IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 17, 2018, accepted January 2, 2019, date of publication January 14, 2019, date of current version February 12, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2892716

Analysis and Optimization of Unmanned Aerial Vehicle Swarms in Logistics: An Intelligent Delivery Platform

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ABSTRACT Deploying unmanned aerial vehicle (UAV) swarms in delivery systems are still in its infancy with regard to the technology, safety, and aviation rules and regulations. Optimal use of UAVs in dynamic environments is important in many aspects, e.g., increasing efficacy and reducing the air traffic, resulting in a safer environment, and it requires new techniques and robust approaches based on the capabilities of UAVs and constraints. This paper analyzes several delivery schemes within a platform, such as delivery with and without using air highways and delivery using a hybrid scheme along with several delivery methods (i.e., optimal, premium, and first-in first-out) to explore the use of UAV swarms as part of the logistics operations. In this platform, a dimension reduction technique, "dynamic multiple assignments in multi-dimensional space," and several other new techniques along with Hungarian and cross-entropy Monte Carlo techniques are forged together to assign tasks and plan 3D routes dynamically. This particular approach is performed in such a way that UAV swarms in several warehouses are deployed optimally given the delivery scheme, method, and constraints. Several scenarios are tested on the simulator using small and big data sets. The results show that the distribution and the characteristics of data sets and constraints affect the decision on choosing the optimal delivery scheme and the method. The findings are expected to guide the aviation authorities in their decisions before dictating rules and regulations regarding effective, efficient, and safe use of UAVs. Furthermore, the companies that produce UAVs are going to take the demonstrated results into account for their functional design of UAVs along with other companies that aim to deliver their products using UAVs. Additionally, private industries, logistics operators, and municipalities are expected to benefit from the potential adoption of the simulator in strategic decisions before embarking on the practical implementation of UAV delivery systems.

INDEX TERMS Unmanned aerial vehicle swarms, UAV delivery, logistics, cross-entropy Monte-Carlo, Hungarian route optimization, simulation.

I. INTRODUCTION

UAVs (Unmanned Aerial Vehicles) have been commonly used for several military, commercial [1] and public services such as disaster recovery and rescue mission applications [2], intelligence collection/reconnaissance mission, pollution/fire detection, damage assessment [1], mapping, news gathering. There have already been several promising attempts by several leading prominent companies to use UAVs in commercial purposes, particularly in delivery. Amazon aims to use drones to deliver packages directly to customer's doorstep within 30 minutes [3]. Murray and Chu [4] have given other examples of attempts to deploy UAVs by several other companies in their study such as Australian textbook distributor Zookal, UPS, Google with Project Wing, Alibaba, Singapore Post. In early 2015, China's largest online retailer Alibaba carried out a three-day trial of drone delivery [5]. Singapore Post is another package delivery company to trial drone-based deliveries [6]. The Civil Aviation Authority (CAA) in the UK reports that they have issued permissions to 350 organisations to fly drones for business purposes, including BBC [7]. The US Federal Aviation Authority (FAA) did make significant strides towards relaxing its rules on drone use [8]. The FAA estimates that by 2020 there will be around 30 thousand commercial drones and many more civilian devices in use in America [9], [10]. Drones can use short-cuts and packages can be delivered in a time-optimal manner with less environmental impact to the contrary of traditional truck delivery system in which a delivery truck must visit other customers or other places to reach its destination with respect to dedicated fixed roads.

Sense and avoid technologies embedded in drone systems have already provided a great deal of safety on drone uses [11], even though these technologies are still needed to be improved significantly [12], [13]. Motlagh *et al.* [14] addressed the regulations and standardization efforts, and public safety concerns on the ground. While extensive research efforts have focused on the technical aspects of UAVs along with the regulations and standardization, this paper seeks to provide new techniques and approaches designed to optimize the operational elements of a delivery-by-drone system. In particular, the purpose of this paper is to discuss several schemes and methods for optimizing delivery routes and efficient deployment of resources using several approaches and simulation techniques to manage multidimensional complexities of **m**ultiple **w**arehouses, **m**ultiple **d**rones with **m**ultiple cargo **c**arriers using **m**ultiple air **h**ighways (**mWmDmCmH**) without being restricted to the current technical constraints of UAVs - e.g., UAVs can carry several packages at a time to deliver to several customers in a sortie.

In the literature, there are a number of studies that aim to solve several distinct parts of this entire problem space. Murray and Chu [4] and Ferrandez *et al.* [15] proposed a combination of two delivery approaches i.e., the use of traditional delivery trucks to a point near to customers from which a UAV can be launched to deliver parcels. Regarding UAV route/path optimization, Ragi and Chong [16] analyzed UAV path planning in a dynamic environment via partially observable Markov decision process whereas Roberge *et al.* [17] studied a comparison of parallel genetic algorithm and particle swarm optimization for real-time UAV path planning. Zhang and Duan [18] proposed an improved constrained differential evolution algorithm to generate an optimal feasible route for UAVs as a constrained optimization problem in the three-dimensional environment and Huang *et al.* [19] proposed a novel coordinated path planning method using k-degree smoothing for multi-UAVs to reach the targets simultaneously (strong coordination) or with an acceptable time interval (weak coordination). Similarly, Ergezer [20] explored a path planning in 3D environment for multiple UAVs by introducing an evolutionary operator in Genetic Algorithm and the utilization of mTSP. Yang and Yoo [21] analyzed the UAV path planning with respect to wireless sensor networks (WSN). Several other studies [22]–[31] focused their attention on UAV route/path planning for various objectives, such as target tracking, obstacle avoidance, landmark-based navigation, cluster-based routing to reduce dependencies on human operators and task assignment.

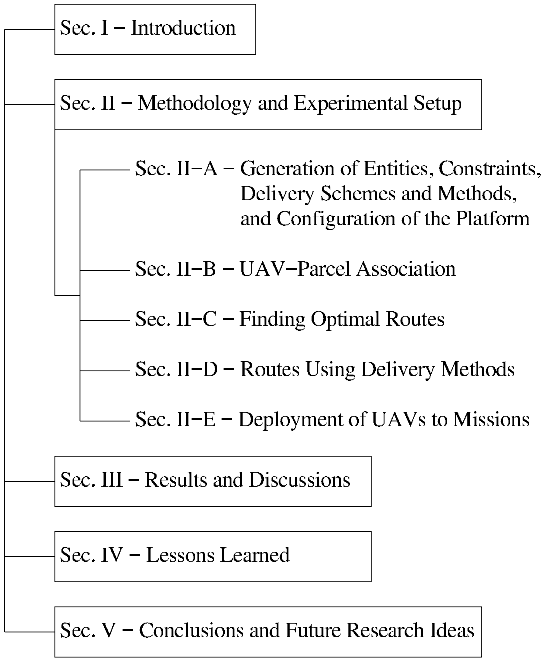

FIGURE 1. Outline of the manuscript.

There are a limited number of studies that simultaneously explore 3D route planning and task assignment, in which assigned tasks may dynamically change the routing given the constraints. For instance, Zhu *et al.* [32] examined a dynamic task assignment and path planning of multi-AUV system based on an improved self-organizing map and velocity synthesis method in 3D underwater workspace by using the improved self-organizing map (SOM) neural network and a velocity synthesis approach. On the other hand, Faust *et al.* [33] presented reinforcement learning approaches for very small scale of single cargo delivery in a route planning using UAVs. However, to our knowledge, there is no study in the literature that concurrently explores the optimization of dynamic multiple task assignment and 3D route planning, in particular considering heterogeneous UAV swarms based on several types of delivery schemes and methods with respect to the complexity of mWmDmCmH.

In this study, a sophisticated multi-variable delivery problem is aimed to be explored and in this manner, different approaches are analyzed to find out the optimal visual delivery decision using the optimal available route. The main objectives are i) to use the resources effectively and efficiently, ii) to give decisions about deploying new resources or reallocating current resources by testing different scenarios, iii) consequently to both increase the customer happiness by delivering the orders in a time-optimal manner and reduce the cost of delivery in a minimized and safer air traffic using both optimal routing and optimal use of resources. In this sense, throughout the manuscript, we would like to unveil how to a) manage a very complex multi-dimensional/ multi-variable delivery problem; b) optimize

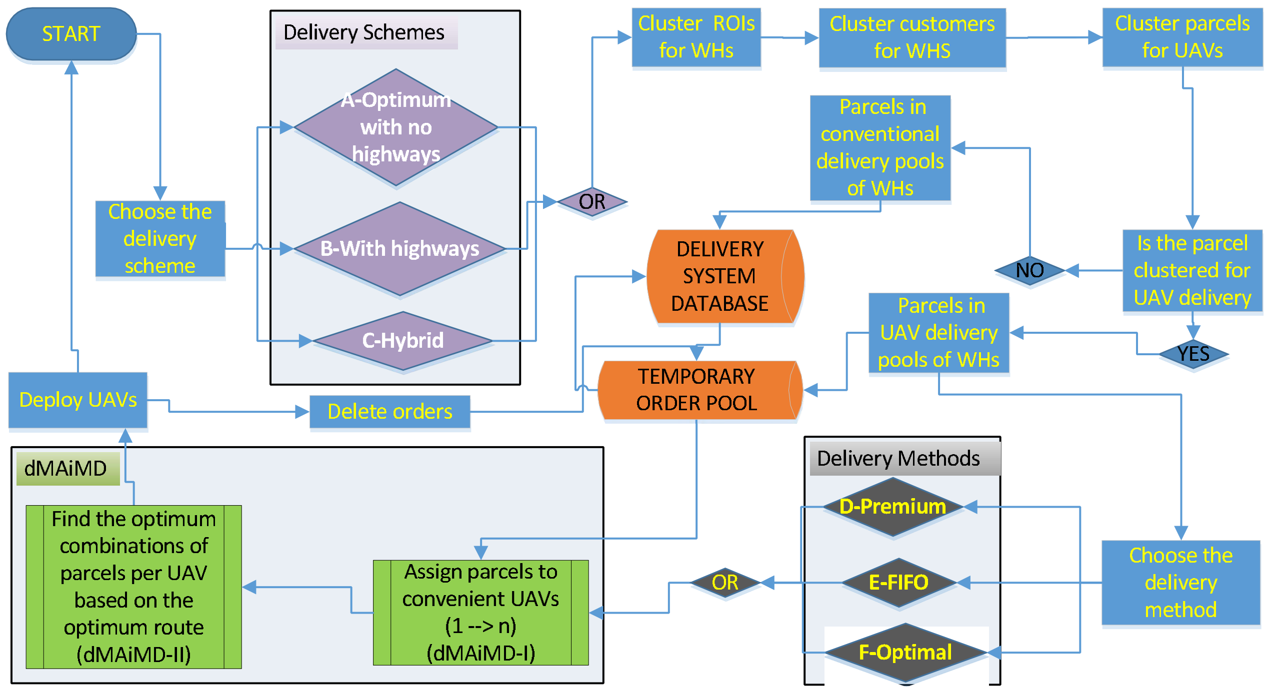

FIGURE 2. **Overall methodology.**

logistic operations using UAVs; c) test/discuss several delivery schemes and methods; d) find the optimal visual delivery decisions; e) reduce environmental pollution impacts; f) enlighten the aviation authorities in their decisions; g) guide the companies that produce UAVs in their design; h) guide delivery companies; i) help these three stakeholders model/simulate their systems and decisions. At the moment, there is no off-the-shell simulation tool to realize these objectives, and the platform built in this study is a good candidate to cover all these objectives at once.

To clarify the novelty of this paper, the contributions are outlined as follows.

1) A distinct UAV delivery platform has been built to test delivery capabilities of UAVs under several constraints and scenarios on various real time map samples.
2) Delivery of multiple packages in one sortie by a single UAV within multiple delivery sorties using UAV swarms is analyzed.
3) Several delivery methods along with various delivery schemes are proposed for delivering multiple parcels via optimal routes.
4) A new dynamic and hybrid delivery method for UAVs has been designed and explored with its merits.
5) An effective methodology has been developed to deploy UAV swarms with multiple carriers.

The remainder of this paper is organized as follows. Section I provides a comprehensive state-of-the-art literature on existing UAV delivery systems. Section II explores the proposed methodology based on our experimental setup. The results are demonstrated in Section III along with discussions. Section IV emphasizes the lessons learnt. Section V draws conclusions and provides directions for potential future works. Readers are referred to Fig. 1 for an explicit structure overview of the paper.

II. METHODOLOGY AND EXPERIMENTAL SETUP

The methodology implemented using Java[1] and Matlab Simulink MatWorks R2017b is delineated in Fig. 2. Interested reader can find the detailed methodology in the supplementary materials (fig.1) with each and every step. The main interface is presented in Fig. 3. Firstly, a GPS-specified map that may be any specific region of interest (ROI) is created using geospatial data by the user. Secondly, other necessary components are generated using the specific interfaces to simulate/model imaginary/real warehouses (WHs) and customer locations as delivery way-points and target destinations. For the third step, several delivery schemes and methods are explored along with the techniques employed. Lastly, an experimental setup is established to analyze how the results are affected under the consideration of various scenarios.

A. GENERATION OF ENTITIES, CONSTRAINTS, DELIVERY SCHEMES AND METHODS, AND CONFIGURATION OF THE PLATFORM

1) GENERATION OF ENTITIES

a: GENERATION OF CUSTOMERS

This can be carried out in three ways; one of which is to import customer information from a file (e.g., csv) that can

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[1] Java was employed to process the multi task operations simultaneously.

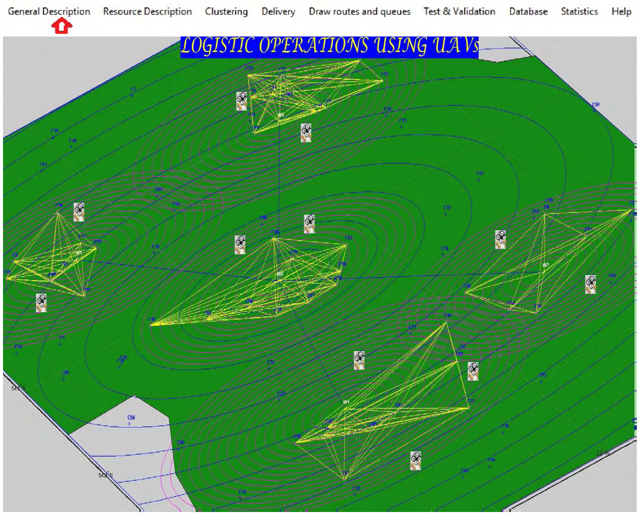

FIGURE 3. Main interface of the implementation.

be obtained from any database actively used; the second one is to enter customer information on the customer description interface; the last method is to randomly create as many customers as desired on the pre-created map.

b: GENERATION OF UAV HIGHWAYS (HWs)

UAV HWs can be defined with regards to directions and altitudes in 3 dimensional (3D) space depending on the no-fly geospatial cubic zones (NFGCZ). Each HW has two lanes with opposite direction to provide much better safety in regards to preventing collisions, although collisions can be prevented using travel altitudes, which is also implemented in our model.

c: GENERATION OF PARCELS

Parcels can be generated similarly as explained in II-A1-a using various dimension and weight ranges.

d: GENERATION OF ORDERS

Selected pre-created parcels are assigned to the available customers and subsequently, orders are created using the order creation interface.

e: GENERATION OF WHs

Each WH is associated with a geographic location (longitude and latitude) in the XY plane of the local coordinate system, which can be generated automatically by the application or entered manually by the user.

f: GENERATION OF UAVs

Characteristics of UAVs are very important for overall efficacy of the system; the more abilities that UAVs have the more areas are covered, consequently the more customers can be served and the more packages can be delivered within shorter time frames. The number of cargo carriers with bigger capacities (i.e., volume and weight) is substantially important to decrease the air traffic. For our system model, we provide the features of UAVs in Table 1.

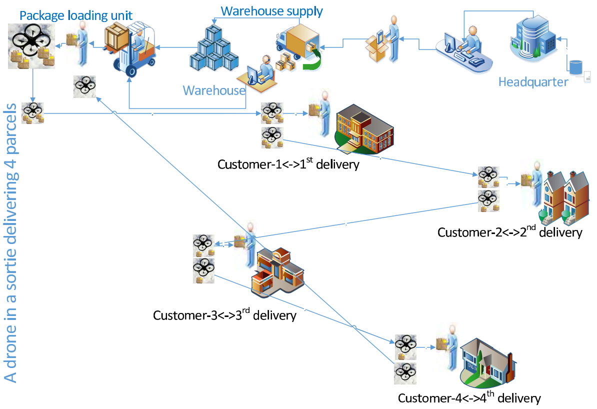

FIGURE 4. Delivery scheme without HWs.

g: ASSIGNMENT OF UAVs TO WHs

Several number of UAVs can be assigned to each prespecified WH as assets using the UAV assignment interface with distinct ID numbers.

2) CONSTRAINTS

Successful commercial use of UAVs for longer missions lies in the improvement of battery charge and load capacity. There should be several distribution WHs and each of which may have several number of UAVs with various features with respect to the other components of the system, such as customers, orders and parcels to establish an efficient and robust UAV delivery platform to cover ROIs better. Each type of UAVs may have various cargo capacities by means of weight (payload they can carry), the number of cargo carriers and their volumes as detailed in Table 1. The total weight of parcels assigned to cargo carriers of UAVs cannot exceed UAVs' total payload capacity. The total maximum distance to be transported by each UAV is not fixed and determined based on the total load -i.e., the more load the less distance to travel. Each UAV can deliver several customers' parcels in a mission with cargo carriers attached to UAVs. Each UAV must return to its base without depleting its entire battery charge (e.g., 10% remaining charge) to guarantee its safe return to the base. Each UAV should be used optimally by means of maximum distance and cargo capacity to increase the overall efficacy of the delivery system. Each UAV is associated with a geodetic coordinate (longitude, latitude, altitude) by GPS to track instant positions. Parcels exceeding carriers' maximum load capacity or requiring a signature are not eligible for the drone delivery system and are opt to be sent using conventional delivery system. Packages can be transferred between WHs using UAVs to supply products that are not in stocks, especially from the center WH to others. Only customers within ROIs of UAVs from a remotely-located WH can be served with the delivery-by-drone system.

3) DELIVERY SCHEMES

The three delivery schemes are illustrated in Figs. 4, 5, and 6, and briefly explained in the following Subsections II-A3 -a, -b, and -c briefly.

TABLE 1. Features of UAVs (capabilities & constraints).

Fields	Definition	Justification	Explanation
ID	unique ID	used for data search and join operations	
Title	description of drone type	used for the easy understanding of the user about the types of UAVs	
Max parcel count	# of the parcel count that a UAV can carry at a time that is the # of the cargo carriers on a UAV	used for routing, shows the ability of a UAV to deliver ordered parcels to several customers up to this count on a mission	a UAV can serve more than one customer on a mission. For instance; a UAV can deliver 4 parcels at a time if this number is 4 when a mission starts without returning to the base.
Max parcel volume dimension 1	shows the eligibility of a parcel carried by one of the cargo carrier's volume dimensions on a UAV	parcels must be in the limits of the volume of cargo carriers of UAVs	indicates one of the maximum sizes of any cargo carriers (i.e., width)
Max parcel volume dimension 2	shows the eligibility of a parcel carried by one of the cargo carrier's volume dimensions on a UAV	parcels must be in the limits of the volume of cargo carriers of UAVs	indicates one of the maximum sizes of any cargo carriers (i.e.,length)
Max parcel volume dimension 3	shows the eligibility of a parcel carried by one of the cargo carrier's volume dimensions on a UAV	parcels must be in the limits of the volume of cargo carriers of UAVs	indicates one of the maximum sizes of any cargo carriers (i.e., height)
Dimension unit	unit of the dimension, default is cm	used for comparison between the dimensions of cargo carriers and dimensions of parcels to find out if parcels fit in cargo carriers	this unit can be converted to other units such as inch by the user using the system
Max travel distance	distance that a UAV can travel without any load	used for designating ROIs and clustering customers	UAVs must return to their bases without consuming all battery charge which can be specified by the user (e.g., 10%). Max travel distance is calculated after taking off this value.
Travel unit	unit of the distance travelled by a UAV, default is mile	used for conversion between distance units: the default is mile	this unit can be converted to meter by the user using the system
Max travel in minutes	maximum battery usage in minutes including hovering in the air	used for safety reason for UAVs to return their bases before it is to late along with the maximum travel distance	sometimes UAVs may need to hover and using the variable, max travel distance, may not be enough to decide the return point of a UAV to its base
Max weight shipping	maximum weight capacity that can be carried by any UAV	used for determining the assignment of parcels to UAVs	a UAV carries fever number of parcels than the # of cargo carriers if the maximum shipping weight capacity is exceeded with the total weight of assigned parcels
Weight of a UAV	weight of a UAV without any load	used to calculate the total weight of a UAV with parcels it is loaded	
Weight unit	unit of the weight, the default is kg	used for conversion between weight units	this unit can be converted to lbs by the user using the system
Distance loss (mile/kg)	max travel distance of a UAV decreases if the weight of the load increases up to Max weight shipping	used for determining to serve the customers with regard to their distances	max travel distance decreases as the weight of the load increases, this variable shows the functional correlation between total load and maximum distance that can be travelled
Reserved for	a UAV can serve a customer if it is reserved for customers	used for determining the assignments of orders to UAVs; the default is reserved for customers; otherwise it is reserved for the delivery between WHs	this parameter can be changed by the user, there are some fixed-wing UAVs not suitable for customer delivery, but suitable for delivery between WHs, the value for this is WHs delivery
Charging time	battery charge time in minutes of a UAV to be ready for the next mission	used for scheduling, and determining the next UAV for the delivery mission	UAVs must be fully charged before deployed for a mission

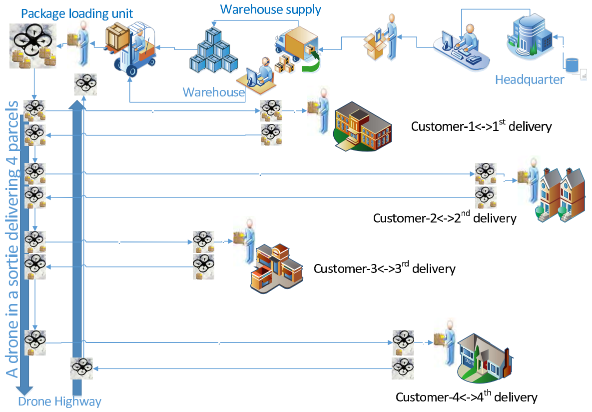

FIGURE 5. Delivery scheme using HWs.

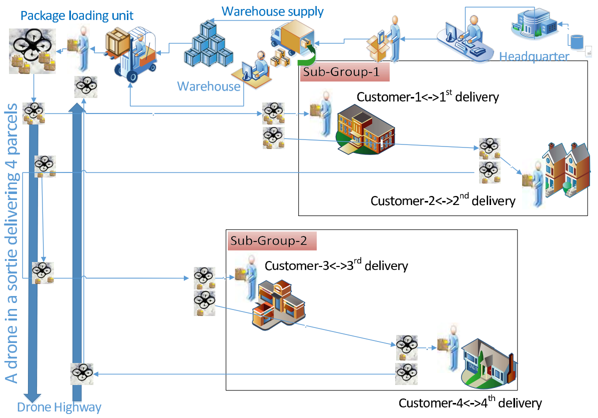

FIGURE 6. Hybrid delivery scheme.

a: DELIVERY SCHEME WITH NO HWs

All possible shortcuts among WHs and customers are utilized in a mission as illustrated in Fig. 4.

b: DELIVERY SCHEME USING AIR HWs

Pre-specified HWs are tracked as delineated in Fig. 5. Delivery between customers is not allowed.

c: DELIVERY SCHEME USING A COMBINATION OF THE TWO SCHEMES (HYBRID)

On one hand, the delivery scheme with no HWs may cause a chaos when the number of UAVs is increased. On the other hand, the delivery scheme strictly using HWs may reduce the number of customers served in a mission within smaller ROIs, which requires more sorties to deliver orders and reduces

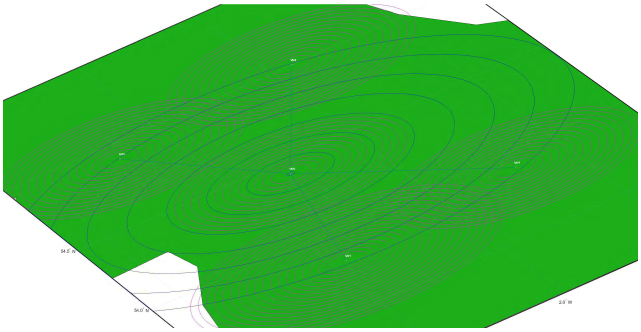

FIGURE 7. ROIs of WHs with no HWs.

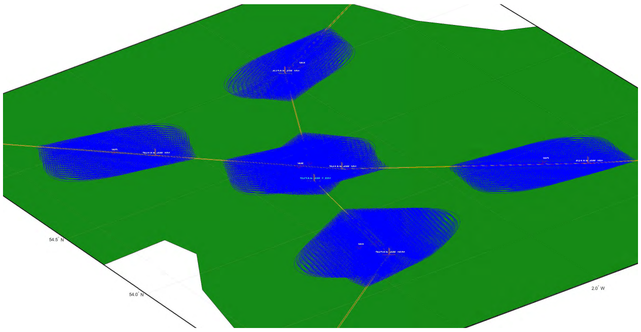

FIGURE 8. ROIs of WHs with HWs.

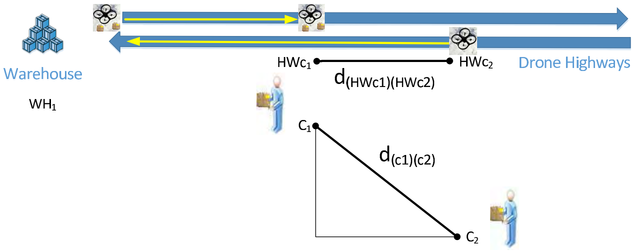

FIGURE 9. Distance decision limits for hybrid delivery.

the overall efficacy of the delivery system as can be noticed in Figs. 7 and 8 regarding UAV trajectories. These two delivery schemes are merged to alleviate these shortcomings as illustrated in Fig. 6 in which customers in a mission are clustered into subgroups in terms of the distances between the customers' HW connection points (e.g., $d_{(HW_{C1})(HW_{C2})}$) and/or their direct distances to each other (e.g., $d_{(C_1)(C_2)}$) as displayed in Fig. 9. Highways are used between these sub-groups.

4) DELIVERY METHODS

The three delivery methods are explained in the following Subsections II-A4-a, -b, and -c briefly. Firstly, we would like to reveal several general concepts applicable to all these three methods. Orders/parcels which cannot be assigned to an available UAV in a WH are queued to be assigned to next available UAVs along with further orders that may be ordered in order to both ensure the effective use of the resources and reduce the air traffic. More explicitly, these orders are not assigned to the UAVs which are already on mission; they are put in a queue to be evaluated together with other orders being ordered by customers. However, previous orders that are not assigned to the UAVs are prioritized for the consequent assignments for further missions to establish a fair system. The abstract phases of delivery methods are illustrated in Fig. 10 in an algorithmic chart along with the delivery schemes.

a: OPTIMAL DELIVERY

Orders are delivered optimally in a particular routing path in which the assignment of orders to available UAVs are carried out without prioritizing any customer.

b: PREMIUM DELIVERY

Customers who are in the premium delivery are prioritized. Prioritization is performed by means of assigning premium orders to next available UAVs. However, routing is performed optimally in order to both reduce the air traffic and use the resources effectively.

c: FIRST-IN-FIRST-OUT (FIFO) DELIVERY

Orders are sorted in ascending order with respect to date and time. Assignment of orders is performed by means of orders' times to next available UAVs, however, routing is performed optimally without any prioritization as explained in the above-mentioned premium delivery method.

5) CONFIGURATION OF ROIs FOR WHs

ROIs are designated based on the resources that WHs have. Maximum delivery distances of UAVs play a critical role for specifying ROIs; the more maximum travel distance that UAVs have in WHs, the larger ROIs for those WHs. A ROI in a WH is less than the half of the maximum travel distance of the longest range UAV in that WH to make sure that UAVs return to their bases safely with an amount of remaining battery charge. The percentage of the remaining battery charges of UAVs after mission can be specified by the user: the more remaining battery charges, the less maximum delivery distance of UAVs. The required remaining battery charge of UAVs in our experimental setup is defined as 10%. Furthermore, ROIs are not static, but, dynamic based on the total load of cargo carriers using the distance function defined for the UAV types, which is explained in Section II-E in detail. The more the load the less the maximum delivery distance. The created 5 WHs depicted in Fig. 7 and in Table 2 are utilized to explore our approaches throughout the manuscript. Automatic configuration of ROIs are explained in the following Subsections II-A5-a, -b and -c with respect to the delivery schemes and constraints.

a: ROIs WITH THE SCHEME USING NO HWs

UAVs can travel around WHs depending on their maximum delivery distances using the shortcuts between nodes. An example is depicted in Fig. 7. ROIs for WHs are marked

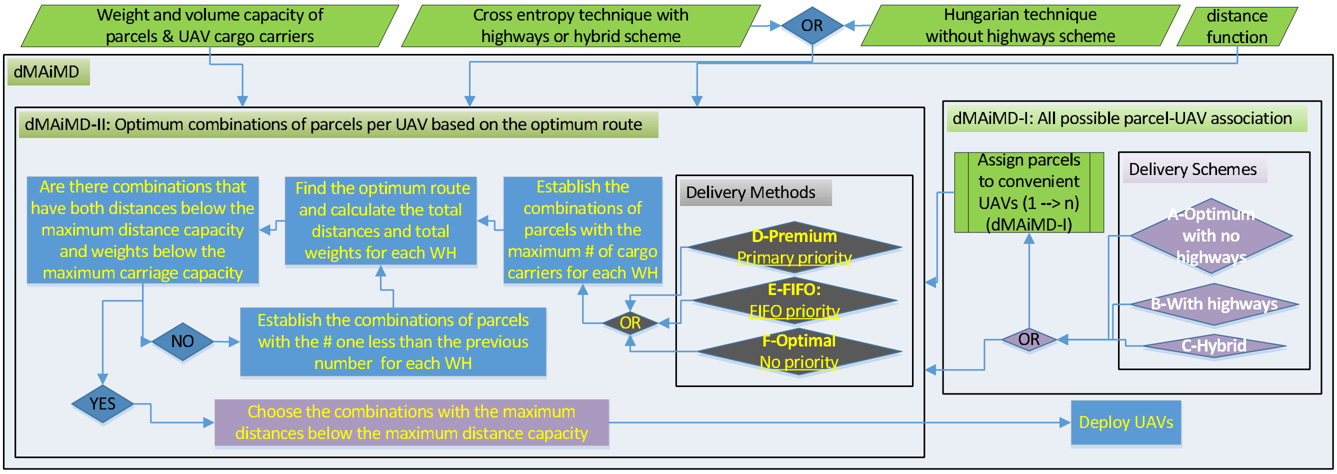

FIGURE 10. Schematic presentation of delivery approaches and delivery methods within the platform.

by circles from the centers of WHs. The UAV reserved for "delivery between WHs" in W_5 has a maximum travel distance of 100 miles and thus, W_5 has a larger ROI (i.e., the area marked by the circles, 50 miles of maximum delivery distance) than the other WHs. The outer circles show the maximum delivery distances of UAVs without any load, and consequently these distances get shorter as the payload increases.

b: ROIs WITH THE SCHEME USING HWs

UAVs must track pre-specified HWs between WHs and customers. Travelling between customers is not allowed. The closer the WHs to HWs, the larger the ROIs, which can be readily observed in Fig. 8.

c: ROIs WITH THE HYBRID SCHEME

ROIs are specified based on the parts coming from two schemes with respect to the two pre-specified distance values as illustrated in Fig. 5, one of which is the distance between consecutive nodes (e.g., $d_{(C_1)(C_2)}$) and the other one is the distance between their connection points to HWs (e.g., $d_{(HW_{C1})(HW_{C2})}$) as depicted in Fig. 9. Customers are served using the shortest paths without using HWs within subgroups when distances between consecutive customers are smaller than the pre-specified distance values. Note that $d_{(HW_{C1})(HW_{C2})}$ might be bigger than $d_{(C_1)(C_2)}$ wherever these customers are served using different HWs. This is such a flexible approach that the number of customers served in missions increases when these two values increase, which is elaborated in the following sections within scenarios.

6) CONFIGURATION OF CUSTOMERS

a: CONFIGURATION OF CUSTOMERS WITH THE SCHEME USING NO HWs

Customers are grouped based on all possible shortcuts to WHs as explained in Section II-A5. An example is depicted in Fig. 12. A customer can be served by a UAV if one is within the ROI of any WHs.

b: CONFIGURATION OF CUSTOMERS WITH THE SCHEME USING HWs

Customers are grouped using the locations of HWs with respect to WHs as explained in Section II-A5. An example is depicted in Figs. 11 and 13.

c: CONFIGURATION OF CUSTOMERS WITH THE HYBRID SCHEME

The configuration is performed dynamically based on the two parameters explained in Section II-A5-c.

7) CONFIGURATION OF ORDERS

The system incorporates orders into the UAV delivery system as presented in Table 2, if and only if the parcels can be carried by at least one of the cargo carriers with regards to the constraints mentioned earlier in Section II-A2.

a: CONFIGURING ORDERS WITH THE SCHEME WITHOUT USING HWs

Orders are incorporated into the UAV delivery system as mentioned in Section II-A6-a. 50 orders out of 66 are included in the UAV delivery system (readers are referred to Table 2 and Fig. 12).

b: CONFIGURING ORDERS WITH THE SCHEME USING HWs

Orders are incorporated into the UAV delivery system as mentioned in Section II-A6-b. This scheme may reduce the number of customers to be served compared to the scheme without using HWs, since the requirement of HW usage reduces the overall covering area of ROIs, as mentioned in Section II-A6-b. 38 orders out of 66 are included in the UAV delivery system in our case study (readers are referred to Table 2 and Fig. 13).

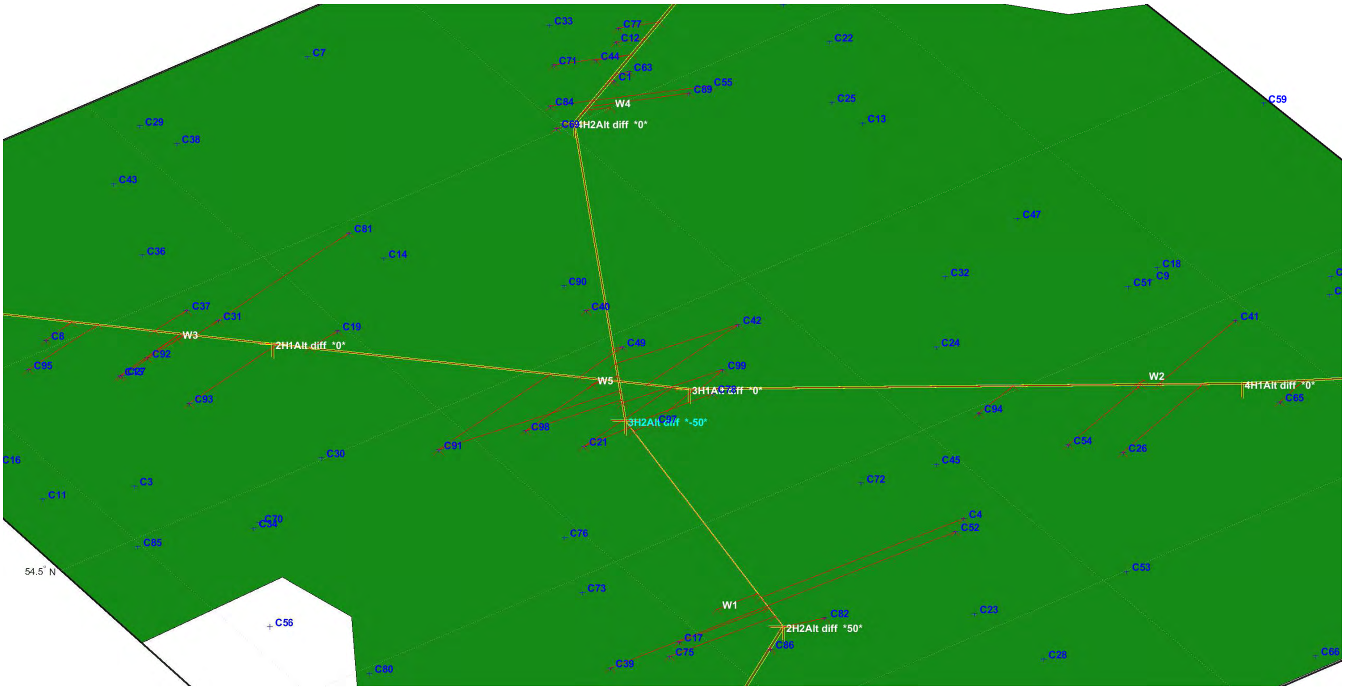

FIGURE 11. Grouping customers using HWs with respect to ROIs: The red lines between the customers and HWs denote the shortest distances. Customers without any red lines are out of the ROIs of WHs (Fig. 8).

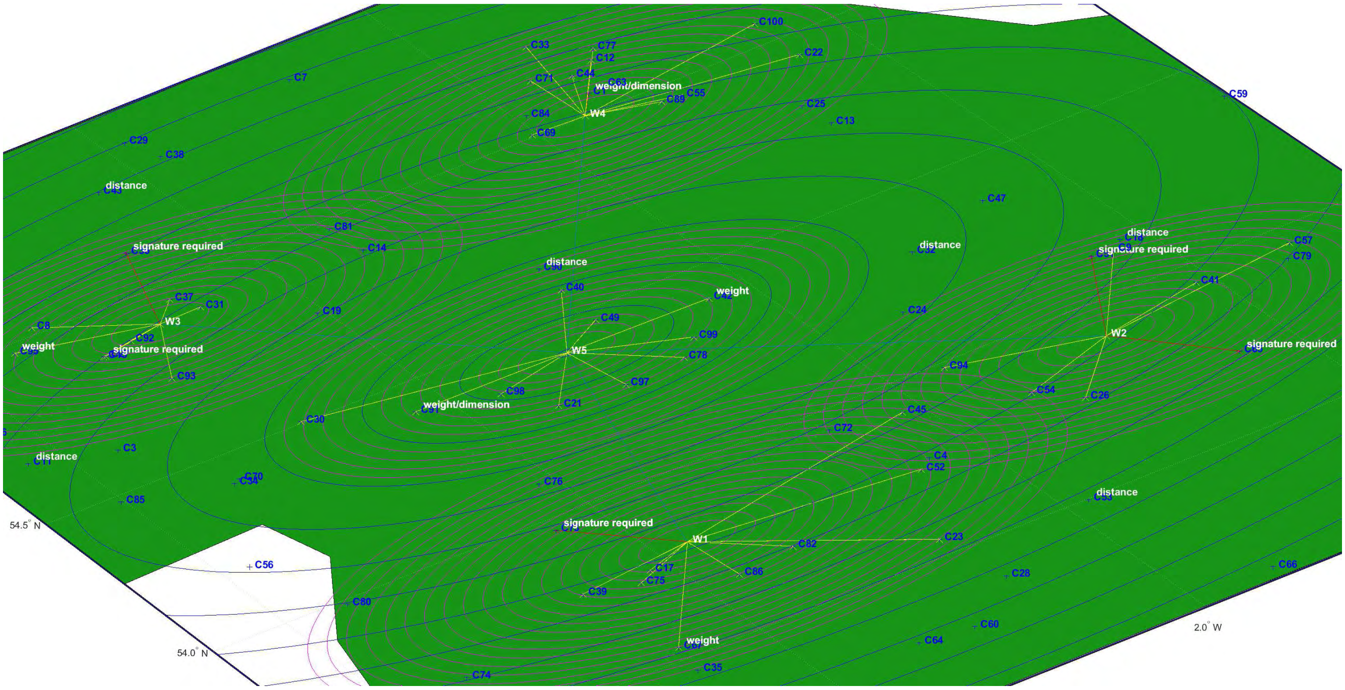

FIGURE 12. Configuring orders without HWs: The orders to be delivered are displayed by yellow lines. The orders that cannot be delivered and within the maximum delivery distances are displayed by red lines and signified with the reason such as "signature required" or "weight". The orders out of the ROIs are not specified with lines, but, signified with the reason such as "distance".

c: CONFIGURATION OF ORDERS WITH THE HYBRID SCHEME

Orders are incorporated into the system as mentioned in Section II-A6-c. The number of customers included in the delivery system is 38.

B. UAV-PARCEL ASSOCIATION

UAV-parcel association is carried out in parallel with finding the optimal routes. Maximum delivery distances vary depending on the load that UAVs carry at the start of the mission and during the mission as parcels are delivered, and

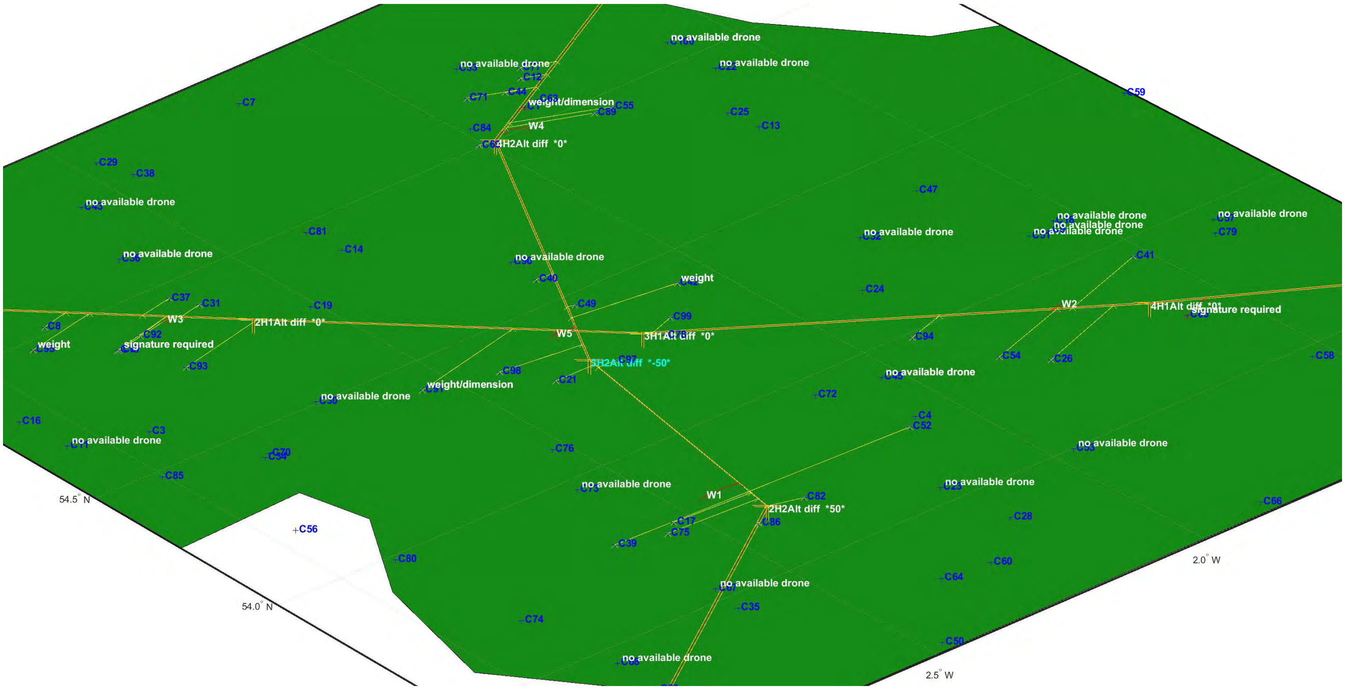

FIGURE 13. Configuring orders using HWs: The same caption as in Fig. 12.

thus, once the payload decreases. In this manner, there is no predefined weight/distance lookup table between WHs and customers. Therefore, all the calculations are performed dynamically based on the constraints, properties of customers assigned to the mission, ordering of these customers in routes and dynamically changing circumstances as new orders enter the system while previous orders are being delivered.

There are multi agents (UAVs) with different capabilities and limitations (Table 1) to be assigned to various tasks in the complexity of the problem space along with the constraints mentioned above in Section II-A2. To manage this multidimensional problem space, a new approach titled ‘‘dynamic multiple assignments in multiple dimensions in expanding and contracting data sets’’ (dMAiMD) was developed. With this technique parcels are assigned to available UAVs in WHs dynamically in which not only decisions are made by taking all necessary features of the components and constraints into consideration, but also, effects of the decisions are evaluated in advance in terms of the overall optimality of the system, and accordingly final assignment decisions are determined regarding the likely overall future assignments. The particular use of dMAiMD is presented in the general illustration of the methodology in Fig. 2 and general functions are displayed in Fig 10: dMAiMD has two main functions, ‘all likely UAV-parcel associations’ and ‘optimum combinations of parcels per UAV based on the optimum route’. Data in a high dimensional space are projected down to a low dimensional space, not only for the purpose of visualization, but also for efficient and robust implementation of the problem. Assignment of parcels to UAVs is performed using a Likelihood assignment Matrix (LaM) in which the features/constraints of UAVs in columns and of parcels in rows are placed as presented in Eq. (1), as shown at the bottom of the next page. A cell in the matrix corresponds to all necessary dimensional relationships between a resource and a parcel using a sub-Likelihood assignment Matrix (sLaM) as displayed in Eq. (2), as shown at the bottom of the next page, by which the constraints and abilities of a UAV along with its cargo carriers and the properties of a parcel are represented in 2D space. This mapping of cells not only represents the relationship between UAVs and parcels, but also, unveils the overall assignment strategy from a broader perspective, which helps the overall likely selection of orders for missions with respect to obtaining the optimal total distance travelled by all UAVs. In the cells of LaM, ‘1’ represents the likelihood assignment, ‘0’ indicates the necessary assignment, whereas ‘∞’ denotes the unlikelihood/impossible assignment. More explicitly, ‘1s’ show that a parcel can be carried by corresponding UAVs in terms of the abilities/constraints: 1-dimensions and weights of the parcels with respect to maximum cargo payloads and volumes of cargo carriers, 2-distances of customers with respect to the maximum travel distances of UAVs, 3-total weight of the parcels with respect to the total maximum cargo payloads of UAVs. ‘∞’, takes place where at least one of these constrains is not satisfied; ‘0’ takes place where parcels cannot be carried by other available UAVs different from the UAV in the current column after a mission starts. ‘0s’ designate the assignment prioritization of parcels to corresponding UAVs against the other parcels marked as ‘1’ or ‘∞’.

TABLE 2. **Orders in the system: the orders are sorted with respect to time within WHs. The 12 customers out of the ROIs using HWs are highlighted. "P" stands for "premium" and "N" stands for "conventional delivery method".**

WH	Cus	Ord	Par	Time	M	Wei	Dim1	Dim2	Dim3
W_1	C_{52}	O_6	P_6	04:10:11	N	0.7	5.01	27.2	28.1
W_1	C_{45}	O_7	P_7	04:10:11	P	1.81	10.9	11.8	19.41
W_1	C_{45}	O_{14}	P_8	08:14:35	N	0.57	5.96	18.2	18.86
W_1	C_{82}	O_{16}	P_8	08:14:45	P	0.57	5.96	18.2	18.86
W_1	C_{86}	O_{17}	P_6	08:15:45	N	0.7	5.01	27.2	28.1
W_1	C_{75}	O_{41}	P_{62}	08:26:00	P	0.31	8.23	17.2	18.1
W_1	C_{75}	O_{42}	P_{63}	08:26:22	N	1.31	8.38	14.2	18.03
W_1	C_{23}	O_{43}	P_{64}	08:26:42	N	1.3	5.51	10	15.79
W_1	C_{67}	O_{44}	P_{65}	08:27:35	N	15.11	10.87	11.77	15.98
W_1	C_{39}	O_{54}	P_{62}	10:03:17	N	0.31	8.23	17.2	18.1
W_1	C_{17}	O_{55}	P_6	10:04:31	N	0.7	5.01	27.2	28.1
W_2	C_{54}	O_{12}	P_8	08:14:30	P	0.57	5.96	18.2	18.86
W_2	C_{94}	O_{15}	P_6	08:14:35	P	0.7	5.01	27.2	28.1
W_2	C_{26}	O_{13}	P_6	08:14:45	N	0.7	5.01	27.2	28.1
W_2	C_{26}	O_{38}	P_{56}	08:24:52	P	5.18	11.33	28.2	29.1
W_2	C_{41}	O_{52}	P_{73}	08:32:00	N	1.76	5.45	21.2	22.1
W_2	C_9	O_{62}	P_{44}	10:29:53	N	0.74	10.93	11.83	14.72
W_2	C_{57}	O_{63}	P_{44}	10:30:48	N	0.74	10.93	11.83	14.72
W_3	C_{31}	O_{10}	P_8	08:14:25	P	0.57	5.96	18.2	18.86
W_3	C_{37}	O_{11}	P_6	08:14:35	N	0.7	5.01	27.2	28.1
W_3	C_{31}	O_{23}	P_6	08:18:40	N	0.7	5.01	27.2	28.1
W_3	C_8	O_{32}	P_{72}	08:21:45	N	0.79	8.11	19.2	20.1
W_3	C_{92}	O_{34}	P_{46}	08:23:15	N	1.17	9.35	10	19.52
W_3	C_{92}	O_{35}	P_{47}	08:23:23	P	2.37	1.78	22.2	23.1
W_3	C_{36}	O_{37}	P_{52}	08:24:42	P	0.49	10.43	11.33	18.52
W_3	C_{95}	O_{58}	P_{44}	10:26:18	N	0.74	10.93	11.83	14.72
W_3	C_{27}	O_{59}	P_{44}	10:27:57	N	0.74	10.93	11.83	14.72
W_3	C_{15}	O_{60}	P_{44}	10:28:24	N	0.74	10.93	11.83	14.72
W_3	C_{93}	O_{61}	P_{44}	10:28:47	N	0.74	10.93	11.83	14.72
W_4	C_{69}	O_{19}	P_8	08:16:45	N	0.57	5.96	18.2	18.86
W_4	C_{71}	O_{20}	P_8	08:17:45	N	0.57	5.96	18.2	18.86
W_4	C_{44}	O_{21}	P_8	08:18:05	P	0.57	5.96	18.2	18.86
W_4	C_{100}	O_{22}	P_6	08:18:20	N	0.7	5.01	27.2	28.1
W_4	C_{12}	O_{24}	P_6	08:19:40	P	0.7	5.01	27.2	28.1
W_4	C_{77}	O_{25}	P_{100}	08:19:55	P	3.16	9.75	10	13.29
W_4	C_{33}	O_{27}	P_{98}	08:20:25	P	4.43	13.47	14.37	18.16
W_4	C_{100}	O_{51}	P_{72}	08:31:57	N	0.79	8.11	19.2	20.1
W_4	C_{89}	O_{65}	P_{44}	10:34:35	N	0.74	10.93	11.83	14.72
W_4	C_{55}	O_{66}	P_{44}	10:35:44	N	0.74	10.93	11.83	14.72
W_4	C_{22}	O_{67}	P_6	10:36:40	N	0.7	5.01	27.2	28.1
W_5	C_{49}	O_8	P_8	01:10:11	P	0.57	5.96	18.2	18.86
W_5	C_{99}	O_9	P_8	02:10:11	P	0.57	5.96	18.2	18.86
W_5	C_{98}	O_2	P_2	08:11:15	P	1.22	4.18	25.36	26.26
W_5	C_{97}	O_3	P_3	08:11:45	N	1.96	10.39	21.23	22.13
W_5	C_{21}	O_{28}	P_{95}	08:21:25	P	2.54	1.58	24.24	25.14
W_5	C_{40}	O_{31}	P_{83}	08:21:35	N	2.51	5.9	10	11.05
W_5	C_{78}	O_{29}	P_{80}	08:21:35	P	0.98	3.88	19.24	20.14
W_5	C_{30}	O_{47}	P_{68}	08:29:07	N	2.71	13.26	14.16	15.06
W_5	C_{91}	O_{56}	P_6	10:08:58	N	0.7	5.01	27.2	28.1
W_5	C_{42}	O_{57}	P_{44}	10:11:16	N	0.74	10.93	11.83	14.72

Strictly speaking, potential assignments in LaM are determined by forging the characteristics of both parcels and remaining UAVs into a coherent value using dynamic sLaM matrices as many as the multiplication of the number of columns and rows in LaM. A new LaM is established in each step for determining potential assignments. '1s' in the previous established LaM may turn out to be '0s' for the same parcels and same UAVs where there is no other available UAV left to carry these parcels. In mathematical terms, a row cannot have more than one '0' at a time; '0' can be seen in a cell, if and only if, all other cells have the value of '∞' which means that there is no chance to deliver the parcel using all other UAVs. An order is removed from LaM to be placed in the queue for later assignments to UAVs that are currently in mission if all cells in a row turn out to be '∞', which means that there is no available UAV to carry that parcel in terms of the constraints (e.g., dimension, distance or weight). This matrix shrinks as missions along with routes are established whereas it expands as new orders enter the system. To summarize, the values in the cells representing UAVs and parcels are dynamically updated each time with respect to the updated values in all other cells in a broader perspective regarding the remaining orders and UAVs at WHs. LaM reveals the selection priorities of orders during establishment of assignments and routes with regard to overall optimal delivery. Necessary assignments are carried out using LaM in such a way that most likely parcels are prioritized and, thus, useless queues are avoided. In this way, resources are not wasted and consequently customers are served faster by reducing the multi-dimensional problem space into 2D space throughout finding the optimal routes for sorties. The second function 'optimum combinations of parcels per UAV based on the optimum route' of dMAiMD is explained in the following sections II-C, II-E and II-D within the routing schemes along with the other techniques employed with respect to the delivery schemes and methods.

LaM: Columns denote UAVs and rows denote parcels/orders.

$$\left\{\begin{array}{cccccc}
 & D_1 & D_2 & D_3 & \ldots & D_x \\
 & & & & & \\
O_1 & L_{val(D_1 P_{O_1})} & L_{val(D_2 P_{O_1})} & L_{val(D_3 P_{O_1})} & \ldots & L_{val(D_x P_{O_1})} \\
O_2 & L_{val(D_1 P_{O_2})} & L_{val(D_2 P_{O_2})} & L_{val(D_3 P_{O_2})} & \ldots & L_{val(D_x P_{O_2})} \\
O_3 & L_{val(D_1 P_{O_3})} & L_{val(D_2 P_{O_3})} & L_{val(D_3 P_{O_3})} & \ldots & L_{val(D_x P_{O_3})} \\
O_4 & L_{val(D_1 P_{O_4})} & L_{val(D_2 P_{O_4})} & L_{val(D_3 P_{O_4})} & \ldots & L_{val(D_x P_{O_4})} \\
\ldots & \ldots & \ldots & \ldots & \ldots & \\
O_y & L_{val(D_1 P_{O_y})} & L_{val(D_2 P_{O_y})} & L_{val(D_3 P_{O_y})} & \ldots & L_{val(D_x P_{O_y})}
\end{array}\right\} \tag{1}$$

sLaM for the first UAV in Eq. (1): columns denote the UAV's cargo carriers and rows denote parcels.

$$\left\{\begin{array}{cccccc}
 & D_{1_a} & D_{1_b} & D_{1_c} & \ldots & D_{1_k} \\
 & & & & & \\
O_1 & L_{val(dim_{D_{1a}P_{O_1}})} \wedge L_{val(w_{D_{1a}P_{O_1}})} & L_{val(dim_{D_{1b}P_{O_1}})} \wedge L_{val(w_{D_{1b}P_{O_1}})} & L_{val(dim_{D_{1c}P_{O_1}})} \wedge L_{val(w_{D_{1c}P_{O_1}})} & \ldots & L_{val(dim_{D_{1k}P_{O_1}})} \wedge L_{val(w_{D_{1k}P_{O_1}})} \\
O_2 & L_{val(dim_{D_{1a}P_{O_2}})} \wedge L_{val(w_{D_{1a}P_{O_2}})} & L_{val(dim_{D_{1b}P_{O_2}})} \wedge L_{val(w_{D_{1b}P_{O_2}})} & L_{val(dim_{D_{1c}P_{O_2}})} \wedge L_{val(w_{D_{1c}P_{O_2}})} & \ldots & L_{val(dim_{D_{1k}P_{O_2}})} \wedge L_{val(w_{D_{1k}P_{O_2}})} \\
O_3 & L_{val(dim_{D_{1a}P_{O_3}})} \wedge L_{val(w_{D_{1a}P_{O_3}})} & L_{val(dim_{D_{1b}P_{O_3}})} \wedge L_{val(w_{D_{1b}P_{O_3}})} & L_{val(dim_{D_{1c}P_{O_3}})} \wedge L_{val(w_{D_{1c}P_{O_3}})} & \ldots & L_{val(dim_{D_{1k}P_{O_3}})} \wedge L_{val(w_{D_{1k}P_{O_3}})} \\
O_4 & L_{val(dim_{D_{1a}P_{O_4}})} \wedge L_{val(w_{D_{1a}P_{O_4}})} & L_{val(dim_{D_{1b}P_{O_4}})} \wedge L_{val(w_{D_{1b}P_{O_4}})} & L_{val(dim_{D_{1c}P_{O_4}})} \wedge L_{val(w_{D_{1c}P_{O_4}})} & \ldots & L_{val(dim_{D_{1k}P_{O_4}})} \wedge L_{val(w_{D_{1k}P_{O_4}})} \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
O_n & L_{val(dim_{D_{1a}P_{O_n}})} \wedge L_{val(w_{D_{1a}P_{O_n}})} & L_{val(dim_{D_{1b}P_{O_n}})} \wedge L_{val(w_{D_{1b}P_{O_n}})} & L_{val(dim_{D_{1c}P_{O_n}})} \wedge L_{val(w_{D_{1c}P_{O_n}})} & \ldots & L_{val(dim_{D_{1k}P_{O_n}})} \wedge L_{val(w_{D_{1k}P_{O_n}})}
\end{array}\right\} \tag{2}$$

TABLE 3. Techniques employed in the problem space.

Schemes	Methods	Parcel-UAV association	Routing	Distance function
Optimum	premium	dMAiMD	Hungarian	Eq. 4)
	FIFO	dMAiMD	Hungarian	Eq. 4)
	optimal	dMAiMD	Hungarian	Eq. 4)
HW	premium	dMAiMD	Cross-entropy Monte Carlo	Eqs. (8) and (9)
	FIFO	dMAiMD	Cross-entropy Monte Carlo	Eqs. (8) and (9)
	optimal	dMAiMD	Cross-entropy Monte Carlo	Eqs. (8) and (9)
Hybrid	premium	dMAiMD	Hungarian (for sub-groups) + Cross-entropy Monte Carlo	Eq. (10)) (for sub-groups) Eqs. (8) and (9)
	FIFO	dMAiMD	Hungarian (for sub-groups) + Cross-entropy Monte Carlo	Eq. (10) (for sub-groups) Eqs. (8) and (9)
	optimal	dMAiMD	Hungarian (for sub-groups) + Cross-entropy Monte Carlo	Eq. (10) (for sub-groups) Eqs. (8) and (9)

C. FINDING OPTIMAL ROUTES

Following likely assignments of parcels to UAVs using the cell values, namely '0', '1' or '∞' as mentioned above, our technique runs to find i) optimal selections and assignments of parcels to UAVs, and ii) optimal routes similar to Markov Decision Process (MDP) in a dynamic programming in order to increase the total reward. The objective of our assignment and optimization approaches along with several other optimization techniques such as Hungarian and cross-entropy Monte Carlo techniques is to use the resources optimally, and to minimize the air traffic in terms of completing overall delivery with the least number of missions (i.e., sorties) in a timely-manner. Particularly, Hungarian technique is employed for finding optimal routes for the delivery scheme with no HWs, whereas cross-entropy Monte Carlo technique is adapted for the delivery schemes using HWs. More explicitly, the techniques and functions employed for the specific parts of the problem space are presented in Table 3. The Hungarian technique is generally used in combinatorial optimization, particularly for solving the assignment problems in polynomial time. Cross-entropy Monte Carlo is a general Monte Carlo technique employed in combinatorial and continuous multi-extremal optimization and sampling.

Distance matrix for the Hungarian technique.

$$\left\{\begin{array}{c|cccccc} & W_1 & C_1 & C_2 & C_3 & \dots & C_n \\ \hline W_1 & \infty & d_{W_1C_1} & d_{W_1C_2} & d_{W_1C_3} & \dots & d_{W_1C_n} \\ C_1 & d_{C_1W_1} & \infty & d_{C_1C_2} & d_{C_1C_3} & \dots & d_{C_1C_n} \\ C_2 & d_{C_2W_1} & d_{C_2C_1} & \infty & d_{C_2C_3} & \dots & d_{C_2C_n} \\ C_3 & d_{C_3W_1} & d_{C_3C_1} & d_{C_3C_2} & \infty & \dots & d_{C_3C_n} \\ \dots & \dots & \dots & \dots & \dots & \dots & \\ C_n & d_{C_nW_1} & d_{C_nC_1} & d_{C_nC_2} & d_{C_nC_3} & \dots & \infty \end{array}\right\} \tag{3}$$

1) ALL POSSIBLE ROUTES

In this section, we would like to disclose the complexity of routing problem in terms of the distances among the nodes based on the selected delivery scheme.

a: ALL POSSIBLE ROUTES FOR THE SCHEME WITHOUT USING HWs

Complexity of routing with respect to distances between nodes is displayed in Fig. 14. It should be noted that finding an optimal route even with regards to two dimensional distance space is beyond human perception, not to mention the other dimensions explained throughout the manuscript.

b: ALL POSSIBLE ROUTES FOR THE SCHEME USING HWs

The aim is to reduce the air traffic out of HWs. Orders should be delivered using the shortest possible connections to HWs. For instance, all the customers, except C_{40}, in the ROI of WH_5 are in the delivery range of HW_1 and HW_2 delivery (i.e., customers' connections to both HWs can be seen in Fig. 11). Switching from one HW to another can be performed using WH locations that are linked to HWs with perpendicular lines.

2) END-TO-END OPTIMAL ROUTING

Optimal routes for WHs are selected throughout all possible node connections mentioned in the previous section. How to select the nodes that contribute to the optimal route and the method to specify their ordering in routes are explained in the following Subsections II-C2-a, -b and -c. This explanation is given with respect to the delivery schemes without taking other constrains into consideration mentioned in Section II-A2 to make it simpler to understand. Explicitly, it is assumed that all the parcels can be carried by a competent UAV regarding the number of carriers, maximum distance and maximum payload in a mission.

a: END-TO-END OPTIMAL ROUTING FOR THE SCHEME WITH NO HWs

The matrix that we employ while implementing Hungarian technique is displayed in Eq. (3). The cells in the matrix indicate the distances between the nodes. Note that this matrix keeps the entire distance information between nodes, depicted as yellow lines in Fig. 14 for each WH. The main diagonal of the matrices is set to '∞' in order not to assign the same customers to each other. The same customer codes in the rows and columns may appear, if there are more orders demanded by a single customer. In this case, the cell takes the value of zero to deliver all the orders at once when a customer is visited, which is explained in the succeeding sections with examples. The visual outcome of optimal routing for the customers shown in Fig. 12 and more specifically in Fig. 14 is depicted in Fig. 15 in which an order list of customers to be served is maintained for each WH. The information about the mission such as total distance travelled and total weight carried is printed at the end of the missions on the map. The total distance is calculated by the sum of all distances between nodes in optimized routes as formulated in Eq. (4), where d_{tot} indicates the total distance a UAV travels through, in order, first customer, neighboring customers, last customer and the

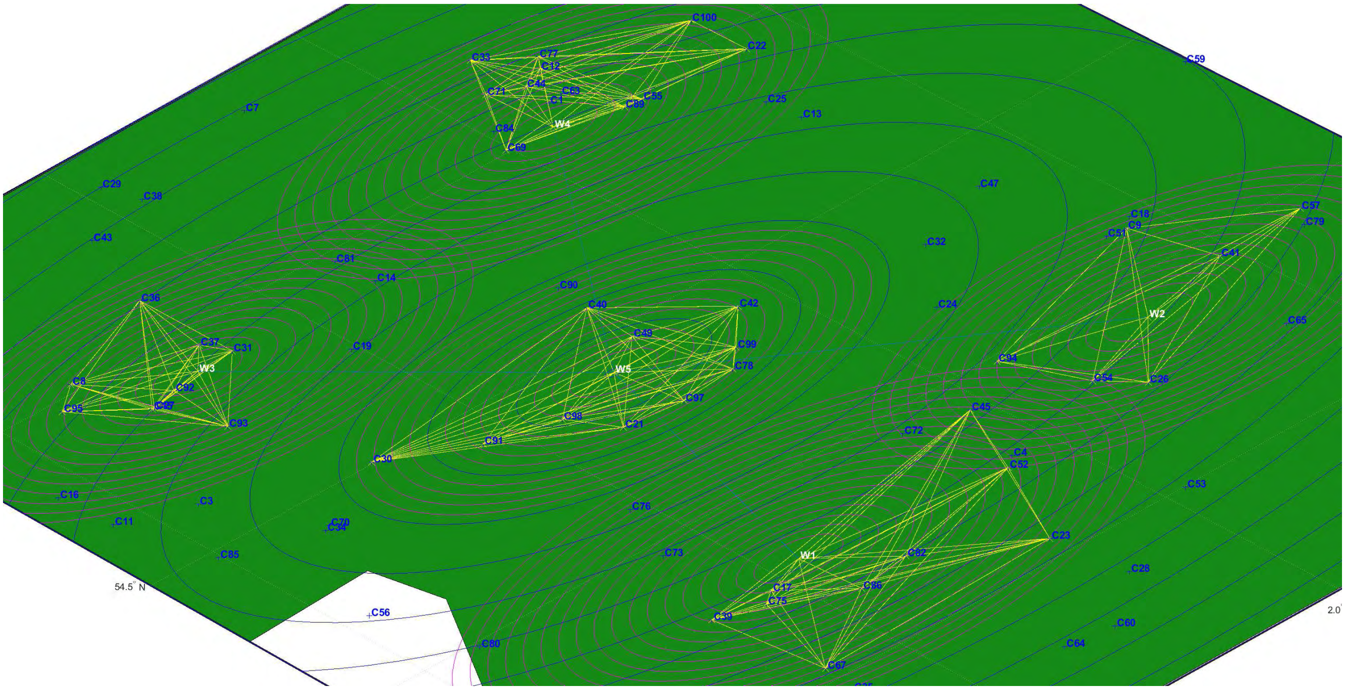

FIGURE 14. All possible routes without HWs.

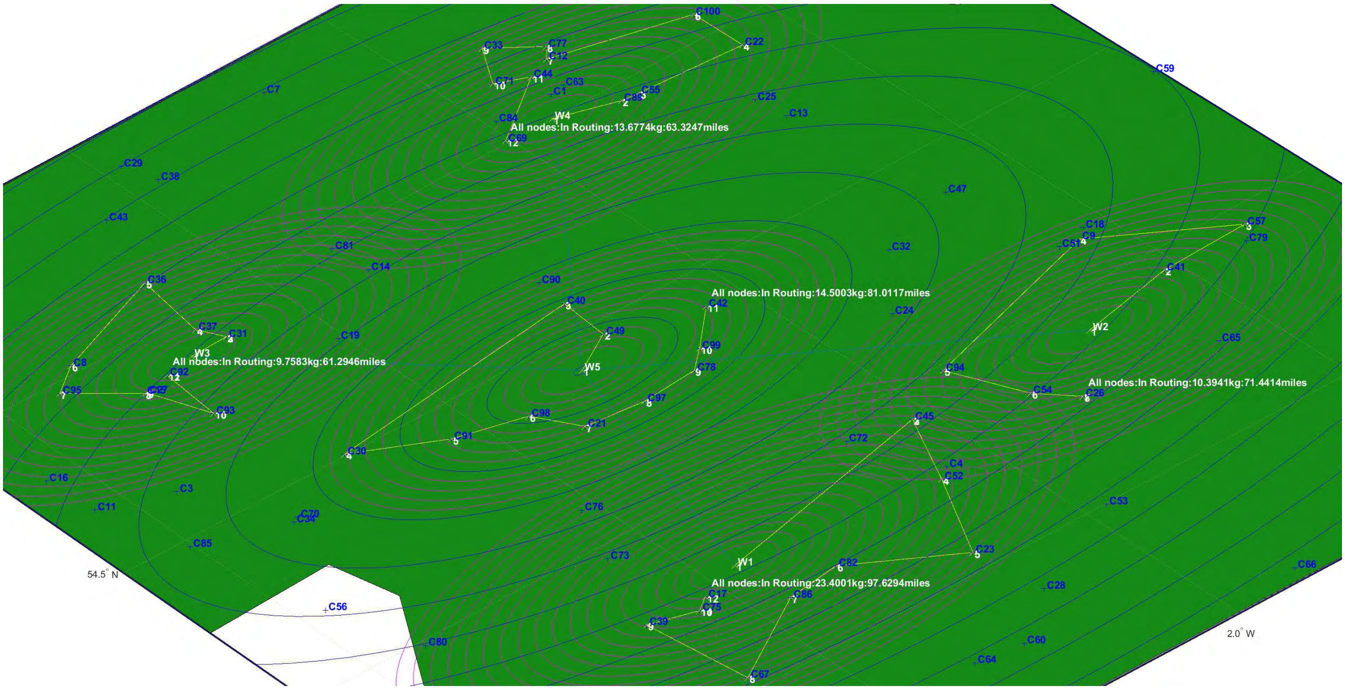

FIGURE 15. All possible optimal routes without HWs.

route back to its WH, while n indicates the nodes, by way of explanation, the total number of customers in a mission.

$$d_{tot} = d_{W_j C_1} + (\sum_{i=1}^{n-1} d_{C_i C_{i+1}}) + d_{C_n W_j} \tag{4}$$

In Eq. (4), $d_{W_j C_1}$ corresponds to the distance between the j^{th} WH and first customer in the route; $\sum_{i=1}^{n-1} d_{C_i C_{i+1}}$ indicates the total distance between customers in a route, where $i = \{1, ..., n-1\}$; $d_{C_n W_j}$ corresponds to the distance from the last customer in the route to the j^{th} WH.

Distance matrix for the cross-entropy technique using HWs.

$$\left\{\begin{array}{c|cccccc} & W_1; O_{00} & C_1; O_1 & C_2; O_2 & C_3; O_3 & \dots & C_n; O_n \\ \hline W_1; O_{00} & \infty & d_{H_{W_1}H_{C_1}} & d_{H_{W_1}H_{C_2}} & d_{H_{W_1}H_{C_3}} & \dots & d_{H_{W_1}H_{C_n}} \\ C_1; O_1 & d_{H_{C_1}H_{W_1}} & \infty & d_{H_{C_1}H_{C_2}} & d_{H_{C_1}H_{C_3}} & \dots & d_{H_{C_1}H_{C_n}} \\ C_2; O_2 & d_{H_{C_2}H_{W_1}} & d_{H_{C_2}H_{C_1}} & \infty & d_{H_{C_2}H_{C_3}} & \dots & d_{H_{C_2}H_{C_n}} \\ C_3; O_3 & d_{H_{C_3}H_{W_1}} & d_{H_{C_3}H_{C_1}} & d_{H_{C_3}H_{C_2}} & \infty & \dots & d_{H_{C_3}H_{C_n}} \\ \dots & \dots & \dots & \dots & \dots & \dots & \\ C_n; O_n & d_{H_{C_n}H_{W_1}} & d_{H_{C_n}H_{C_1}} & d_{H_{C_n}H_{C_2}} & d_{H_{C_n}H_{C_3}} & \dots & \infty \end{array}\right\} \tag{5}$$

Distance matrix for the cross-entropy technique in WH 1.

$$\left\{\begin{array}{c|cccccccc} & W_1; & C_{17}; & C_{39}; & C_{52}; & C_{75}; & C_{75} & C_{82}; & C_{86}; \\ \hline & O_{00} & O_{55} & O_{54} & O_{06} & O_{42} & O_{41} & O_{16} & O_{17} \\ W_1; O_{00} & \infty & 2.94 & 2.52 & 2.52 & 4.62 & 4.62 & 6.72 & 9.53 \\ C_{17}; O_{55} & 2.94 & \infty & 0.42 & 0.42 & 1.68 & 1.68 & 3.78 & 6.59 \\ C_{39}; O_{54} & 2.52 & 0.42 & \infty & 0 & 2.10 & 2.10 & 4.20 & 7.01 \\ C_{52}; O_{06} & 2.52 & 0.42 & 0 & \infty & 2.10 & 2.10 & 4.20 & 7.01 \\ C_{75}; O_{42} & 4.62 & 1.68 & 2.10 & 2.10 & \infty & 0 & 2.10 & 4.91 \\ C_{75}; O_{41} & 4.62 & 1.68 & 2.10 & 2.10 & 0 & \infty & 2.10 & 4.91 \\ C_{82}; O_{16} & 6.72 & 3.78 & 4.20 & 4.20 & 2.10 & 2.10 & \infty & 2.81 \\ C_{86}; O_{17} & 9.53 & 6.59 & 7.01 & 7.01 & 4.91 & 4.91 & 2.81 & \infty \end{array}\right\} \tag{6}$$

Distance matrix for the cross-entropy technique in WH 5.

$$\left\{\begin{array}{c|cccccccccc} & W_5; & C_{21}; & C_{40}; & C_{42}; & C_{49}; & C_{78}; & C_{91}; & C_{97}; & C_{98}; & C_{99}; \\ & O_{00} & O_{28} & O_{31} & O_{57} & O_{08} & O_{29} & O_{56} & O_{03} & O_{02} & O_{09} \\ \hline W_5; O_{00} & \infty & 8.8 & 12.1 & 2.0 & 4.6 & 10.1 & 4.5 & 9.7 & 4.0 & 8.8 \\ C_{21}; O_{28} & 8.8 & \infty & 20.9 & 10.8 & 13.4 & 20.9 & 15.3 & 0.8 & 4.8 & 19.6 \\ C_{40}; O_{31} & 12.1 & 20.9 & \infty & 10.1 & 7.6 & 24.2 & 18.7 & 21.8 & 16.2 & 22.9 \\ C_{42}; O_{57} & 2.0 & 10.9 & 10.1 & \infty & 2.5 & 14.1 & 8.6 & 11.7 & 6.1 & 12.8 \\ C_{49}; O_{08} & 4.5 & 13.4 & 7.6 & 2.5 & \infty & 16.7 & 11.1 & 14.2 & 8.6 & 15.4 \\ C_{78}; O_{29} & 10.1 & 20.9 & 24.2 & 14.1 & 16.7 & \infty & 14.6 & 21.8 & 16.1 & 1.3 \\ C_{91}; O_{56} & 4.5 & 15.4 & 18.7 & 8.6 & 11.1 & 14.6 & \infty & 16.2 & 10.6 & 13.3 \\ C_{97}; O_{03} & 9.7 & 0.8 & 21.8 & 11.7 & 14.2 & 21.8 & 16.2 & \infty & 5.6 & 20.5 \\ C_{98}; O_{02} & 4.0 & 4.8 & 16.2 & 6.0 & 8.6 & 16.1 & 10.6 & 5.6 & \infty & 14.9 \\ C_{99}; O_{09} & 8.8 & 19.6 & 22.9 & 12.8 & 15.4 & 1.3 & 13.3 & 20.5 & 14.9 & \infty \end{array}\right\} \tag{7}$$

b: END-TO-END OPTIMAL ROUTING FOR THE SCHEME USING HWs

The matrix that we employ while implementing cross-entropy technique is displayed in Eq. (5), as shown at the top of this page. The cells in the matrix indicate the distances between nodes' connections to HWs. Values in the orthogonal cells of the matrix are set to ∞ (i.e., cost is set to biggest number possible) in order not to assign the same customers to each other. However, these cells are set to zero to deliver all parcels ordered by the same customers at once. Therefore, we keep order codes together with customer codes to discern if they indicate the same or different customers. For instance, in our experimental design, notice 0 and ∞ values in the distance matrices of WH_1 in Eq.(6), as shown at the top of this page, and WH_5 in Eq. (7), as shown at the top of this page. The visual outcome of the optimal routes for the orders in Fig. 13 is presented in supplementary materials. Total distance is calculated by the sum of all distances between nodes in the optimized routes, as formulated in Eqs. (8) and (9).

$$\begin{aligned} d_{tot_{W_j}} &= d_{W_jC_1} + f(x) + d_{C_nW_j} \\ f(x) &= \begin{cases} \sum_{i=1}^{n-1} d_{C_iC_{i+1}} & \text{if } H_{C_i} = H_{C_{i+1}} \\ \sum_{i=1}^{n-1} d_{C_iW_j} + d_{W_jC_{i+1}} & \text{otherwise} \end{cases} \end{aligned} \tag{8}$$

$$\begin{aligned} d_{C_iC_{i+1}} &= d_{C_iH_{k_{C_i}}} + d_{H_{k_{C_i}}H_{k_{C_{i+1}}}} + d_{H_{k_{C_{i+1}}}C_{i+1}}; \\ d_{C_iW_j} &= d_{C_iH_{k_{C_i}}} + d_{H_{k_{C_i}}H_{k_{W_j}}} + d_{H_{k_{W_j}}W_j}; \\ d_{W_jC_{i+1}} &= d_{W_jH_{k_{W_j}}} + d_{H_{k_{W_j}}H_{k_{C_{i+1}}}} + d_{H_{k_{C_{i+1}}}C_{i+1}}, \\ & \text{where } \forall C_i \in W_j, \end{aligned} \tag{9}$$

where 'j' denotes WHs, d_{tot} indicates the total distance in a route; n indicates the total number of customers to be delivered; $d_{W_jC_1}$ indicates the distance between a WH and the first customer; $\sum_{i=1}^{n-1} d_{C_iC_{i+1}}$ indicates the total distance between customers in a route if customers are clustered for same HW; $\sum_{i=1}^{n-1} d_{C_iW_j} + d_{W_jC_{i+1}}$ indicates the distance between customers if they are clustered for different HWs; $d_{C_iW_j}$ indicates the distance between the last customer and way back to the WH. Moreover, the explanation for $d_{C_iC_{i+1}}$, $d_{C_iW_j}$ and $d_{W_jC_{i+1}}$ are given in Eq. (9). H_k corresponds to k^{th} HW and H_{kC_i} corresponds to the i^{th} customer's connection point to the k^{th} HW. Similarly, $H_{kC_{i+1}}$ and H_{kW_j} correspond to the $(i+1)^{th}$ customer and j^{th} WH connection points to the k^{th} HW, respectively.

c: END-TO-END OPTIMAL ROUTING FOR THE HYBRID SCHEME

This scheme uses two parameters defined by the user, one of which is the maximum distance limit between customers' connection to HWs (e.g., 2 miles in our experimental setup, $d_{(HW_{C1})(HW_{C2})}$); the other one is the maximum shortcut distance limit between customers (e.g., 2 miles, $d_{(C_1)(C_2)}$), as illustrated in Fig. 9. The scheme behaves close to the scheme without using HWs, whereas these distance values are increased, vice versa, behaves close to the scheme with HWs whereas they are reduced. In other words, the characteristics of this hybrid scheme are flexibly switched between the two other schemes discussed in Sections II-A3-c based on the two predefined distance limits. For instance, if these values are set to 10 miles and all the distances between nodes or nodes' connection points to HWs with respect to delivery orders of the customers are smaller than 10 miles, all the packages are delivered after a UAV leaves for a mission without using any HWs. Likewise, if these numbers are set to 1 mile and the distances between the customers or customers' connection points to HWs with respect to delivery orders of the customers bigger than 1 mile, then the UAV delivers all the parcels as exactly in the scheme with HWs without using any shortcuts, returning to HWs to deliver the next parcels. The routes in WHs are depicted in the supplementary materials. The total distances in sub-groups as illustrated in Fig. 6 are calculated as displayed in Eq. (10) for each sub-group. The total distance of a UAV is calculated as exactly in Eqs. (8) and (9) by taking these sub-groups into consideration as nodes, as illustrated in Fig.16. The sum of the calculated total distances for the sub-groups and the other distances out of the sub-groups results in the final distance that a UAV travels.

$$d_{subTot} = \sum_{i=1}^{n-1} d_{C_iC_{i+1}} \tag{10}$$

D. ROUTES USING DELIVERY METHODS

1) ROUTES TO COMPLETE THE MISSION WITH NO HWs

Optimal routing (Fig. 4) is performed using Hungarian technique as explained in Section II-C2 based on the delivery methods as discussed earlier in Section II-A4 (Fig. 10).

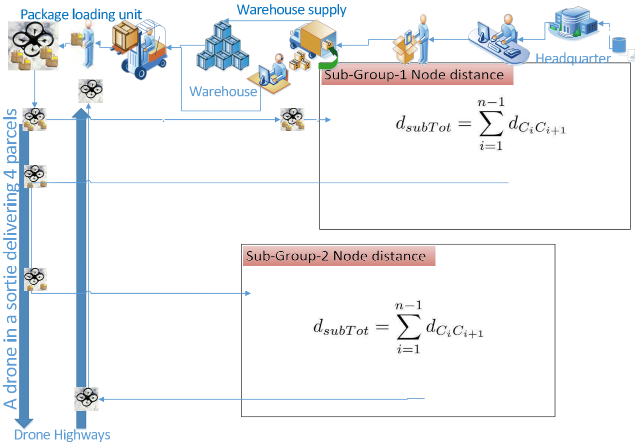

FIGURE 16. Calculation of the total distance.

TABLE 4. The UAVs in WHs and their capabilities.

WH code	UAV type	UAV code	# of carriers	Max dist	Max weight	Vol dim1	Vol dim2	Vol dim3	Reserved
WH_1	A	DA1	4	40	15	40	40	120	C
WH_1	A	DA6	4	40	15	40	40	120	C
WH_1	C	DB2	6	50	25	50	50	150	C
WH_2	A	DA2	4	40	15	40	40	120	C
WH_2	A	DA7	4	40	15	40	40	120	C
WH_3	A	DA3	4	40	15	40	40	120	C
WH_3	A	DA8	4	40	15	40	40	120	C
WH_4	A	DA4	4	40	15	40	40	120	C
WH_4	A	DA9	4	40	15	40	40	120	C
WH_5	A	DA10	4	40	15	40	40	120	C
WH_5	A	DA5	4	40	15	40	40	120	C
WH_5	B	DB1	6	100	20	40	100	140	WH

a: OPTIMAL DELIVERY METHOD IN THE SCHEME WITH NO HWs

The technique of finding optimal parcels in the delivery pool for the optimal delivery along with optimal routing is depicted in the supplementary materials of the manuscript. To summarize: 1) The optimal number of parcels is selected with respect to the number of cargo carriers of existing UAVs if the number of the parcels in the delivery pool is bigger than the carrier count of existing UAVs; 2) All the combinations of remaining number of parcels (i.e., the remaining parcels (c) = the number of all customer array list (i.e., custnodeArray) per WH to be delivered - the maximum parcel count) are found; 3) These combinations of changing customers (i.e., combi = combnk(custnodeArray,c)) are removed from all customer array list, respectively, in order to obtain distinct parcel combinations based on the optimum number of parcels obtained in the first step; 4) Then, the total distance and total cargo weight are measured after optimal routing for selected parcels is determined with respect to optimal delivery method as illustrated in the supplementary materials; the total distance and total weight are compared to the previous total distances and total weights obtained using the previous combinations; 5) Finally, the combination with the biggest total distance and cargo weight under the maximum delivery distance and maximum cargo weight of UAVs is retained and

TABLE 5. Assignment of the customers using optimal delivery method without HWs: the highlighted cells correspond to the first assignments in WHs.

WH code	Assigned #	UAV code	Route	Max carr.	Max dist.	Distance	Weight
WH_1	6	DA1	$W_1, C_{75}, C_{75}, C_{52}, W_1$	4	40	39.91	2.3
WH_1	11	DA6	W_1, C_{45}, C_{45}, W_1	4	40	37.62	2.4
WH_1	1	DB2	$W_1, C_{82}, C_{86}, C_{67}, C_{39}, C_{17}, W_1$	6	50	49.5	17.4
WH_2	2	DA2	$W_2, C_{54}, C_{26}, C_{26}, C_{41}, W_2$	4	40	38.32	8.2
WH_2	7	DA7	W_2, C_9, W_2	4	40	31.38	0.7
WH_3	3	DA3	$W_3, C_{95}, C_8, C_{36}, C_{37}, W_3$	4	40	39.9	15
WH_3	8	DA8	$W_3, C_{31}, C_{31}, C_{93}, C_{15}, W_3$	4	40	28.37	2.8
WH_4	4	DA4	$W_4, C_{77}, C_{100}, C_{100}, C_{89}, W_4$	4	40	39.8	5.4
WH_4	9	DA9	$W_4, C_{44}, C_{12}, C_{33}, C_{69}, W_4$	4	40	38.1	6.3
WH_5	5	DA10	$W_5, C_{99}, C_{78}, C_{98}, C_{91}, W_5$	4	40	39.98	3.5
WH_5	10	DA5	$W_5, C_{49}, C_{42}, C_{97}, C_{21}, W_5$	4	40	39.15	5.8
WH_5	N/A	DB1	N/A: Reserved for WHs	6	100	N/A	N/A

TABLE 6. Assignment of the customers using premium delivery without HWs: the highlighted cells correspond to the first assignments in WHs. The highlighted customers correspond to the premium orders.

WH code	Assigned #	UAV code	Route	Max carr.	Max dist.	Distance	Weight
WH_1	6	DA1	W_1, C_{45}, C_{45}, W_1	4	40	37.62	2.4
WH_1	11	DA6	W_1, C_{52}, W_1	4	40	29.87	0.7
WH_1	1	DB2	$W_1, C_{17}, C_{75}, C_{75}, C_{86}, C_{23}, C_{82}, W_1$	6	50	47.31	4.9
WH_2	2	DA2	$W_2, C_{94}, C_{54}, C_{26}, C_{26}, W_2$	4	40	37.18	7.2
WH_2	7	DA7	W_2, C_{41}, C_9, W_2	4	40	35.14	2.5
WH_3	3	DA3	$W_3, C_{92}, C_{92}, C_{36}, C_{37}, W_3$	4	40	34.62	4.7
WH_3	8	DA8	$W_3, C_{31}, C_{31}, C_8, C_{15}, W_3$	4	40	29.71	2.8
WH_4	4	DA4	$W_4, C_{69}, C_{33}, C_{77}, C_{12}, W_4$	4	40	38.33	8.7
WH_4	9	DA9	$W_4, C_{89}, C_{55}, C_{22}, C_{44}, W_4$	4	40	38.94	2.8
WH_5	5	DA10	$W_5, C_{49}, C_{78}, C_{21}, C_{98}, W_5$	4	40	38.70	5.3
WH_5	10	DA5	$W_5, C_{42}, C_{99}, C_{97}, W_5$	4	40	32.64	3.3
WH_5	N/A	DB1	N/A: Reserved for WHs	6	100	N/A	N/A

TABLE 7. The assignment results of the customers using FIFO delivery without HWs: the highlighted cells correspond to the first assignments in WHs.

WH code	Assigned #	UAV code	Route	Max carr.	Max dist.	Distance	Weight
WH_1	6	DA1	$W_1, 6C_{75}, 7C_{75}, 5C_{86}, 4C_{82}, W_1$	4	40	26.71	2.9
WH_1	11	DA6	$W_1, 11C_{17}, 10C_{39}, W_1$	4	40	16.4	1.0
WH_1	1	DB2	$W_1, 1C_{52}, 2C_{45}, 3C_{45}, W_1$	6	50	45.5	3.1
WH_2	2	DA2	$W_2, 2C_{94}, 1C_{54}, 3C_{26}, 4C_{26}, W_2$	4	40	37.18	7.2
WH_2	7	DA7	$W_2, 5C_{41}, 6C_9, W_2$	4	40	35.14	2.5
WH_3	3	DA3	$W_3, 2C_{31}, 3C_{31}, 2C_{37}, 4C_8, W_3$	4	40	25.60	2.8
WH_3	8	DA8	$W_3, 7C_{36}, 9C_{27}, 5C_{92}, 6C_{92}, W_3$	4	40	38.30	4.8
WH_4	4	DA4	$W_4, 3C_{44}, 5C_{12}, 2C_{71}, 1C_{69}, W_4$	4	40	28.30	2.4
WH_4	9	DA9	$W_4, 6C_{77}, 4C_{100}, 8C_{100}, 9C_{89}, W_4$	4	40	39.80	5.4
WH_5	5	DA10	$W_5, 3C_{98}, 4C_{97}, 2C_{99}, 1C_{49}, W_5$	4	40	37.58	4.3
WH_5	10	DA5	$W_5, 7C_{78}, 5C_{21}, 9C_{91}, W_5$	4	40	39.85	4.2
WH_5	N/A	DB1	N/A: Reserved for WHs	6	100	N/A	N/A

TABLE 8. All remaining customers using optimal delivery method without HWs.

WH	#	Route	Distance	Weight
WH_1	1	W_1, C_{23}, W_1	41.18	1.3
WH_2	2	W_2, C_{94}, C_{57}, W_2	47.19	1.4
WH_3	1	$W_3, C_{27}, C_{92}, C_{92} W_3$	9.39	4.3
WH_4	3	$W_4, C_{55}, C_{22}, C_{71}, W_4$	43.65	2.0
WH_5	2	W_5, C_{30}, C_{40}, W_5	48.99	5.2

the parcels in this combination are assigned to a UAV. The algorithm goes forward with similar calculations by removing a parcel each time until the total maximum distance and weight under the maximum delivery distance and payload of UAVs is reached. The main purpose of using this approach is to include as many customers as possible into missions starting from the first delivery. The remaining orders placed in a queue are shown in Table 8.

b: PREMIUM DELIVERY METHOD IN THE SCHEME WITH NO HWs

The technique of finding the optimal parcels with the premium delivery along with optimal routing is depicted in the supplementary material. This technique works similar to the optimal method explained in Section II-D1-a, but this time prioritizing "premium" parcels. Prioritization is performed by means of assigning premium orders to the first and succeeding available UAVs. However, routing is carried out in an optimal way to reduce the air traffic and to use the resources optimally along with the assignment phases. Some of the customers may have more than one order (e.g., C_{75}, C_{26}, C_{92}, C_{31}) and one of which might be premium. In this case, all other orders that are not premium are put in the same route with the prioritized premium orders of these customers as it is shown in the supplementary materials and in Table 6. If there are premium orders more than the number of cargo carriers on a UAV (e.g., WH_5:C_{49}, C_{78}, C_{21}, C_{98}, C_{99}), some of these premium orders along with other non-premium orders belonging to the same customers are assigned to a UAV and the rest is either assigned to the next UAV or placed in a queue. For instance, the highlighted four customers in the Assigned #, 5, in Table 6 ensure the total maximum distance in the mission less than the maximum distance of the UAV. When you replace one of these customers with the other premium customer, C_{99} that is in Assigned # 10, the distance of the route becomes less than 38.70 miles which demolishes optimality. The remaining orders in the queue are shown in Table 9 in which there is no premium order.

TABLE 9. All remaining customers using premium delivery method without HWs.

WH	#	Route	Distance	Weight
WH_1	1	W_1, C_{39}, C_{67}, W_1	43.58	15.4
WH_2	2	W_2, C_{57}, W_2	27.95	0.7
WH_3	1	$W_3, C_{93}, C_{27}, C_{95} W_3$	36.95	5.0
WH_4	3	$W_4, C_{100}, C_{100}, C_{71}, W_4$	38.13	2.0
WH_5	2	$W_5, C_{91}, C_{30}, C_{40}, W_5$	50.56	5.9

c: FIFO DELIVERY METHOD IN THE SCHEME WITH NO HWs

The technique of finding optimal parcels with the FIFO delivery along with optimal routing is depicted in the supplementary material. This technique works similar to above-mentioned premium delivery method considering a prioritization based on first come first assigned in a mission. The aim is to find the optimal combinations of parcels per UAV by means of the times of orders. An example of this approach is presented in the supplementary materials. The orders are sorted in ascending in Table 2. The first three orders in W_1 are C_{52}, C_{45} and C_{45} that are assigned to the first UAV (i.e., DB2); the following orders, C_{75}, C_{75},C_{86},C_{82} that are assigned to the next UAV (i.e., DA1) and the other orders, C_{39}, C_{17} out of C_{23}, C_{67}, C_{39} and C_{17} are assigned to the last UAV (i.e., DA6) instead of the customers, C_{23}, C_{67} in line, because these customers are not within the limits of UAV DA6: the distance to the WH is 41.2 miles for C_{23} that is out of the ROI of the last UAV and the weight for C_{67}, 15.11 is bigger than the maximum cargo capacity (i.e., $>$15.00); therefore they are put in a queue. C_{27} is selected instead of C_{95} in the assignment to second UAV (i.e., DA8) in W_3. Since, adding C_{95} into the route makes the distance bigger

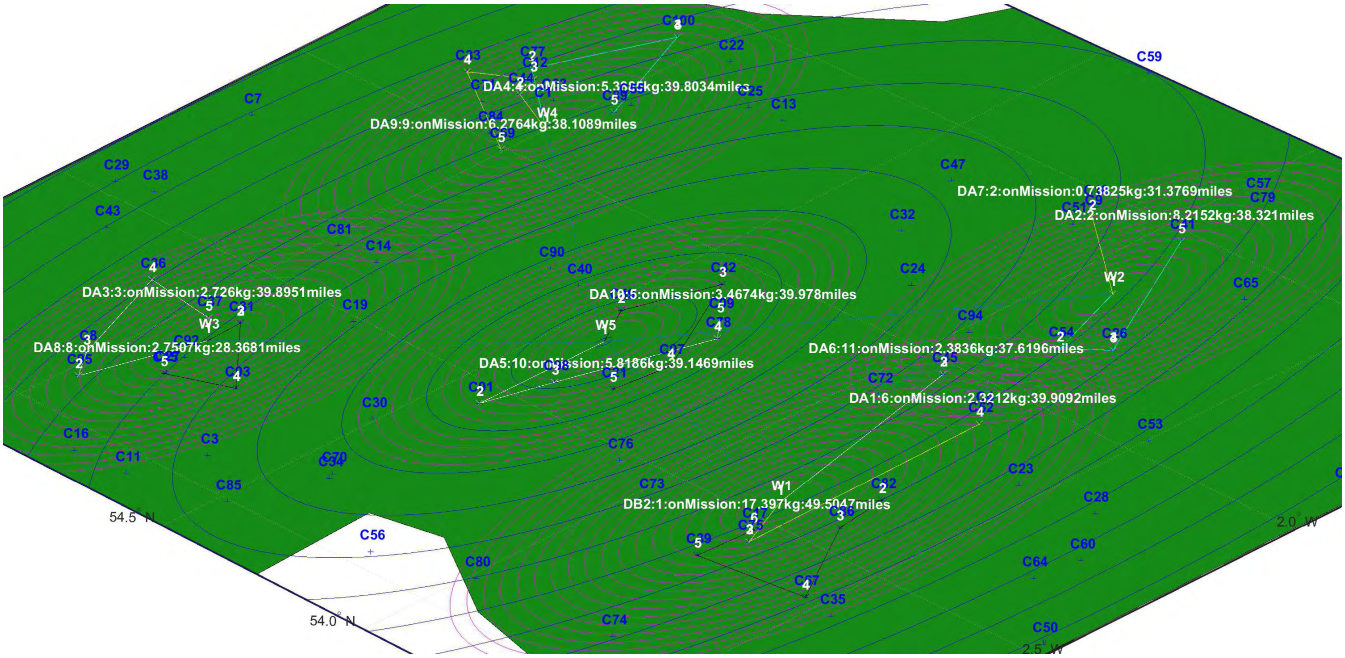

FIGURE 17. All deliveries using optimal delivery method with no HWs: the routes of UAVs in WHs are drawn in different colors.

TABLE 10. All remaining customers using FIFO delivery method without HWs.

WH	#	Route	Distance	Weight
WH_1	1	$W_1, 9C_{67}, 8C_{23}, W_1$	57.80	16.4
WH_2	2	$W_2, 7C_{57}, W_2$	27.98	0.7
WH_3	1	$W_3, 8C_{95}, 10C_{15}, 11C_{93}, W_3$	36.92	2.2
WH_4	3	$W_4, 10C_{55}, 11C_{22}, 7C_{33}, W_4$	54.07	5.9
WH_5	2	$W_5, 9C_{42}, 6C_{40}, 8C_{30}, W_5$	59.67	6.0

than the reach of the UAV and the system searches through next available orders with respect to order time; consequently, the next best available order belonging to C_{27} is selected. Likewise, the other assignments can be examined in Table 7. The remaining orders in the queue are shown in Table 10.

2) ROUTES TO COMPLETE THE MISSION USING HWs

The difference from the approaches mentioned in previous section for the delivery methods with no HWs is that UAVs must follow pre-specified HWs during delivery and customers are served from the nearest HW connections (i.e. the connection between the line drawn to a HW from a customer and HW is perpendicular, 90°). Optimal routing using HWs that is illustrated in Fig. 5 is performed using cross-entropy Monte Carlo technique as explained in Section II-C2 with respect to the delivery methods as explained in Section II-A4 (Fig. 10). Routing is determined using all pre-specified HWs. For instance, a customer can be served using HW_1 whereas another customer can be served using HW_2 and changing HWs between these customers by UAVs is executed on the WH locations (e.g., UAV DA10). The distance between two nodes are measured using Eqs. (8) and (9): distances of nodes to HWs connection along with the distance between these connections on HWs are summed up. The distance values highlighted in the distance column in tables indicate how optimal the first assignments are with respect to the maximum travel distances of UAVs: the closer the values to the maximum value along with more customers, the better decision is given. The total distance (i.e., $d_{Di_{tot}}$) and total cargo weight (i.e., $\varpi_{Di_{tot}}$) of a UAV are measured while optimal routing is being determined in delivery pool that keeps customers and order codes (e.g., C_1:O_{70}). If parcels of all customers in delivery array list can be delivered with regard to this total distance along with other constraints, these parcels in the delivery array list are assigned to an available UAV in a WH and the mission starts according to optimal routing using HWs by disregarding any chosen delivery method. Otherwise, the routing along with assignments is performed with respect to the chosen delivery method as follows:

TABLE 11. Remaining customers with the optimal delivery using HWs.

WH	#	Route	Distance	Weight
WH_1	1	N/A	N/A	N/A
WH_2	2	W_2, C_{41}, W_2	18.62	1.8
WH_3	1	$W_3, C_{31}, C_{31}, C_{95}, C_{27}, W_3$	41.49	2.8
WH_4	3	W_4, C_{89}, C_{77}, W_4	42.64	3.9
WH_5	2	$W_5, C_{91}, C_{99}, C_{78}, C_{40}, W_5$	81.88	4.8

a: OPTIMAL DELIVERY METHOD IN THE SCHEME WITH HWs

This particular methods works similar to the method as mentioned in Section II-D1-a, but, this time delivery is carried out using HWs. An example of this approach is presented in Fig. 18. The assignment results of the customers for all WHs are shown in Table 17. The remaining orders in the queue are shown in Table 11.

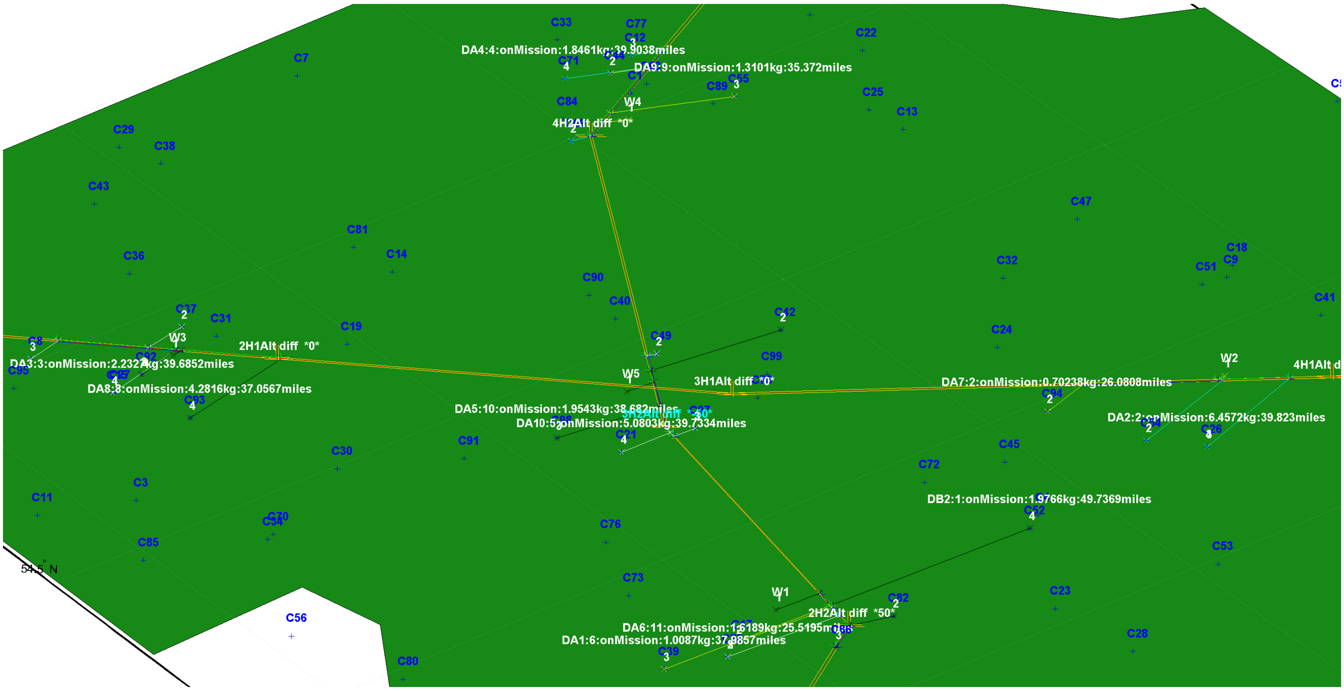

FIGURE 18. **All deliveries using Optimum with HWs.**

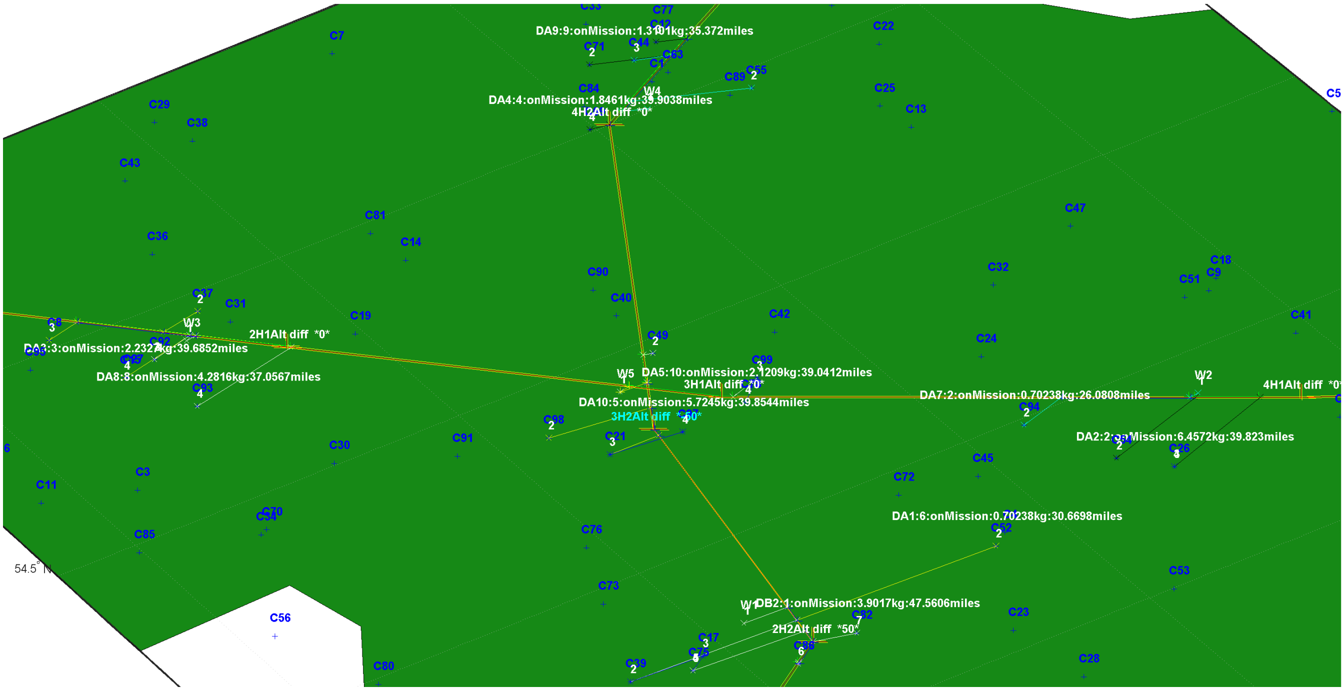

FIGURE 19. **All deliveries using Optimum with hybrid scheme.**

b: PREMIUM DELIVERY METHOD IN THE SCHEME WITH HWs

This particular methods works similar to the method as discussed in Section II-D1-b, but, this time delivery is carried out using HWs. The assignments are presented in Table 18. There are two premium orders $C_{82} : O_{16}$ and $C_{75} : O_{41}$ in WH_1 as seen in Table 2. These orders are delivered along with the non premium orders, $C_{17} : O_{55}$ and $C_{75} : O_{42}$ by UAV DB2 for the first assignment. The system adds the order, $C_{75} : O_{42}$, into the route to ensure optimality of the delivery system, because the UAV must visit this customer

TABLE 12. Remaining customers with the premium delivery using HWs.

WH	#	Route	Distance	Weight
WH_1	1	W_1, C_{86}, W_1	20.07	0.7
WH_2	2	W_2, C_{41}, W_2	18.62	1.8
WH_3	1	$W_3, C_8, , C_{93}, W_3$	55.26	1.5
WH_4	3	W_4, C_{71}, C_{89}, W_4	38.56	1.3
WH_5	2	$W_5, C_{97}, C_{40}, C_{42}, C_{91}, W_5$	91.24	5.9

TABLE 13. Remaining customers with the FIFO delivery using HWs.

WH	#	Route	Distance	Weight
WH_1	1	$W_1, N/A, W_1$	20.07	0.7
WH_2	2	$W_2, 5C_{41}, W_2$	18.62	1.8
WH_3	1	$W_3, 8C_{27}, 10C_{93}, C_{15}, W_3$	50.42	2.2
WH_4	3	$W_4, 7C_{55}, 6C_{89}, W_4$	31.56	0.9
WH_5	2	$W_5, 5C_{21}, 6C_{40}, 9C_{42}, 8C_{91}, W_5$	92.59	6.5

TABLE 14. Remaining customers with the optimal delivery in hybrid scheme.

WH	#	Route	Distance	Weight
WH_1	1	N/A	N/A	N/A
WH_2	2	W_2, C_{41}, W_2	18.62	1.8
WH_3	1	$W_3, C_{31}, C_{31}, C_{27}, C_{95}, W_3$	41.49	2.8
WH_4	3	W_4, C_{89}, C_{77}, W_4	42.64	3.9
WH_5	2	$W_5, C_{40}, C_{42}, C_{91}, W_5$	69.65	3.4

TABLE 15. Remaining customers with the premium delivery in hybrid scheme.

WH	#	Route	Distance	Weight
WH_1	1	N/A	N/A	N/A
WH_2	2	W_2, C_{41}, W_2	18.62	1.8
WH_3	1	W_3, C_8, C_{93}, W_3	55.26	1.5
WH_4	3	W_4, C_{55}, W_3	19.30	0.7
WH_5	2	$W_5, C_{40}, C_{42}, C_{91}, W_5$	69.65	4.0

TABLE 16. Customers in queue with the optimal delivery in hybrid scheme.

WH	#	Route	Distance	Weight
WH_1	1	N/A	N/A	N/A
WH_2	2	$W_2, 5C_{41}, W_2$	18.62	1.8
WH_3	1	$W_3, 8C_{27}, 10C_{93}, W_3$	40.05	1.5
WH_4	3	$W_4, 7C_{55} - 6C_{89}, W_4$	18.78	1.5
WH_5	2	$W_5, 6C_{40}, 9C_{42}, 8C_{91}, W_5$	69.65	4.0

TABLE 17. Assignment using the optimal delivery with HWs.

WH code	Assigned #	UAV code	Route	Max carr.	Max dist.	Distance	Weight
WH_1	6	DA1	W_1, C_{17}, C_{39}, W_1	4	40	37.99	1.0
WH_1	11	DA6	W_1, C_{75}, C_{75}, W_1	4	40	25.52	1.6
WH_1	1	DB2	$W_1, C_{82}, C_{86}, C_{52}, W_1$	6	50	49.74	2.0
WH_2	2	DA2	$W_2, C_{54}, C_{26}, C_{26}, W_2$	4	40	39.82	6.5
WH_2	7	DA7	W_2, C_{94}, W_2	4	40	26.08	0.7
WH_3	3	DA3	$W_3, C_{37}, C_8, C_{15}, W_3$	4	40	39.69	9.3
WH_3	8	DA8	$W_3, C_{92}, C_{92}, C_{93}, W_3$	4	40	37.06	7.0
WH_4	4	DA4	$W_4, C_{69}, C_{12}, C_{71}, W_4$	4	40	39.90	1.9
WH_4	9	DA9	$W_4, C_{44}, C_{55} W_4$	4	40	35.37	1.3
WH_5	5	DA10	$W_5, C_{49}, C_{97}, C_{21}, W_5$	4	40	39.73	5.1
WH_5	10	DA5	W_5, C_{42}, C_{98}, W_5	4	40	38.68	2.0
WH_5	N/A	DB1	N/A: Reserved for WHs	6	100	N/A	N/A

TABLE 18. Assignment of the customers using the premium delivery with HWs: the highlighted customers correspond to the premium orders in the routes.

WH code	Assigned #	UAV code	Route	Max carr.	Max dist.	Distance	Weight
WH_1	6	DA1	W_1, C_{52}, W_1	4	40	30.67	0.7
WH_1	11	DA6	W_1, C_{39}, W_1	4	40	27.18	0.3
WH_1	1	DB2	$W_1, C_{17}, C_{75}, C_{75}, C_{82}, W_1$	6	50	44.30	2.9
WH_2	2	DA2	$W_2, C_{54}, C_{26}, C_{26}, W_2$	4	40	39.82	6.5
WH_2	7	DA7	W_2, C_{94}, W_2	4	40	26.08	0.7
WH_3	3	DA3	$W_3, C_{92}, C_{92}, C_{95}, C_{37}, W_3$	4	40	36.97	9.3
WH_3	8	DA8	$W_3, C_{31}, C_{31}, C_{27}, C_{15}, W_3$	4	40	26.00	2.8
WH_4	4	DA4	$W_4, C_{12}, C_{77}, C_{69}, W_4$	4	40	39.71	4.4
WH_4	9	DA9	W_4, C_{55}, C_{44}, W_4	4	40	35.37	1.3
WH_5	5	DA10	$W_5, C_{49}, C_{99}, C_{78}, W_5$	4	40	39.62	2.1
WH_5	10	DA5	W_5, C_{21}, C_{98}, W_5	4	40	36.20	3.8
WH_5	N/A	DB1	N/A: Reserved for WHs	6	100	N/A	N/A

for his/her premium order, $C_{75} : O_{41}$. Similarly, there are two premium orders for the customers $C_{54} : O_{12}$ and $C_{26} : O_{38}$ in WH_2. These orders must be delivered with the non premium order $C_{26} : O_{13}$ that is for a premium customer (i.e., $C_{26} : O_{38}$) already put in the route. Likewise, the premium orders, $C_{31} : O_{10}$ and $C_{92} : O_{35}$ in WH_3, $C_{44} : O_{21}$, $C_{12} : O_{44}$ and $C_{77} : O_{25}$ in WH_4 are assigned to the first UAVs in their WHs. We would like to explain the deliveries in WH_5 with more details: there are 5 premium orders (i.e., $C_{49} : O_8$, $C_{99} : O_9$, $C_{98} : O_2$, $C_{21} : O_{28}$ and $C_{78} : O_{29}$ in WH_5) and these orders cannot be delivered by any UAV in a mission together. In this case, the system assigns some of these orders to the first delivery as many as possible and the rest are assigned to the following deliveries. In other words, the three premium orders that are $C_{49} : O_8$, $C_{99} : O_9$ and $C_{78} : O_{29}$ are assigned to the first delivery with the constraint $d_{tot} < d_{DA10_{max}}$ (i.e., $39.62 < 40$), but as close as possible to $d_{DA10_{max}} = 40$ to use the resources optimally; the other two premium orders that are $C_{98} : O_2$ and $C_{21} : O_{28}$ are assigned to the second delivery ($d_{DA5_{max}} = 40$) with $d_{tot} = 36.20$. The remaining non premium orders ($C_{97} : O_8$,$C_{40} : O_9$, $C_{42} : O_{29}$ and $C_{91} : O_{29}$) are put in a queue (Table 12). The deliveries are depicted in the supplementary materials. The remaining orders in the queue are shown in Table 12 in which there is no premium order.

c: FIFO DELIVERY METHOD IN THE SCHEME WITH HWs

This particular methods works similar to the method as discussed in Section II-D1-c, but this time delivery is carried out using HWs and this particular methods works similar to the method as described in the premium delivery using HWs mentioned above, but this time prioritizing orders is executed using first come first put in a mission. The aim is to find the optimal combinations of parcels per UAV to serve as many customers as possible by means of order times using HWs. The orders are sorted in ascending in Table 2 and the cells not highlighted in customer column show the customers in the ROI of WHs. The assignment decisions can be examined in Table 19. The first three orders in W_1 are $C_{52} : O_6$, $C_{82} : O_{16}$ and $C_{86} : O_{17}$ that are assigned to the first UAV (i.e., DB2); the following orders, $C_{17} : O_{55}$, $C_{75} : O_{41}$, $C_{75} : O_{42}$, are assigned to the next UAV (i.e., DA1). The system assigns the order, $C_{17} : O_{55}$, instead of $C_{39} : O_{54}$ in line, because assigning the other order makes the distance much bigger than the UAV maximum distance. The other remaining order, $C_{39} : O_{54}$, is assigned to the last UAV (i.e., DA6). Likewise, in W_2, $C_{26} : O_{13}$ and $C_{26} : O_{16}$ instead of $C_{94} : O_{15}$ are assigned to the first UAV (i.e., DA2); in W_5, $C_{78} : O_{29}$ instead of $C_{98} : O_2$, $C_{21} : O_{28}$, $C_{40} : O_{31}$ is assigned to

TABLE 19. **Assignment of the customers using the FIFO delivery with HWs: the highlighted numbers show the ordering sequence of the parcels regarding order time.**

WH code	Assigned #	UAV code	Route	Max carr.	Max dist.	Distance	Weight
WH_1	6	DA1	$W_1, 7C_{17}, 4C_{75}, 5C_{75}, W_1$	4	40	35.48	2.6
WH_1	11	DA6	$W_1, 6C_{39}, W_1$	4	40	27.18	0.3
WH_1	1	DB2	$W_1, 2C_{82}, 3C_{86}, 1C_{52}, W_1$	6	50	49.74	2.0
WH_2	2	DA2	$W_2, 2C_{54}, 3C_{26}, 4C_{26}, W_2$	4	40	39.82	6.5
WH_2	7	DA7	$W_2, 2C_{94}, W_2$	4	40	26.08	0.7
WH_3	3	DA3	$W_3, 1C_{31}, 3C_{31}, 2C_{37}, 4C_8, W_3$	4	40	35.49	2.8
WH_3	8	DA8	$W_3, 5C_{92}, 6C_{92}, 7C_{95}, W_3$	4	40	32.32	4.3
WH_4	4	DA4	$W_4, 3C_{44}, 2C_{71}, 1C_{69}, W_4$	4	40	36.29	1.7
WH_4	9	DA9	$W_4, 5C_{77}, 4C_{12} W_4$	4	40	34.28	3.9
WH_5	5	DA10	$W_5, 1C_{49}, 4C_{97}, 5C_{21}, W_5$	4	40	39.73	5.1
WH_5	10	DA5	$W_5, 9C_{42}, 3C_{98}, W_5$	4	40	38.68	2.0
WH_5	N/A	DB1	N/A: Reserved for WHs	6	100	N/A	N/A

TABLE 20. **Assignments with the optimal delivery using the hybrid scheme.**

WH code	Assigned #	UAV code	Route	Max carr.	Max dist.	Distance	Weight
WH_1	6	DA1	W_1, C_{52}, W_1	4	40	30.67	0.70
WH_1	11	DA6	N/A	4	40	N/A	N/A
WH_1	1	DB2	$W_1, C_{39} - C_{17} - C_{75}, C_{75}, C_{86}, C_{82}, W_1$	6	50	47.56	3.9
WH_2	2	DA2	$W_2, C_{54}, C_{26}, C_{26}, W_2$	4	40	39.82	6.5
WH_2	7	DA7	W_2, C_{94}, W_2	4	40	26.08	0.7
WH_3	3	DA3	$W_3, C_{37}, C_8, C_{15}, W_3$	4	40	39.69	2.2
WH_3	8	DA8	$W_3, C_{92}, C_{92}, C_{93}, W_3$	4	40	37.06	4.3
WH_4	4	DA4	$W_4, C_{71} - C_{12}, C_{69}, W_4$	4	40	39.90	1.9
WH_4	9	DA9	W_4, C_{55}, C_{44}, W_4	4	40	35.37	1.3
WH_5	5	DA10	$W_5, C_{98}, C_{21} - C_{97}, W_5$	4	40	39.85	5.7
WH_5	10	DA5	$W_5, C_{49} - C_{98}, C_{78}, W_5$	4	40	39.04	6.1
WH_5	N/A	DB1	N/A: Reserved for WHs	6	100	N/A	N/A

TABLE 21. **Assignments with the premium delivery using the combination of the two schemes (hybrid scheme).**

WH code	Assigned #	UAV code	Route	Max carr.	Max dist.	Distance	Weight
WH_1	6	DA1	W_1, C_{52}, W_1	4	40	30.67	0.7
WH_1	11	DA6	N/A	4	40	N/A	N/A
WH_1	1	DB2	$W_1, C_{39} - C_{17} - C_{75}, C_{75}, C_{86}, C_{82}, W_1$	6	50	47.56	3.9
WH_2	2	DA2	$W_2, C_{54}, C_{26}, C_{26}, W_2$	4	40	39.82	6.5
WH_2	7	DA7	W_2, C_{94}, W_2	4	40	26.08	0.7
WH_3	3	DA3	$W_3, C_{92}, C_{92}, C_{95}, C_{37}, W_3$	4	40	36.97	4.5
WH_3	8	DA8	$W_3, C_{31}, C_{31} - C_{27} - C_{15}, W_3$	4	40	16.45	2.8
WH_4	4	DA4	$W_4, C_{12}, C_{77}, C_{69}, W_4$	4	40	39.71	4.4
WH_4	9	DA9	$W_4, C_{89}, C_{44} - C_{71}, W_4$	4	40	38.95	1.9
WH_5	5	DA10	$W_5, C_{49}, C_{99} - C_{78}, W_5$	4	40	39.04	2.1
WH_5	10	DA5	$W_5, C_{21} - C_{97}, C_{98}, W_5$	4	40	39.85	5.7
WH_5	N/A	DB1	N/A: Reserved for WHs	6	100	N/A	N/A

the first UAV (i.e., DA10). In W_3 and W_4, all the orders are assigned regarding order time. Some of the customers may have more than one order (e.g., $C_{75}, C_{26}, C_{92}, C_{31}$) and one of which might be ordered previously and there might be other orders belonging to other customers between these orders. In this case, all other orders that are not ordered previously are put in the same route with the prioritized orders as you can see in the supplementary materials and Table 19. The remaining orders in the queue are shown in Table 13.

3) ROUTES TO COMPLETE THE MISSION USING THE HYBRID SCHEME

The methodology using the hybrid scheme works by taking account the points mentioned in both II-D1 and II-D2 in such a way that the delivery assignments are performed with and without using HWs as illustrated in Fig. 6 based on the *two pre-specified limits* that can be updated by the user, one of which is the distance among the nodes (e.g., 2 miles in our experiment) and the other one is the distance between their connection points to HWs (e.g., 2 miles in our experiment). The system approaches to using delivery scheme without HWs as these two values are increased, and vice versa, it approaches to using the HW scheme as these numbers are reduced. Routing without using HWs (Fig. 4) is performed using Hungarian technique as explained in Section II-C2-a, and routing using HWs (Fig. 5) is performed using cross-entropy technique as explained in Section II-C2-b with respect to the delivery methods as explained in Section II-A4 (Fig. 10).

a: OPTIMAL DELIVERY METHOD IN THE HYBRID SCHEME

It works by taking account the points mentioned in both II-D1-a and II-D2-a in such a way that the delivery assignments are carried out with/without using HWs as illustrated in Fig. 6. An example of this approach is presented in the supplementary materials. Assignments for all WHs are shown in Table 20. The remaining orders in the queue are shown in Table 14. There are two shortcut deliveries between C_{39} and C_{17}, and C_{17} and C_{75} in W_1, thus, two more customers (n $=$ 5; $C_{39}, C_{17}, C_{75}, C_{75}, C_{86}, C_{82}$) are served in W_1 in the first assignment to UAV DB2, as depicted in Table 20, when compared to optimal delivery with HWs (n $=$ 3; C_{82}, C_{86}, C_{52}) (Table 17). Likewise, there is a shortcut between C_{97} and C_{21} in W_5, which changes the assignment of customers (i.e., more distance is travelled in the first assignment, $39.85 > 39.73$) and consequently one more customer is served in the second assignment to UAV DA5. There is no difference for the delivery assignments in W_2, W_3 and W_4 because there is no shortcut available in these WHs.

b: PREMIUM DELIVERY METHOD IN THE HYBRID SCHEME

This technique works by taking account the points mentioned in both II-D1-b and II-D2-b in such a way that the delivery assignments are carried out with/without using HWs as illustrated in Fig. 6. Routes are determined using optimal delivery method mentioned above if there is no premium order in WH. An example of this approach for W_1 is presented in Fig. 20. Assignments for all WHs are shown in Table 21. The remaining orders in the queue are shown in Table 15. There are two shortcuts between C_{39} and C_{17}, and C_{17} and C_{75} in W_1, thus, two more customer (n $=$ 6; $C_{39} - C_{17} - C_{75}, C_{75}, C_{86}, C_{82}$) are served in W_1 in the first assignment to UAV DB2, as depicted in Table 21 when compared to the premium delivery method using HWs (n $=$ 4; $C_{17}, C_{75}, C_{75}, C_{82}$) (Table 18) and consequently the third UAV, DA6, is not needed to be sent to another mission. Like wise, there is a shortcut between C_{44} and C_{71} in W_4. In a similar comparison, there are two shortcuts between C_{99} and C_{78}, and C_{44} and C_{71} in W_5 which decreases the remaining customer number in queue to 3 from 4. There is no difference for the delivery assignment in W_2, because there is no shortcut available in this WH.

FIGURE 20. Deliveries with the delivery using HWs (up) and using the hybrid scheme (down) for W_1.

c: FIFO DELIVERY METHOD IN THE HYBRID SCHEME

This technique works by taking the points into account that are mentioned in both II-D1-c and II-D2-c in such a way that the delivery assignments are carried out with/without using HWs as illustrated in Fig. 6. An example of this approach for W_1 is presented in the supplementary materials. Assignments for all WHs are shown in Table 22. The remaining orders in the queue are shown in Table 16. The direct delivery connections between the sub-groups (Fig. 6) are shown using dashed line in Table 22. All the orders are assigned to two UAVs (i.e., DB2 and DA1) in W_1 and one of the UAVs (i.e., DA6) is not needed to be sent to another mission. There is no shortcut between the nodes in W_2, that‘s why, there is no difference in routes with the FIFO delivery method using HWs mentioned in Section II-D2. One more customer (i.e., C_{15}) previously in queue (Section II-D2-c; Table 16) is assigned to the UAV DA8 in W_3.

E. DEPLOYMENT OF UAVs TO MISSIONS

UAVs are deployed based on their capabilities presented in Section II-A2 and in Table 1. The objective is to serve as many customers as possible each time with a reduced the air traffic given the delivery scheme and method. UAVs are mainly restricted with the maximum travel distances and cargo capacities. The maximum travel distance must be greater than the mission route distance (i.e., $d_{D_{k_{maxTravel}}} > d_{tot}$) and the

TABLE 22. Assignments with the FIFO delivery using the hybrid scheme.

WH code	Assigned #	UAV code	Route	Max carr.	Max dist.	Distance	Weight
WH_1	6	DA1	$W_1, 6C_{39}, 7C_{17} - 4C_{75}, 5C_{75}, W_1$	4	40	32.69	2.6
WH_1	11	DA6	N/A	4	40	N/A	N/A
WH_1	1	DB2	$W_1, 2C_{82}, 3C_{86}, 1C_{52}, W_1$	6	50	49.74	2.0
WH_2	2	DA2	$W_2, 1C_{54}, 3C_{26}, 4C_{26}, W_2$	4	40	39.82	6.5
WH_2	7	DA7	$W_2, 2C_{94}, W_2$	4	40	26.08	0.7
WH_3	3	DA3	$W_3, 1C_{31}, 3C_{31}, 2C_{37}, 4C_8, W_3$	4	40	35.49	2.8
WH_3	8	DA8	$W_3, 5C_{92}, 6C_{92} - 9C_{15}, 7C_{95}, W_3$	4	40	36.73	5.0
WH_4	4	DA4	$W_4, 3C_{44} - 2C_{71}, 1C_{69}, W_4$	4	40	32.59	1.7
WH_4	9	DA9	$W_4, 4C_{12}, 5C_{77} W_4$	4	40	34.28	3.9
WH_5	5	DA10	$W_5, 1C_{49}, 2C_{99} - 7C_{78}, W_5$	4	40	39.04	2.1
WH_5	10	DA5	$W_5, 3C_{98}, 5C_{21}, 4C_{97}, W_5$	4	40	39.85	5.7
WH_5	N/A	DB1	N/A: Reserved for WHs	6	100	N/A	N/A

TABLE 23. Abbreviations for result analysis.

Abbreviation	Stands for
TotD-Q (WH-1)	The total distance travelled by UAVs in WH1 after the queue distance is removed
TotD-Q (WH-2)	The total distance travelled by UAVs in WH2 after the queue distance is removed
TotD-Q (WH-3)	The total distance travelled by UAVs in WH3 after the queue distance is removed
TotD-Q (WH-4)	The total distance travelled by UAVs in WH4 after the queue distance is removed
TotD-Q (WH-5)	The total distance travelled by UAVs in WH5 after the queue distance is removed
AllTotD-Q	The total measurement in 5 WHs mentioned above
QTOT	The total measurement of queue distances in 5 WHs
AllDistTot	The total measurement of all distances in 5 WHs including queue distances
#C(all-Q)	The total number of the customers served by UAVs in 5 WHs
#O(all-Q)	The total number of the orders served by UAVs in 5 WHs
#C(Q)	The total number of the customers in queues in 5 WHs
#O(Q)	The total number of the orders in queues in 5 WHs
#C(all)	The total number of the customers in 5 WHs including the customers in the queue
#O(all)	The total number of the orders in 5 WHs including the orders in the queue

total cargo capacity must be greater than the total weight of all parcels (i.e., $\varpi_{D_{k_{maxTravel}}} > \varpi_{tot} = \sum_{m=1}^{q} \varpi_{P_{C_{tm}}}$, where ϖ_{tot} indicates the total weight of all parcels, q indicates the number of orders, $\varpi_{P_{C_{tm}}}$ indicates the weight of the m^{th} order of the customer C_t). The maximum delivery distance of a UAV becomes shorter as the total load increases. A correlation function should be provided by the companies that produce UAVs to do accurate measurements. We were not able to find a similar correlation function provided by UAV companies and in our experimental design, the user can define this correlation in a function defined as $f(d, \varpi) = (d * \varpi)/(d_u * \varpi_u)$, where d indicates the distance, ϖ indicates the total cargo load, d_u indicates the unit distance and ϖ_u indicates the unit cargo load. The function (the loss of the maximum distance) can be found for each UAV using the application interface based on the specific values of d and ϖ for each UAV and unit parameters, d_u and ϖ_u defined by the user. For instance, the maximum distance that a UAV can travel is shortened 1 mile for ϖ_u kg cargo weight (e.g., 5 kg) in a travel distance of d_u miles (e.g., 25 miles) in our experimental set-up. The weight reduces as the parcels are delivered at the nodes and the total loss of distance based on the changing cargo weight carried is measured as in Eq. (11), as shown at the bottom of this page, where n is the number of customers, q is the number of parcels ordered by each customer and α is the number of the previous customers visited by a UAV at a node along with orders delivered. The constrained total travel distance is indicated by $d_{D_{k_{travelLimit}}}$, whereas $d_{totLoss_{D_k}}$ denotes the travel distance loss due to the weight carried on the k^{th} drone. UAVs are deployed in terms of routes explored in preceding sections.

III. RESULTS AND DISCUSSIONS

In this study a sophisticated multi-variable dynamic delivery problem is solved and in this sense, different approaches are discussed to find out the optimal visual delivery decision using the optimal available route. The data in this multi-dimensional problem space are projected from a high dimensional space down to a low dimensional space not only for the purpose of visualization, but also for efficient and robust implementation of the problem as mentioned in Section II. To the extent of our knowledge, this treatise is the only comprehensive analysis of several delivery methods (i.e., optimal, premium and FIFO) along with several delivery schemes (i.e., delivery with and without using air HWs, and delivery using a hybrid scheme) using a 3D route planning. It incorporates new techniques into well-known approaches to deploy UAVs in the optimal possible way as part of the logistic operations by orchestrating the resources in a multi dimensional complexity (i.e., mWmDmCmH).

Two scenarios were analyzed to explore the outcomes of the UAV delivery system given the components, delivery scheme/method and constraints. The first scenario was validated using relatively small data sets (i.e., small number of customers and orders) by taking into account several number of UAVs (i.e., 2-3) in each WHs. For the second scenario, the amount of UAVs, customers and orders were doubled to observe the results regarding bigger data sets in order to exhibit the scalability of our proposed delivery platform. These two scenarios were tested 25 times with the same number of customers, orders, but different customers and orders with different features created by the application randomly as mentioned in Section II and there was no significant difference between the results and mean values after 25 trials based on the statistical Z-test, which confirmed that 25 trials would be sufficient for a safe conclusion. Indeed, for the first scenario on small dataset, we observed similar results in each tests. The results of one of these tests are explained throughout the manuscript in details with the aid of figures and tables. Regarding this scenario, assignments and routes of the 5 WHs and remaining queues in terms of delivery schemes and methods are presented in Table 24 and

$$\begin{aligned} d_{D_{k_{travelLimit}}} &= d_{D_{k_{maxTravel}}} - d_{totLoss_{D_k}}, \\ \Longrightarrow d_{totLoss_{D_k}} &= d_{Loss_{W_j C_1}} + \Big(\sum_{i=1}^{n-1} f\big(d_{C_i C_{i+1}}, (\varpi_{tot} - \sum_{t=1}^{\alpha} \sum_{m=1}^{q} \varpi_{P_{C_{tm}}})\big)\Big) + d_{Loss_{C_n W_j}}, \\ &\text{where } d_{Loss_{W_j C_1}} = f(d_{W_j C_1}, \varpi_{tot}) \quad \text{and} \quad d_{Loss_{(C_n W_j)}} = 0 \quad \text{and} \quad \forall C_i \in W_j, P_{C_{tm}} \in C_t. \end{aligned} \tag{11}$$

TABLE 24. **The assignment results of the 5 WHs and remaining queues acquired throughout the manuscript in terms of delivery schemes and methods: the results are presented in Figs. 21 and 22. The explanations of the headings used in the table are as follows, where a comprehensive abbreviation list can also be found in Table 23: Dist=distance travelled by all UAVs; C=# of customers; O=# of orders delivered; TotD=total distance travelled by all UAVs in terms of WHs including the distance to be travelled for the customers in the queue; DTOT= all the total distance including the distances in the queue for all WHs; QTOT= all the total distance to be travelled to deliver the orders in the queue for all WHs.**

	WH-1-													WH-2-										WH-3-										WH-4-										WH-5-										All WHs			
Scheme & Method	Assignment-1-			Assignment-2-			Assignment-3-			Queue				Assignment-1-			Assignment-2-			Queue				Assignment-1-			Assignment-2-			Queue				Assignment-1-			Assignment-2-			Queue				Assignment-1-			Assignment-2-			Queue				General Totals			
Optimum scheme	Dist	C	O	Dist	C	O	Dist	C	O	Dist	C	O	TotD	Dist	C	O	Dist	C	O	Dist	C	O	TotD	Dist	C	O	Dist	C	O	Dist	C	O	TotD	Dist	C	O	Dist	C	O	Dist	C	O	TotD	Dist	C	O	Dist	C	O	Dist	C	O	TotD	DTOT	C	O	QTOT
Optimal delivery	49.50	5	5	39.91	2	3	37.62	1	2	41.18	1	1	168.21	38.32	3	4	31.38	1	1	47.19	2	2	116.89	39.90	4	4	28.37	3	4	9.39	2	3	77.66	39.80	3	4	38.10	4	4	43.65	3	3	121.55	39.98	4	4	39.15	4	4	48.99	2	2	128.12	612.43	34	39	190.40
Premium delivery	47.31	5	6	37.62	1	2	29.87	1	1	43.58	2	2	158.38	37.18	3	4	35.14	2	2	27.98	1	1	100.30	34.62	3	4	39.76	3	4	36.95	3	3	111.33	38.33	4	4	38.94	4	4	38.13	2	3	115.40	39.70	4	4	36.13	3	3	50.56	3	3	126.39	611.80	34	38	197.20
FIFO delivery	45.50	2	3	26.71	3	4	16.40	2	2	57.80	2	2	146.41	37.18	3	4	35.14	2	2	27.98	1	1	100.30	25.60	3	4	38.30	3	4	36.92	3	3	100.82	28.30	4	4	39.80	3	4	54.07	3	3	122.17	37.58	4	4	39.12	3	3	59.67	3	3	136.37	606.07	33	38	236.44
Higway scheme																																																											
Optimal delivery	49.74	3	3	37.99	2	2	25.52	1	2	N/A	N/A	N/A	113.25	39.82	2	3	26.08	1	1	18.62	1	1	84.52	39.69	3	3	37.06	2	3	41.49	3	4	118.24	39.90	3	3	35.37	2	2	42.64	2	2	117.91	39.73	3	3	38.68	2	2	81.88	4	4	160.29	594.21	24	27	184.63
Premium delivery	44.30	3	4	30.67	1	1	27.18	1	1	20.07	1	1	143.33	39.82	2	3	26.08	1	1	18.62	1	1	84.52	36.97	3	4	26.00	3	4	55.26	2	2	118.23	39.71	3	3	35.37	2	2	38.56	2	2	113.64	39.62	3	3	36.20	2	2	91.24	4	4	167.06	626.78	24	28	223.75
FIFO delivery	49.74	3	3	35.48	2	3	27.18	1	1	N/A	N/A	N/A	112.40	39.82	2	3	26.08	1	1	18.62	1	1	84.52	35.49	3	4	32.32	2	3	50.42	3	3	118.23	36.29	3	3	34.28	2	2	31.56	2	2	102.13	39.73	3	3	38.68	2	2	92.59	4	4	171.00	588.28	24	28	193.19
Mixture scheme																																																											
Optimal delivery	47.56	5	6	30.67	1	1	N/A	N/A	N/A	N/A	N/A	N/A	78.23	39.82	2	3	26.08	1	1	18.62	1	1	84.52	39.69	3	3	37.06	2	3	41.49	3	4	118.24	39.90	3	3	35.37	2	2	42.64	2	2	117.91	39.85	3	3	39.04	3	3	69.65	3	3	148.54	547.44	25	28	172.40
Premium delivery	47.56	5	6	30.67	1	1	N/A	N/A	N/A	N/A	N/A	N/A	78.23	39.82	2	3	26.08	1	1	18.62	1	1	84.52	36.97	3	4	16.45	3	4	55.26	2	2	108.68	39.71	3	3	38.95	3	3	19.30	1	1	97.96	39.04	3	3	32.59	3	3	69.65	3	3	141.28	510.67	27	31	162.83
FIFO delivery	49.74	3	3	32.69	3	4	N/A	N/A	N/A	N/A	N/A	N/A	82.43	39.82	2	3	26.08	1	1	18.62	1	1	84.52	35.49	3	4	36.73	3	4	40.05	2	2	112.27	32.59	3	3	34.28	2	2	18.78	2	2	85.65	39.04	3	3	39.85	3	3	69.65	3	3	148.54	513.41	26	30	147.10

TABLE 25. **The totals of all schemes and methods presented in Table 24: the values that produce this table are presented in Fig. 23. The explanations of the headings different from the legend in the table above used in this table are as follows: Q=queue; AllTotD=all total distance including the distance in the queue, where a comprehensive abbreviation list can also be found in Table 23.**

Optimum scheme	TotD-Q (WH-1)	TotD-Q (WH-2)	TotD-Q (WH-3)	TotD-Q (WH-4)	TotD-Q (WH-5)	AllTotD-Q	QTOT	AllDistTot	#C(all-Q)	#O(all-Q)	#C(Q)	#O(Q)	#C(all)	#O(all)
Optimal delivery	127.03	69.7	68.27	77.9	79.13	422.03	190.4	612.43	34	39	10	11	44	50
premium delivery	114.8	72.32	74.38	77.27	75.83	414.6	197.2	611.8	33	38	11	12	44	50
FIFO delivery	88.61	72.32	63.9	68.1	76.7	369.63	236.44	606.07	32	38	12	12	44	50
Higway scheme														
Optimal delivery	113.25	65.9	76.75	75.27	78.41	409.58	184.63	594.21	24	27	10	11	34	38
premium delivery	102.15	65.9	62.97	75.08	75.82	381.92	223.75	605.67	24	28	10	10	34	38
FIFO delivery	112.4	65.9	67.81	70.57	78.41	395.09	193.19	588.28	24	28	10	10	34	38
Mixture scheme														
Optimal delivery	78.23	65.9	76.75	75.27	78.89	375.04	172.4	547.44	25	28	9	10	34	38
premium delivery	78.23	65.9	53.42	78.66	71.63	347.84	162.83	510.67	27	31	7	7	34	38
FIFO delivery	82.43	65.9	72.22	66.87	78.89	366.31	147.1	513.41	26	30	8	8	34	38

TABLE 26. **The mean totals of all schemes for 25 different results where two more UAVs are added to WHs and the number of customers and orders are doubled compared to the previous experiment mentioned throughout the manuscript and presented in Table 24: these results are presented in Fig. 23. A comprehensive abbreviation list can be found in Table 23.**

Optimum scheme	TotD-Q (WH-1)	TotD-Q (WH-2)	TotD-Q (WH-3)	TotD-Q (WH-4)	TotD-Q (WH-5)	AllTotD-Q	QTOT	AllDistTot	#C(all-Q)	#O(all-Q)	#C(Q)	#O(Q)	#C(all)	#O(all)
Optimal delivery	234	128	126	143	146	777	98	874	75	85	13	15	88	100
Premium delivery	201	127	130	135	133	726	174	899	70	80	18	20	88	100
FIFO delivery	155	127	112	119	134	647	274	921	67	79	21	21	88	100
Higway scheme														
Optimal delivery	204	119	138	135	141	737	109	846	56	62	12	14	68	76
Premium delivery	179	115	110	131	133	668	289	957	51	59	17	17	68	76
FIFO delivery	185	109	112	116	129	652	250	901	52	60	16	16	68	76
Mixture scheme														
Optimal delivery	156	131	153	150	157	746	78	825	62	68	6	8	68	76
Premium delivery	146	123	100	147	134	650	192	842	57	65	11	11	68	76
FIFO delivery	152	122	134	124	146	678	191	869	55	63	13	13	68	76

summarized in Table 25. These results are concisely exhibited in Figs. 21, 22. For the second scenario on larger dataset, different results were observed from each test. The total mean results of all schemes for these 25 different experimental results are presented in Table 26 and summarized in Fig. 23.

In the first scenario on the small dataset: 1) the first assignments of the optimal method use the resources better than the other two methods (premium and FIFO), particularly in terms of the number of served customers and using the distance effectively with respect to the maximum travel distances of UAVs; 2) however, the results in second assignments of either the premium or FIFO method are similar to or better than the results of optimal method, except the assignments in WH_1 that has a third assignment to another UAV as seen in Table 24; 3) in terms of the total results of delivery scheme without HWs, particularly all the totals of the distances travelled i.e., AllTotD-Q (for the abbreviations please refer to Table 23) in Fig. 23, optimal delivery method works better (i.e., 422) than the other two delivery methods (i.e., 414 and 369 respectively for premium and FIFO methods) with the number of customers 34 compared to the number of the customers, 33 and 32. The remaining total queue distances (QTOT) to be travelled for the remaining customers in the queues are less for the optimal delivery (i.e., 190) than those of the other two methods (i.e., 197, 236). The statistical significance of the differences between the methods was analyzed and the Z-test was applied on the data that are normally distributed. The null hypothesis, that there is no significant difference between the results of optimal delivery method and those of premium (i.e., AllTotD-Q) ($\mu = \mu_0$), can be verified with $p > 0.01$. On the other hand, the same null hypothesis between the results of optimal delivery method and those of FIFO ($\mu = \mu_0$), can be rejected, with $p<0.01$. With regard to the total number of customers served (#C(all-Q)), there is no statistically significant difference between the optimal method (i.e., 34) and premium (i.e., 33) and FIFO (i.e., 32) methods regarding the number of customers served; 4) the optimal delivery method gives better results for the first and second assignments for the HW scheme. The results are similar for the hybrid scheme in the first assignments, but, optimal assignments do not give better results in the second assignments; 5) the first assignments of the optimal method for each scheme use the resources better than the other two methods as it is seen in Figs. 21 and 22. However, the second assignments of the premium and FIFO methods for the scheme without HWs might be better than the optimal delivery based on the distribution of remaining resources, customers and orders; 6) furthermore, more customers (i.e., 25, 27, 26) in the hybrid scheme are served with far less distances (375, 347, 366) compared to the HW scheme in which the numbers of customers are 24, 24 and 24 with distances 409, 381 and 395 respectively in regard to the delivery methods, optimal, premium and FIFO as shown in Fig. 23. The results of the hybrid scheme are significantly

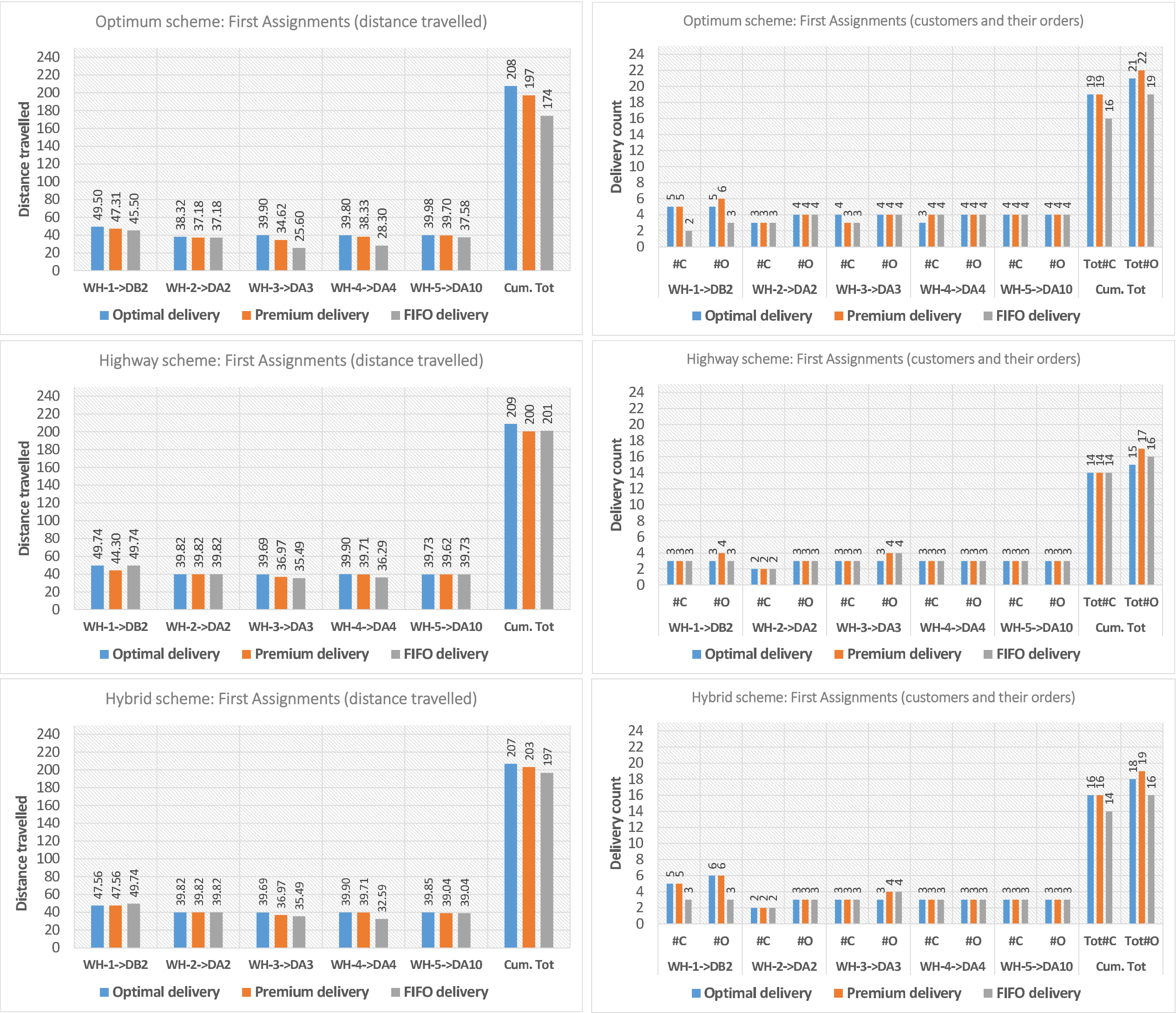

FIGURE 21. **Results of the first assignments of optimum (up), HW (middle) and hybrid (bottom) schemes.**

different from (i.e., better than) the HW scheme ($p<0.01$); 7) the final results converge to almost similar results as displayed in Fig. 23 (i.e., smaller AllDistTot values are desirable, occasionally premium and FIFO delivery methods provide better results).

In the second scenario with bigger dataset, the optimal delivery method outperforms in each method as displayed in Fig. 23 although the efficacy of the method decreases for further assignments (steeply after the first assignments) as the remaining number of customers decreases and the distribution of customers in terms of the distances to each other is not ideally located compared to other delivery methods.

While this treatise assumes total delivery cost based on the cumulative route optimization, which are identified as delivery schemes and methods, relevant objective functions may be considered for different type of environment. For example, one of the potential problems in UAV delivery is the city restrictions, which indeed directly affect the delivery business. It would be interesting to see how our delivery platform techniques would perform in an urban scenario depicting a crowded city with many human-created structures. Additionally, drone's interference with aircrafts may cause potential problems, which this circumstance likely lies within the drone law along with the other city restrictions and regulations in a realistic manner and include them in the optimization problem formulation. From the point of a real-world deployment of such drone delivery platforms, drones, at the time of delivery, may face numerous cyber-physical security issues. As a countermeasure, one can adopt some of the strategies mentioned in [34] in order to increase the safety of the delivery routes and build novel techniques to avoid delivery delays. In this context, heuristic algorithms proposed

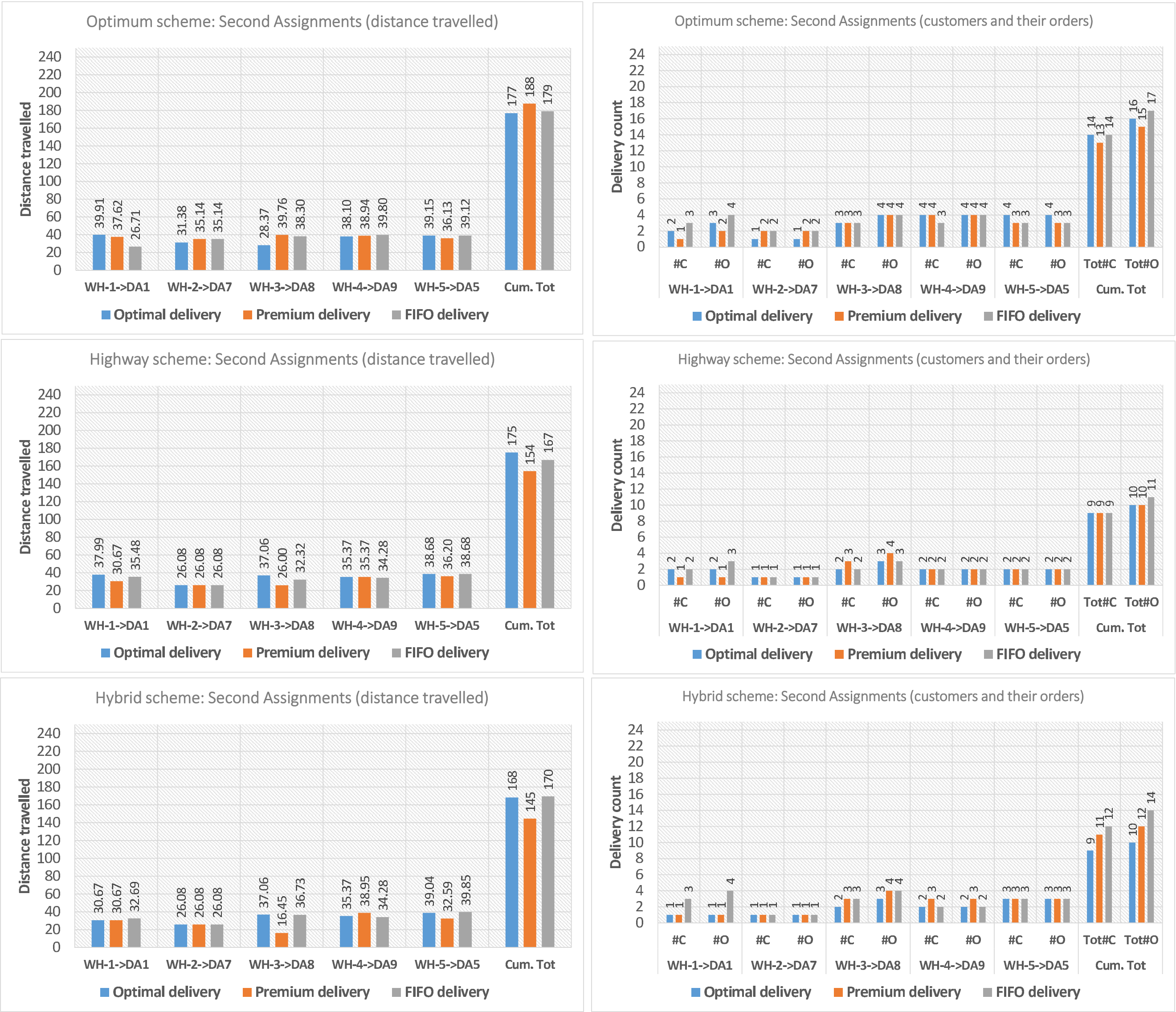

FIGURE 22. Results of the second assignments of optimum (up), HW (middle) and hybrid (bottom) schemes.

by Yang and Yoo [21] may help in finding the optimized route considering sensing, energy, delay and risk metrics by means of a multi-objective design. Moreover, the concept of Internet of Drones (IoD) [29] can be applied in our delivery platform in order to manage delivery traffic more effectively. In this manner, this study also aims to direct researchers in this particular field, who would like to narrow down the literature gap in intelligent delivery platforms using UAVs.

IV. LESSONS LEARNED

The number of drones in use with new features is increasing exponentially and new methods and techniques are urgently required to manage this complex problem space. In this manner, a technique (dMAiMD) is proposed and analyzed in scenarios in this study to direct how to result in optimum solutions in similar multi-dimensional problem spaces. In addition, a dynamic hybrid delivery scheme is built and analyzed along with several other approaches. Similar dynamic approaches should be implemented to overcome the challenges in a dynamically changing environment.

The capabilities of drones (e.g., payloads, carriers, travel distance) should be improved to increase the efficacy of UAVs in delivery system. In particular, a UAV should be able to carry several packages at a time in a sortie. With similar simulation analysis, better decisions can be given based on the acquired results (e.g., better locations can be found for current and future WHs; the optimal delivery method and scheme can be determined).

In the view of the results given above, we can conclude that effective assignments of parcels to UAVs in optimal delivery method decreases for consecutive assignments. This is because, remaining customers are not ideally located and

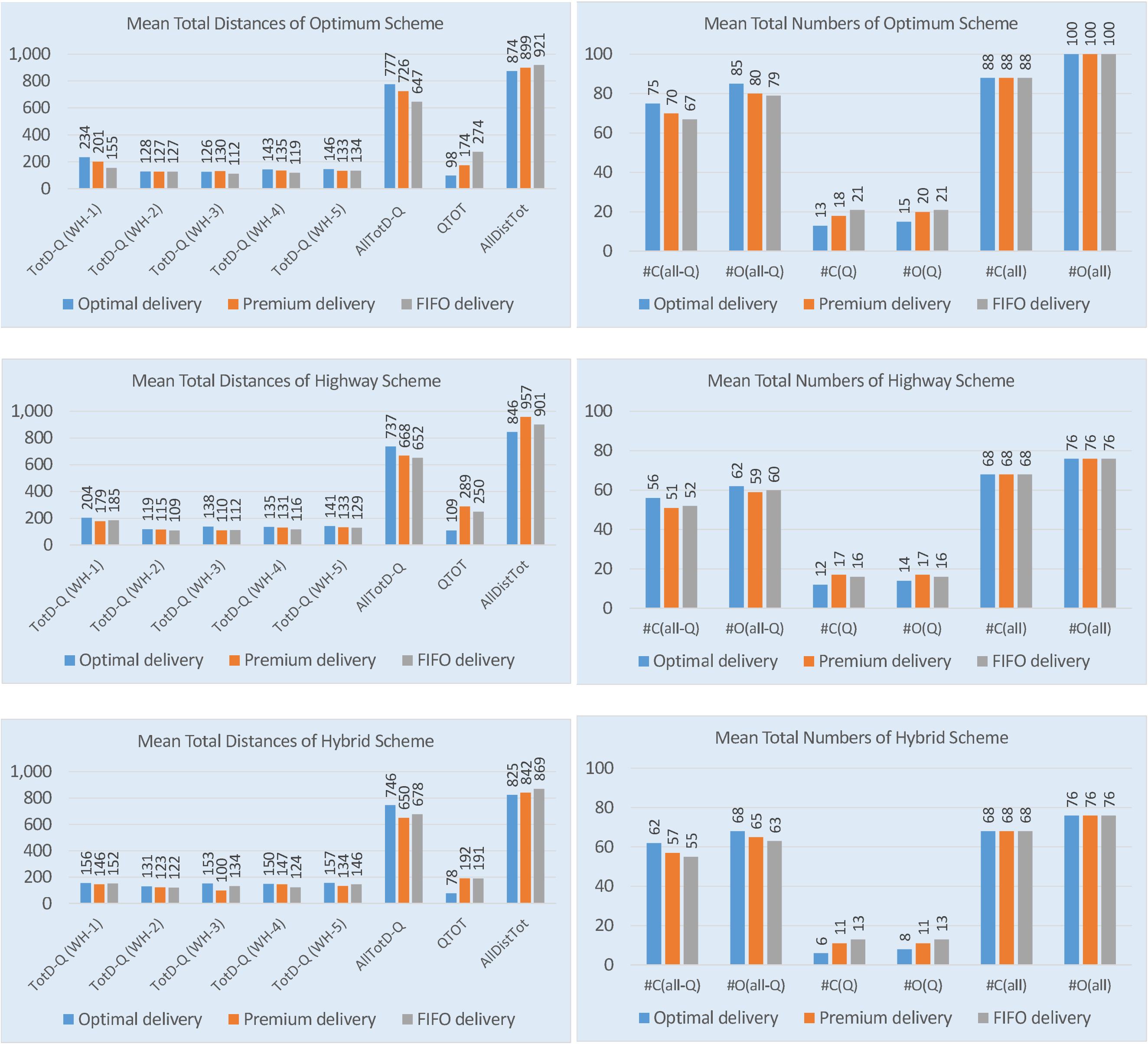

FIGURE 23. **Schematic presentation of the results given in Table 26.**

less number of customers remain due to the optimal selection process in preceding assignments. In other words, effective use of resources on small datasets for further assignments are better using other delivery methods (i.e., premium and FIFO methods) because the preceding assignments in these methods are not performed as effective as the ones in the optimal delivery method. In this manner, in terms of overall efficacy of the system, optimal delivery method for small number of customers, orders and UAVs may not be required and fair delivery using FIFO based on first-in-first-served and premium based on the prioritization of customers can be carried out without increasing the air traffic. However, the use of the optimal delivery method for large number of customers and orders with more UAVs would result better than the other two methods (i.e., premium and FIFO). The optimal delivery method is advantages if all the parcels can be delivered by the UAVs in a WH in the first assignments.

The results above suggest that premium and FIFO delivery methods increase the air traffic of UAVs when compared to the optimal method in terms of optimal use of resources as the number of customers and orders increases. In addition, we demonstrate that the hybrid scheme can be deployed to exploit the dynamic characteristics of the system components: a small sacrifice from using air HWs increases the overall performance of the system significantly.

Considering the above-mentioned characteristics of our delivery platform, the main lessons we learned can be outlined as follows:

1) the use of the resources including their dynamic environments can be illustrated in a virtual reality interface (e.g., the routes of UAVs are animated on a map);
2) our proposed platform can readily adapt to the dynamic characteristics of the system components (e.g., one of the UAVs in a WH may be out of order or a new UAV with different features may be deployed);
3) this platform can be easily merged with the systems of delivery companies that would like to incorporate UAVs into their delivery systems;
4) the delivery approaches can be merged with the conventional delivery scheme in such a way that orders can be carried to a point near to customers or HWs where they can be delivered using UAVs by employing the aforementioned delivery schemes and methods;
5) furthermore, humanitarian missions can be supported with regard to the emergency management following a natural disaster such as floods, earthquakes, and wildfires to assist victims and emergency responders such as providing medical aid, rescue tools and food;
6) various scenarios can be simulated and analyzed based on the delivery schemes and methods by changing the number and characteristics of the system components.

V. CONCLUSIONS AND FUTURE RESEARCH IDEAS

In the study: 1) several routing approaches for several delivery schemes are suggested; 2) cross-entropy Monte Carlo technique is first-ever employed successfully on the delivery scheme using HWs for finding optimal routes for UAVs; 3) route planning and task assignment along with several hybrid approaches are forged together to manage the complexity of the problem space in mWmDmCmH using a novel dynamic task assignment approach, dMAiMD; 4) a new delivery scheme, so-called the hybrid delivery scheme is built as a good candidate to be dictated by aviation authorities to control and reduce the air traffic dynamically based on the current changing components and environments, e.g. congested and sparse areas, capability of UAVs. The approaches and techniques built in this study and the results discussed in the above sections may guide aviation authority and related companies in several aspects: 1) the aviation authorities can test the effectiveness of their rules for various environments and can modify their rules accordingly regarding less air traffic and more safety by engaging in the approaches proposed; 2) companies that aim to deliver their products using UAVs can test all their delivery system by employing our proposed techniques in order to make better-informed decisions. They can also determine what the requirements are for their achievable objectives, particularly in procurement of their resources and deciding on their delivery locations; 3) companies that produce UAVs can test the potency of their UAVs with improving battery performance over time. They can determine how they can improve their products and find out the directions to meet the market needs. Additionally, private industries, logistics operators, municipalities are expected to benefit from the potential adoption of the simulator in strategic decisions before embarking on the practical implementation of UAV delivery systems.

In future research considerations: 1) experiments that scale the techniques in outdoor implementations will be performed, and 2) our proposed platform will be extended to incorporate the concept of Internet of Drones (IoD) into our approaches to establish a compact delivery system that is capable of working harmoniously within cyber-physical smart domains (e.g., smart city, smart home, smart building, in particular, smart transportation) and platforms (i.e., cloud, fog and edge).

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