \in Y$
γ	Auxiliary parameter
l_{ij}^{v}	Travel distance between the node i and j using vehicle type v, $(i, j) \in L$, $v \in V$

$u^{m_v v}$	Average speed for vehicle m_v, $v \in V$
β^{range}	Maximum battery electric range of a robot
β^{time}	Maximum battery operating time of a robot
σ^{rang}	Safety buffer for the battery electric range
σ^{time}	Safety buffer for the battery operating time
ε_{dy}	Arrival time to a customer in the time period y, $d \in D, y \in Y$
θ_{ny}	Arrival time to a satellite n in the time period y, $n \in N_3, y \in Y$
t_{py}^{load}	Loading time at a positioning point p in the time period y, $p \in P$ $y \in Y$
t_{hy}^{load}	Loading time at a locker h in the time period y, $h \in H$ $y \in Y$
WT	Working time

Table 3. Model's Decision Variables

$r_{ony}^{m_v v}$	1, if a vehicle m_v traverses arc $(i, j) \in (o, n) \in N_1$ in the first echelon in the time period y, $n \in N_3$
$r_{ny}^{m_v v}$	1, if vehicle m_v visit a satellite in the time period y, $n \in N_3$
r_o	1, if a depot o is open; 0, otherwise, $o \in O$
$e_{hdy}^{m_v v}$	1, if a vehicle m_v traverses arc $(i, j) \in (h, d) \in N_2$ through locker h, in the time period y, $h \in H$
$e_{pdy}^{m_v v}$	1, if a vehicle m_v traverses arc $(i, j) \in (p, d) \in N_2$ through positioning point p in the time period y, $p \in P$
$e_{dy}^{m_v v}$	1, if vehicle m_v visit a customer d in the time period y, $d \in D$
e_{hdy}	1, if a customer d is assigned to a parcel locker h in the time period y; 0, $otherwise$, $h \in H, d \in D$

e_{pdy}	1, if a customer *d* is assigned to a positioning point *p* in the time period *y*; 0, $otherwise$, $p \in P$, $d \in D$
e_n	1, if a satellite is open; otherwise, 0, $n \in N_3$
$\mu_{hy}^{m_v v}$	The number of parcels delivered to parcel locker *h* by vehicle m_v in the time period *y*
$\mu_{py}^{m_v v}$	The number of parcels delivered to positioning point *p* by vehicle m_v in the time period *y*
μ_{oy}	The number of parcels packed at depot *o*

Table 4. Mathematical Model of 2E-LRP-MVMS

$$Min.\ \boldsymbol{Obj1} = \sum_{o\in O} F_o\, r_o + \sum_{n\in N_3} F_n\, e_n + \sum_{y\in Y}\big(\sum_{v\in V} \sum_{m_v\in M_v} \sum_{i,j\in N_1} C_{ij}^{v} r_{ijy}^{m_v v}\, l_{ij}^{v} + \sum_{v\in V} \sum_{m_v\in M_v} \sum_{i,j\in N_2} C_{ij}^{v} e_{ijy}^{m_v v} l_{ij}^{v} + \sum_{h\in H} \sum_{d\in D} \mu_{oy} W_o r_o + \sum_{d\in D} W_p\, e_n\big(\sum_{p\in P} e_{pdy}\big(\sum_{v\in V} \sum_{m_k\in M_k} \mu_{ny}^{m_v v}\big)\big) + \sum_{d\in D} W_h\, e_n\big(\sum_{h\in H} e_{hdy}\big(\sum_{v\in V} \sum_{m_k\in M_k} \mu_{ny}^{m_v v}\big)\big) + \sum_{o\in O} \sum_{n\in N} \sum_{v\in V} \sum_{m_v\in M_v} F_{1v}\, r_{ony}^{m_v v} + \sum_{p\in P} \sum_{d\in D} \sum_{v\in V} \sum_{m_v\in M_v} F_{2v}\, e_{pdy}^{m_v v} + \sum_{h\in H} \sum_{d\in D} \sum_{v\in V} \sum_{m_v\in M_v} F_{2v}{}'\, e_{hdy}^{m_v v}\big) \tag{1}$$

$$\text{Min. } \boldsymbol{Obj2} = \sum_{o\in O} \tau_o r_o + \sum_{n\in N_3} \tau_n e_n + \sum_{y\in Y}\big(\sum_{v\in V} \sum_{m_v\in M_v} \sum_{i,j\in N_1} \varphi_{ij}^{v} r_{ijy}^{m_v v}\, l_{ij}^{v} + \sum_{v\in V} \sum_{m_v\in M_v} \sum_{i,j\in N_2} \varphi_{ij}^{v} e_{ijy}^{m_v v} l_{ij}^{v} + \sum_{h\in H} \sum_{d\in D} \mu_{oy} \omega_o r_o + \sum_{d\in D} \omega_p\, e_n\big(\sum_{p\in P} e_{pdy}\big(\sum_{v\in V} \sum_{m_k\in M_k} \mu_{ny}^{m_v v}\big)\big) + \sum_{d\in D} \omega_h\, e_n\big(\sum_{h\in H} e_{hdy}\big(\sum_{v\in V} \sum_{m_k\in M_k} \mu_{ny}^{m_v v}\big)\big)\big)$$

Obj1 minimizes the total fixed and variable costs of the network. The first and second item denotes the fixed opening cost of depot and satellite separately. The third and fourth items are transportation costs in the first echelon and second echelon, respectively. The fifth, sixth and seventh items represent handling costs in a depot, positioning point, and locker. The subsequent three items denote the fixed costs of each tour in different echelons.

Obj2 minimizes the total environmental impact of the network. The first and second items are the environmental impact related to opening depot and satellite. The third and fourth items are environmental impacts associate with delivering parcels in the first and second echelon. Finally, the last three items are environmental impacts aroused by operational handling at the depot, positioning point, and locker, respectively.

All the variables are as follows:

I. *Flow-conservation constraints*

$$\sum_{j\in N_1} r_{ijy}^{m_v v} = \sum_{j\in N_1} r_{jiy}^{m_v v} = r_{ny}^{m_v v} \quad \forall\, i \in N_1, m_v \in M_v, v \in V, y \in Y \tag{1}$$

$$\sum_{d\in D}\sum_{v\in V}\sum_{m_v\in M_v} e_{pdy}^{m_v v} = \sum_{p\in P}\sum_{v\in V}\sum_{m_v\in M_v} e_{dpy}^{m_v v} \;\forall\, p \in P, y \in Y \tag{2}$$

$$\sum_{d\in D}\sum_{v\in V}\sum_{m_v\in M_v} e_{pdy}^{m_v v} + \sum_{d\in D}\sum_{v\in V}\sum_{m_v\in M_v} e_{hdy}^{m_v v} = e_n \quad \forall\, p \in P,\ h \in H, y \in Y \tag{3}$$

$$\sum_{i\in N_1{}'}\sum_{j\in N_1{}'} r_{ijy}^{m_v v} = |N_1{}'| - 1 \;\; \forall m_v \in M_v,\ N_1{}' \subseteq N_1,\ \ |N'| \geq 2, y \in Y \tag{4}$$

$$\sum_{i\in N_2}\sum_{v\in V}\sum_{m_v\in M_v} e_{idy}^{m_v v} \leq 1 \quad \forall\, d \in D, y \in Y \tag{5}$$

$$\sum_{n\in N_3} e_{ndy} \leq 1 \qquad \forall\, d \in D, y \in Y \tag{6}$$

$$\sum_{o} \mu_{oy} = \sum_{p\in N_3}\sum_{v\in V}\sum_{m_v\in M_v} e_{pdy}^{m_v v}\, \mu_{py}^{m_v v} + \sum_{h\in N_3}\sum_{v\in V}\sum_{m_v\in M_v} e_{hdy}^{m_v v}\, \mu_{hy}^{m_v v} \;\forall\, m_v \in M_v, v \in V,$$

$$y \in Y \tag{7}$$

$$\sum_{d\in D} e_{pdy}^{m_v v} + \sum_{i\in N_1} e_{diy}^{m_v v} - e_{pdy} \leq 1 \;\; \forall\, m_v \in M_v, v \in V, p \in P, d \in D, y \in Y \tag{8}$$

$$\sum_{d\in D} e_{hdy}^{m_v v} + \sum_{i\in N_1} e_{diy}^{m_v v} - e_{hdy} \leq 1 \;\; \forall\, m_v \in M_v, v \in V, h \in H, d \in D, y \in Y \tag{9}$$

Constraint (1) imposes a flow balance at each depot in each period time. Constraint (3) shows that the positioning point is operationally balanced. If a vehicle comes to a satellite, another vehicle should be departing to a customer. Constraint (3) shows that satellite is operationally balanced. Constraint (4) prohibits sub tours. Constraint (5) imposes that each customer is visited once. Constraint (6) requires that each customer is assigned at exactly one satellite. Constraint (7) requires that the number of parcels to be handled in depot *o* in the time period *y* is equal to the number of parcels that should be delivered from that node. Inequalities (8) imposes that positioning point *p* serves a customer if there is one vehicle (e_{pdy}=1) m_v leaving *p* and arriving at *d*, and also e_{pdy} can be equal to 1 even if no vehicle is available from *p* to *d*. Inequalities (9) imposes that locker *h* serves a customer if e_{hdy}=1.

II. Terminal capacity constraints

$$\sum_{d\in D} x_{dy} e_{hdy} \leq Q_h\, e_n \tag{10}$$

$$\sum_{d\in D} x_{dy} e_{pdy} \leq Q_p\, e_n \tag{11}$$

$$\mu_{oy} \leq Q_o \quad \forall o \in O, y \in Y \tag{12}$$

$$\sum_{p\in P} e_{py}^{m_v v} \leq Q_p \quad \forall\, m_v \in M_v, v \in V,\ y \in Y \tag{13}$$

$$\sum_{h\in H} e_{hy}^{m_v v} \leq Q_h \quad \forall\, m_v \in M_v, v \in V,\ y \in Y \tag{14}$$

Inequality (10) requires if a parcel locker is not open, no customer is allocated to it; or else, the total demand of customers served by an open parcel locker cannot exceed the locker's capacity. Inequality (11) requires that if a positioning point is not open, no customer is allocated to it; otherwise, the total demand of customers cannot exceed the capacity of the served positioning point. Constraint (12) imposes the capacity limitation of depot *o*. Constraint (13) imposes that the number of parcels delivered to a positioning point must not exceed its capacity. Constraint (14) imposes the number of parcels delivered to a locker must observe its capacity.

$$\sum_{o\in O} r_o \leq O_{max}\ \forall\, o \in O \tag{15}$$

$$\sum_{n\in N_3} e_n \leq S_{max}\ \forall\, n \in N_3 \tag{16}$$

Constraints (15) and (16) limit the maximum number of the depots and the satellites, respectively.

III. Vehicle capacity constraints

$$\sum_{i\in N_2} \sum_{d\in D} x_{dy}\, e_{idy}^{m_v v} \leq q_v \quad \forall\, m_v \in M_v, d \in D, y \in Y \tag{17}$$

$$\sum_{p\in P} e_{py}^{m_v v} \leq q_v \times \sum_{p\in P} \sum_{i\in N_2} e_{ipy}^{m_v v} \quad \forall\, m_v \in M_v, v \in V, y \in Y \tag{18}$$

$$e_{pdy}^{m_v v} \leq \left({}^{x_{dy}}/_{q^{ADV}} \right) + 1 - \gamma\ \forall p \in P, y \in Y \tag{19}$$

Constraint (17) limits the capacity of each vehicle. Constraint (18) illustrates that if a vehicle m_v does not visit a positioning point *p*, the number of parcels delivered by that vehicle to the positioning point *p* must be zero, at the same time, the load should not exceed the capacity of vehicles. Constraint (19) ensures that the maximum number of the deliveries is depended on the capacity of the robot and the order quantity.

IV. Battery time limit constraints

$$\sum_{p\in P} \sum_{d\in D} l_{pd}^{v} * e_{pdy}^{m_v v} \leq \beta^{range} - \sigma^{range} \ \ \forall\, p \in P, y \in Y,\ m_v \in M_v, v \in V \tag{20}$$

$$l_{pd}^{v}/u^{m_v v} \leq \beta^{time} - \sigma^{time} \ \ \forall\, p \in P, y \in Y \tag{21}$$

Constraint (20) ensures that each tour should not exceed the maximum travel distance of a battery. The right side of the inequality assures safety buffer is reserved for unexpected events during the tour. Similarly, constraint (21) adds a safety buffer for the maximum usage time of the battery.

V. Time limit constraints

$$\varepsilon_{jy} = (\varepsilon_{iy} + t_{iy}^{load} + l_{ij}^{v}/u^{m_v v})e_{ijy}^{m_v v} \; \forall (i,j) \in N_2, m_v \in M_v, v \in V, y \in Y \tag{22}$$

$$\theta_{jy} = (\theta_{iy} + t_{iy}^{load} + l_{ij}^{v}/u^{m_v v})r_{ijy}^{m_v v} \; \forall (i,j) \in N_1, m_v \in M_v, v \in V, y \in Y \tag{23}$$

Constraints (22) and (23) require that the arrival time at a node *j* in the second echelon is equal to the arrival time at a node *i* in the second echelon plus the service time and the travel time, also the arrival time at a node *j* in the first echelon is equal to the arrival time at a node *i* in the first echelon plus the service time and the travel time.

VI. Definitions of decision variables

$$r_{ony}^{m_v v}, r_{ny}^{m_v v} \in \{0,1\} \quad \forall\, m_v \in M_v, v \in V, o \in O, n \in N_3, y \in Y \tag{24}$$

$$r_o \;, e_n \; \in \{0,1\} \; \forall\, o \in O, \; n \in N_3 \tag{25}$$

$$e_{pdy}^{m_v v}, e_{hdy}^{m_v v}, e_{dy}^{m_v v} \in \{0,1\} \; \forall\, m_v \in M_v, v \in V, p \in P, h \in H, d \in D, y \in Y \tag{26}$$

$$e_{pdy}, e_{hdy} \in \{0,1\} \; \forall\, n \in N_3, \; d \in D, y \in Y \tag{27}$$

$$\mu_{py}^{m_v v}, \; \mu_{hy}^{m_v v}, \; \mu_{oy} \geq 0 \quad \forall\, m_v \in M_v, v \in V, p \in P, h \in H, d \in D, o \in O, y \in Y \tag{28}$$

The domains of the variables are defined in constraints (24)- (28).

4.0 METHODOLOGY

Immune algorithm (IA) is proposed with analogies to the concept and the theory of immunity in biotic science. The epidemic disease concept and its theory are applied to the genetic algorithm, which retains the excellent characteristics of the original algorithm. It tries to select and makes use of some characteristics, information, or knowledge in the question to suppress the degradation of its optimization process purposefully [30].

In this paper, we propose a hybrid immune algorithm (HIA) based on the genetic algorithm [31] [32]. Two improved steps, vaccination, and immunization are introduced in the algorithm. The former is to improve fitness, while the latter is to prevent population degradation.

- Vaccination: Setting individual *x*, vaccination refers to modify the genes at a certain location of *x* according to the prior knowledge, so that the obtained individuals have higher fitness with greater probability. Vaccines are extracted from a priori knowledge of the problem.

- Immune selection: This operation is divided into two steps. The first step is the immune test; if the fitness is not as good as the parent, it recognizes that a serious degradation appears in the process of crossing and mutating. At this time, the individual will be replaced by the parent. If the offspring is better than the parent, the second step is carried out. The second step is an annealing option. In the current child generation E_k= $(x_1, \dots, x_{n_0})$, we choose individuals with probability p,

$$p(x_i) = \frac{e^{f(x_i)}/T_k}{\sum_{i=1}^{n_o} e^{f(x_i)}/T_k} \tag{29}$$

Here, $f(x_i)$ is the fitness of an individual x_i, T_k is the temperate temperature control sequence tending to 0. The specific process and steps of immunization vaccines section about a location-routing problem are discussed in detail.

- Analyze the problem to be solved and collect characteristic information

Suppose one vehicle leaves a depot and moves on to the next satellite. Generally speaking, the first choice is the nearest one. If the target satellite is exactly the satellite that had already been visited, then, a destination to be reached is the satellite with the smallest distance excluding the previous one and so on.

- Generate immune vaccine based on the characteristic information

The characteristic of a location-routing problem can be taken as characteristic information or knowledge used for immune vaccine generation. In the actual implementation process, find out the neighboring satellite of all the satellites with the general circular iteration method. The vaccine is not an individual and therefore, cannot be a solution to the problem. It only has the characteristics of an individual on a certain gene.

- Vaccination

Generally, we suppose the closest satellites S_j to the satellites S_i are not directly linked, which are in the separate sections, $S_{i-1}, S_i, S_{i+1}, S_{j-1}, S_j, S_{j+1}$.The current travel path is: $\pi = \{S_0, \cdots, S_{i-1}, S_i, S_{i+1}, \cdots, S_{j-1}, S_j, S_{j+1}, \cdots S_N\}$, the corresponding path length is

$$L_\pi = \sum_{k=1}^{i-1} l_k + l_i + \sum_{k=i+1}^{j-2} l_k + l_{j-1} + l_j + \sum_{k=j+1}^{N} l_k \tag{30}$$

When the immune probability is P_i, the nearby satellite around the satellite S_i is regarded as the next target satellite. The travel path will be adjusted to $\pi_c = \{S_0, \cdots, S_{i-1}, S_i, S_j, S_{i+1}, \cdots, S_{j-1}, S_{j+1}, \cdots S_N\}$, the corresponding path length will change to

$$L_{\pi_c} = \sum_{k=1}^{i-1} l_k + d_1 + d_2 + \sum_{k=i+1}^{j-2} l_k + d_3 + \sum_{k=j+1}^{N} l_k \tag{31}$$

Compare formula (30) with (31), as S_j is the nearest satellite to S_i, d_1 is the shortest or the second shortest (d_2 is the shortest) edge in the triangle composed with edges $S_i - S_j - S_{i+1}$, while this is different between S_{j-1}, S_j, S_{j+1}. In most cases, the difference between d_3 and l_{j-1}+l_j is more than the difference between $l_1 + l_2$ and l_i. And the more important is that in this local environment, the path was made an optimal adjustment by the operator. Whether the adjustment can contribute to the whole path remains to be determined by the selection mechanism. However, from the analysis process, it is not difficult to draw the following inequality:

$$\mathrm{P}(L_{\pi_c} < L_{\pi}) \geq P(L_{\pi_c} < L_{\pi}) \tag{32}$$

Where *P(S)* represents the probability of occurrence of event *S*. That is, when the location-routing problem is solved, the immunization has been injected based on a specific vaccine.

There are two known *NP*-hard sub-problems in *2E-LRP-MVMS*: Two-echelon location problem and two-echelon vehicle routing problem. Accordingly, the problem in this paper is to find the efficient location of the depot/satellite and the vehicle routes to minimize total cost and environmental effects. The *2E-LRP-MVMS* problem is searching for two integer arrays π=$\{R_1, R_2, \ldots, R_n\}, \tau = \{E_1, E_2, \ldots, E_m\}$ (R_i represents the compilation of the i^{th} satellite in the best path on the first-echelon; E_i represents the compilation of the i^{th} customer on the second-echelon) for coordinates (the locations of the assumed *n* satellites, *m* customers) that satisfies the following conditions,

$$L_{\pi} = \sum_{i=1}^{n-1} l(R_i, R_{i+1}) + l(R_n, R_1) = \lim \sum_{\substack{i,j=1 \\ i \neq j}}^{n} l(R_n, R_1) \tag{33}$$

$$L_{\tau} = \sum_{i=1}^{m-1} l(E_i, E_{i+1}) + l(E_n, E_1) = \lim \sum_{\substack{i,j=1 \\ i \neq j}}^{m} l(E_m, E_1) \tag{34}$$

Each step of the basic algorithm and its relations to the location-routing problem are shown in Fig. 4., which is developed based on Satoshi Endoh (1998) [33]. Firstly, the problem environment is initialized. Then, some candidate solutions are generated. The third is to calculate affinity value of each solution. The fourth step is accelerating and restraining to product antibodies. The fifth are vaccination and immunization. At last, candidate solutions using GA are reproduced. Accordingly, our method aims to combined immune algorithm with genetic search technique to improve the performance.

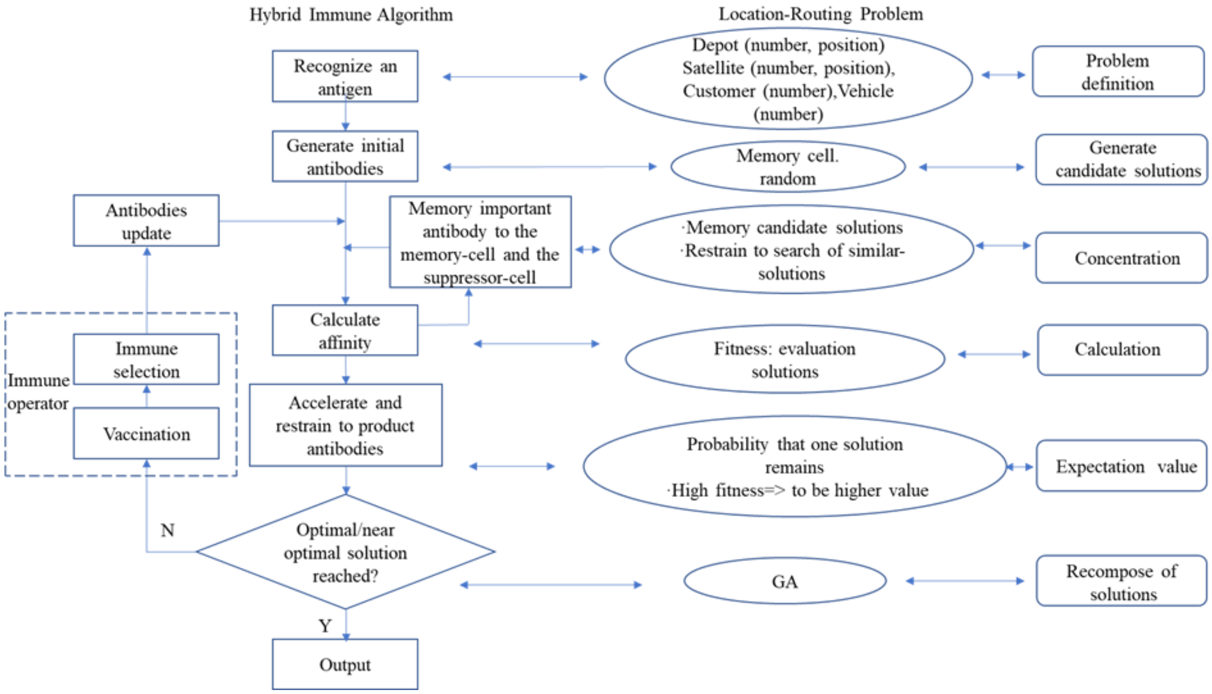


Figure 4. Hybrid Immune Algorithm

5.0 NUMERICAL EXPERIMENTS

5.1 DATA GENERATION

The performance of different multi-objective algorithms are compared through an experiment with 12 problems classified into three scales: small, medium, and large. And each problem is composed of depots (O), satellites (Lockers (H) ∪ Positioning points (P)), Customers (D), and vehicles (V). **Table 5** presents the test data generated for the problem. The average travel cost between two nodes i and j is C_{ij}^{v}, is calculated $C_{ij}^{van} = l_{ij}^{van} \times \vartheta$, that ϑ is distributed uniformly as U (0.5, 1.5), $C_{ij}^{ADV} = l_{ij}^{ADV} \times \omega$, that ω is uniformly distributed as U (1.5, 2.5). The average environmental effect between two nodes i and j φ_{ij}^{v} is calculated, $\varphi_{ij}^{van} = l_{ij}^{van}\phi$, that ϕ is uniformly distributed as U (0.8, 1.2). φ_{ij}^{ADV}= 0. The number of periods is 20. Other test data are estimated as follows:

Table 5. Test data for the algorithms

Factors	**Levels**	**Parameter**
($O\times H/P \times D \times M_{van} \times M_{ADV}$) No. of depots ($O$) No. of lockers/ positioning points (H/P) No. of customers (D) No. of vehicles (M_{van}) No. of vehicles (M_{robot})	Small scale	Pro.1. ($2\times 3 \times 7 \times 2 \times 2$) Pro.2. ($2\times 5 \times 8 \times 2 \times 2$)
		Pro.3. ($3\times 5 \times 10 \times 3 \times 3$) Pro.4. ($4\times 6 \times 11 \times 4 \times 4$)
	Medium scale	Pro.5. ($5\times 9 \times 14 \times 5 \times 5$) Pro.6. ($5\times 10 \times 15 \times 6 \times 5$)
		Pro.7. ($6\times 10 \times 16 \times 6 \times 5$) Pro.8. ($7\times 12 \times 12 \times 6 \times 6$)
	Large scale	Pro.9. ($8\times 14 \times 18 \times 7 \times 6$) Pro.10. ($9\times 15 \times 22 \times 8 \times 6$)
		Pro.11. ($10\times 16 \times 24 \times 8 \times 7$) Pro.12. ($12\times 16 \times 26 \times 9 \times 7$)
Demand of customer	x_{dy}	Normal distribution, N (100, 20)
The variable cost and emission in the locker and positioning point	$(W_h, \varphi_h), (W_P, \varphi_p)$	U (1,10), U (1,5)
Fixed cost of vehicle v	F_{1v}, F_{2v}	$Q_v \times U(10,50)$ $1.5 \times Q_v \times U(10,50)$
The average speed $u^{m_v v}$	u_{van}, u_{ADV}	U (1,4), U (1,4)/2
Arrival time at customer d and satellite n in the time period y	$\varepsilon_{dy,}\theta_{ny}$	U (0.1, 0.9) ×WT
Loading time at positing point p and locker h in the time period y	$t_{py}^{load}, t_{hy}^{load}$	U (0.1, 0.3), U (0.1, 0.5)
Safety buffer for the battery operating time	σ^{time}	U (1.5, 2.5)
Maximum battery operating time of a robot	β^{time}	$l_{nd}^{v}/u^{m_v v}$ + U (1.5, 2.5)

5.2 EVALUATION

Some metrics are used simultaneously [14] [34] to make algorithm comparison, four performance evaluation metrics in this paper are selected as follows:

a. Mean ideal distance (MID): The closeness between Pareto solution and ideal point (0, 0) [14]

$$\text{MID} = \frac{\sum_{i=1}^{n} c_i}{n} \quad (35)$$

Where *n* represents the number of non-dominated set and $c_i = \sqrt{f_{1i}^2 + f_{2i}^2}$. The lower value of MID comes along a better quality solution.

b. Spread of non-dominance solution (SNS): it is used to evaluate the standard deviation of the distance of $\vec{f}_{ideal}$ from pareto solutions [35]. The higher value of SNS comes along a better solution quality.

$$\text{SNS} = \sqrt{\frac{\sum_{i=1}^{n}(MID - c_i)^2}{n-1}} \quad (36)$$

c. Diversification metric (DM): The spread of a pareto solution set is calculated by the DM.

   A higher value in this metric represents a better performance of the algorithm [36].

$$\text{DM} = \sqrt{\left(\frac{max f_{1i} - min f_{1i}}{f_{1,total}^{max} - f_{1,total}^{min}}\right)^2 + \left(\frac{max f_{2i} - min f_{2i}}{f_{2,total}^{max} - f_{2,total}^{min}}\right)^2} \quad (37)$$

d. Rate of achievement to two objectives simultaneously (RAS) [37]

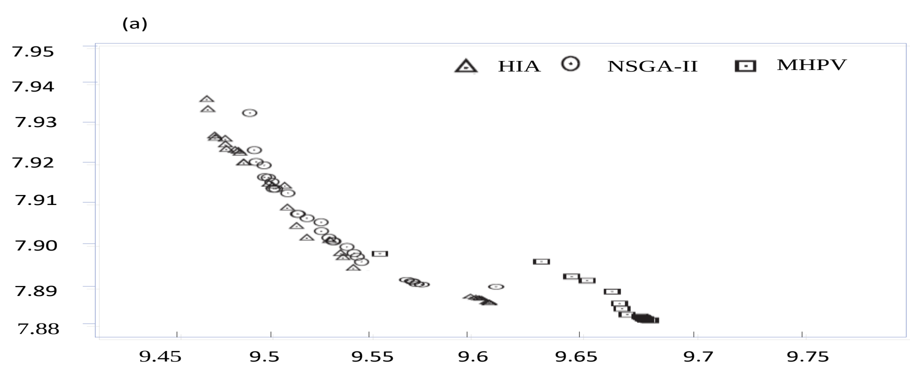
$$\text{RAS} = \frac{\sum_{i=1}^{n}\left(\frac{f_{i1} - F_i}{F_i}\right) + \left(\frac{f_{i2} - F_i}{F_i}\right)}{n} \quad (38)$$

The proposed metrics above are used to compare the performance of algorithms. **Table 6** reports the calculation results of SNS, MID, DM, and RAS to determine if there is a significant difference among the effectiveness of algorithms (The nondominated sorting genetic algorithm II (NSGA-II) and multi-objective hybrid particle swarm optimization (MHPV)) ([38],[14]). The table shows that HIA significantly outperforms other approaches in SNS, DM, and RAS, while in MID, there is no significant difference among the algorithms. Then, the relative percentage deviation (RPD) obtained from the result of each problem is calculated by the following formula:

Table 6. Evaluation of solution for algorithms grouped by problem size and index type

Pro no.	**MID**			**SNS**			**DM**			**RAS**		
	HIA	NSGA-II	MHPV	HIA	NSGA-II	MHPV	HIA	NSGA-II	MHPV	HIA	NSGA-II	MHPV
1	13762	13847	12072	**9022**	7938	6893	**29.879**	27.096	23.456	**0.67**	0.57	0.32
2	**15893**	15267	9378	10359	12993	10590	36.457	40.357	43.560	**1.43**	0.16	0.47
3	**11703**	10280	8150	4609	5734	5991	19.402	20.336	20.882	0.38	1.23	1.19
4	5290	5912	5224	**2950**	2904	2640	11.351	13.447	12.629	**2.33**	0.30	0.23
5	**11368**	9927	8246	12210	12856	12001	**45.150**	42.334	12.590	0.83	2.46	7.56
6	13847	14039	11670	**8378**	7840	6809	**27.710**	26.113	24.092	**0.57**	0.42	0.43
7	15903	16833	13648	**10442**	7783	7341	**41.567**	30.817	26.093	**1.87**	1.45	1.46
8	5376	5899	4690	**3590**	3216	2784	**12.994**	11.225	9.348	**1.96**	0.39	1.57
9	**9002**	8923	7684	4730	5629	4037	**21.341**	17.725	16.773	0.07	0.14	0.23
10	**15285**	13986	11789	**8507**	7589	6636	27.480	29.440	23.659	**3.12**	2.14	2.13
11	19485	19893	15159	**11052**	9941	7340	**43.115**	37.479	28.783	1.08	1.20	0.99
12	13994	14830	12862	13046	14247	9237	**39.447**	35.883	23.502	**0.16**	0.12	0.14

Fig. 5 demonstrates non-dominated solutions in three scales by different algorithms. It can be seen that, the effectiveness of HIA comparing with the other algorithms is obviously observed when the problem size increases.



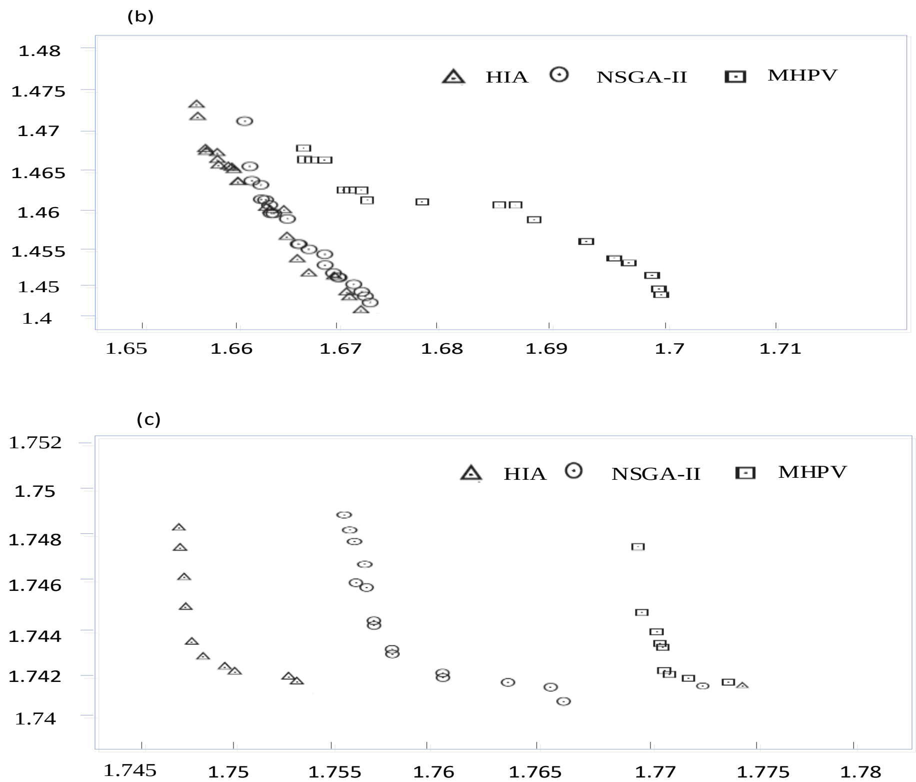


Figure 5. Dispersion of non-dominated solutions obtained by different algorithms in three scales. (a) Small scale（104), (b) Medium scale (105), (c) Large scale (106)

Fig.6 demonstrates that in SNS, DM, and RAS metrics, HIA is significantly better than other algorithms. Also, **Fig. 7** demonstrates LSD intervals and the means plot for all algorithms. It is seen that HIA does not overlap with others on any areas. Therefore, it statistically outperforms NSGA-II and MHPV based on SNS, DM, and RAS metrics. Further NSGA-II shows priority than HIA and MHPV, although there is not any statistically significant difference based on the MID metric.

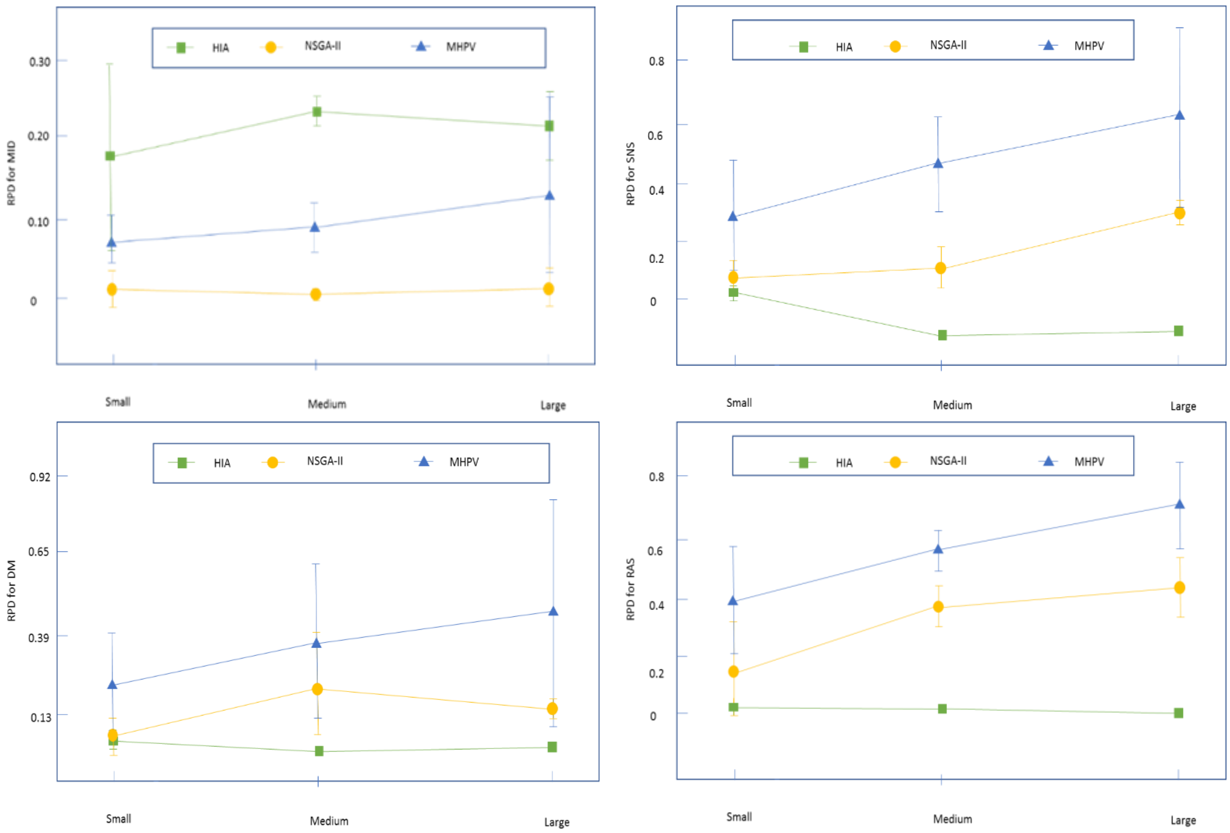


Figure 6. Evaluation metric value for the interaction between the algorithms

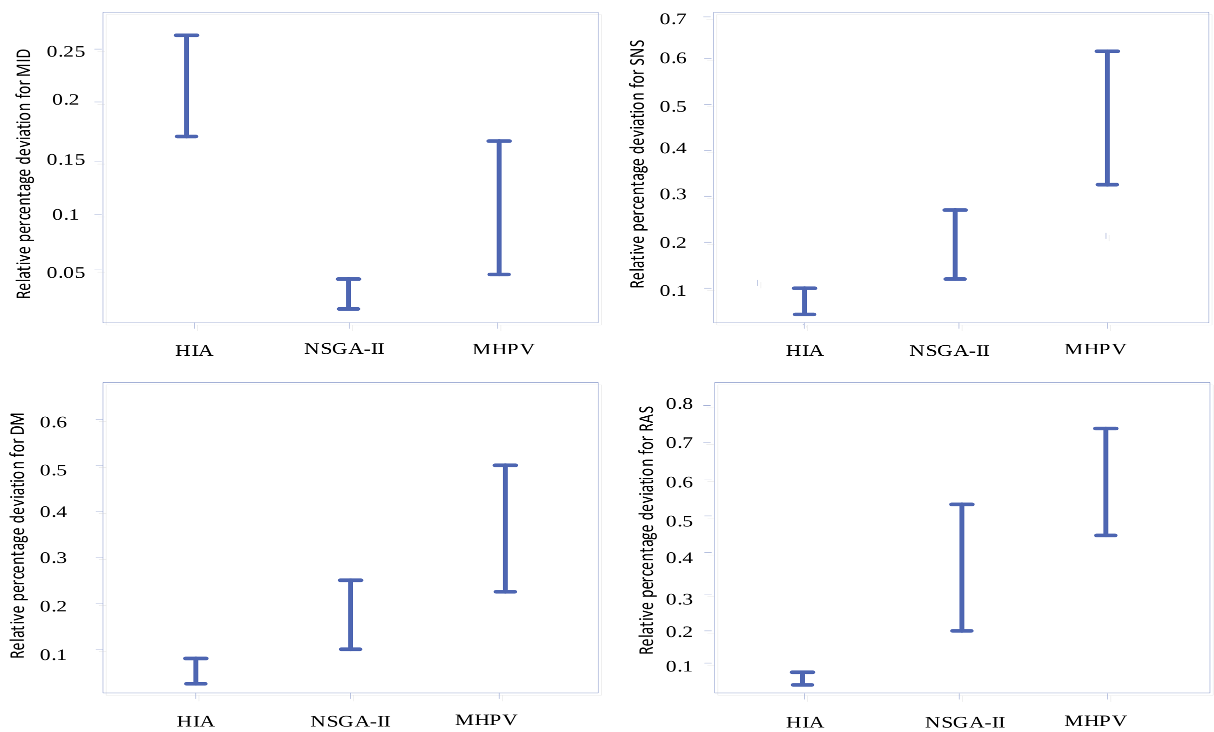


Figure 7. Means plot and LSD intervals for algorithms in DM, MID, SNS and RAS metrics

6.0 CONCLUSIONS

A sustainable urban E-Grocery distribution network is designed in this paper, which integrated van, robot, and parcel locker regarding the last mile delivery. A two-echelon location-routing with mixed fleets problem is utilized. To solve the problem, a hybrid multi-objective, meta-heuristic algorithm called hybrid immune algorithm (HIA) with two improved steps, vaccination and immunization is developed. Then, two algorithms NSGA-II and MHPV that have been used for solving similar problems are compared with HIA. We randomly generate twelve different problems (four small scale, four medium scale, and four large scale problems) and solve them by using the mentioned algorithms. Considering the nature of the multi-objective algorithm, our criteria for analyzing the effectiveness of each algorithm consisted of the following four elements: MID, SNS, DM, rate of RAS. Results were statistically analyzed, and it turned out that the hybrid immune algorithm is superior to NSGA-II and MHPV in the SNS, DM and RAS. With regard to MID, the HIA proved no priority among the algorithms. Considering the superiority of our hybrid algorithm on the evaluation metric, we can recommend its use in solving the multi-objective two-echelon location-routing problem. Further, real-life data can be applied in the proposed model and algorithm.

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