In the context of post-disaster situation, a cooperative two-echelon truck and drone system is formally proposed in this section. Trucks are ground vehicles and use transportation network, and drones are aerial vehicles and can go to any node from another node, therefore the graph of drone routes is a complete graph. Considering first echelon trucks and second echelon drones traverse through the edges of the undirected graphs and complete graph , respectively, where is the set of good edges of the transportation network containing nodes, and is the set of all edges among the nodes in . The customers on the better side of the transportation network are expected to get delivery from truck and the customers on the disrupted side are expected to get delivery from drones. Assuming the set contains all the customer nodes, and they are partitioned into truck customers, rendezvous nodes (which are also truck customers) and drone customers as and , respectively, and . The set of the depot node is denoted as , nodes of the transportation network , and nodes of the drone network . The graph represents the ground transportation network, and the graph represents the aerial transportation network of the disaster-affected area. In this problem setting, emergency supplies are delivered from a depot location to the customer locations by cooperative truck and drone operations, and the objective is to minimize the total routing cost of trucks and drones. The most important assumptions of this problem are as follows:

* Multiple number of trucks are available at the depot
* Each truck can carry multiple drones
* There is a payload capacity limit for each truck and drone
* A drone can serve multiple people in a single flight
* Trapped people are served by drones
* Truck customers are served by trucks and drone customers are served by drones
* Payload capacity and flying range limitations may put some drone customers unserved
* Every deployed drone must return to its carrier truck at the end of its flight.

For developing the mathematical formulations of the proposed last-mile distribution system, the necessary parameters and variables are presented in Table 1 and Table 2, respectively.

Table 1: List of parameters

|  |  |
| --- | --- |
| Symbol | Parameter Name |
|  | Number of first echelon trucks at the depot |
|  | Number of drones carried by each truck |
|  | Payload capacity of each UAV |
|  | Demand of customer |
|  | Road distance between nodes and , where |
|  | Aerial distance between nodes and , where |
|  | Drone travel time between nodes and , where |
|  | Maximum battery usage time limit of a drone |

Table 2: List of variables

|  |  |
| --- | --- |
| Symbol | Variable Name |
|  | Binary variable and its value equals to 1 if a first echelon truck visits node from node , where . |
|  | Binary variable and its value equals to 1 if arc is traversed by a drone deployed from rendezvous node or satellite . |
|  | Continuous variable and its value is the node potential of node which is used in the subtour elimination constraints for first echelon trucks. |
|  | Continuous variable and its value is the node potential of node which is used in the subtour elimination constraints for second echelon UAVs. |
|  | Flight time of drone at satellite . |

The mixed-integer linear programming formulation for the cooperative two-echelon truck and drone routing problem is

|  |  |  |  |
| --- | --- | --- | --- |
| min |  |  | (1a) |
|  |  |  | (1b) |
|  |  |  | (1c) |
|  |  |  | (1d) |
|  |  |  | (1e) |
|  |  |  | (1f) |
|  |  |  | (1g) |
|  |  |  | (1h) |
|  |  |  | (1i) |
|  |  |  | (1j) |
|  |  |  | (1k) |
|  |  |  | (1l) |
|  |  |  | (1m) |
|  |  |  | (1n) |
|  |  |  | (1o) |
|  |  |  | (1p) |
|  |  |  | (1q) |

The objective function (1a) minimizes the global routing cost of the first echelon trucks and second echelon drones. Constraint (1b) ensures that each truck customer get emergency supplies from a truck. Constraints (1c) ensure the flow balance of the first echelon trucks. Constraints (1d) are the Miller-Tucker-Zemlin (MTZ) subtour elimination constraints of truck routes. Constraint (1e) ensures that number of trucks must be deployed from the depot node. Constraints (1f) ensure that a drone customer is satisfied if it is within the flying range limitation of a drone. Constraints (1g) are the flow balance constraints of the drone routes. Constraints (1h) are the capacitated MTZ constraints for the drone routes. Constraints (1i) ensure that maximum number of drones can be deployed from a rendezvous node. Constraints (1j) ensure that no drone should have different launching and landing rendezvous nodes in a single flight. Constraints (1k) and (1l) ensure that each drone path must satisfy maximum flying time limitation. Constraints (1m) to (1q) impose restrictions on the binary and continuous variables of the model.