Applied Computer Science, vol. 15, no. 3, pp. 5–20
doi:10.23743/acs-2019-17

Submitted: 2019-08-23
Revised: 2019-09-03
Accepted: 2019-09-11

optimization, UAVs , routing and scheduling

Grzegorz RADZKI [0000-0002-0688-1764]*,
Amila THIBBOTUWAWA [0000-0002-5443-8839]**,
Grzegorz BOCEWICZ [0000-0002-5181-2872]*

UAVS FLIGHT ROUTES OPTIMIZATION IN CHANGING WEATHER CONDITIONS – CONSTRAINT PROGRAMMING APPROACH

Abstract

The problem of delivering goods in a distribution network is considered in which a fleet of Unmanned Aerial Vehicles (UAV) carries out transport operations. The changing weather conditions in which the transport operations take place and the UAVs energy capacity levels influenced by the weather conditions are taken into account as factors that affect the determination of a collision-free route. The goods must be delivered to the customers in a given time window. Establishing the routes are the focus of this study. Solutions maximizing the level of customer satisfaction are focused and the computational experiments presented in the study show the impact of weather conditions on route determination.

1. INTRODUCTION

Every day, transport companies face the challenge of keeping their outlays as small as possible while making sure that the customers are fully satisfied. Decision support in this domain often comes down to solving an appropriate Vehicle Routing Problem (VRP) (Adbelhafiz, Mostafa & Girard, 2010).

* Koszalin University of Technology, Department of Computer Science and Management, Sniadeckich 2, Koszalin, Poland, radzki.grzegorz@gmail.com, bocewicz@ie.tu.koszalin.pl
** Aalborg University, Department of Materials and Production, Aalborg, Denmark, amila@mp.aau.dk

The dynamic development of unmanned aerial vehicle (UAV) technology in the recent decade has allowed the use of those machines, commonly referred to as drones, for the logistic services mainly in transportation of goods. Transportation companies quickly came to realize that the delivery of goods to customers by UAVs was associated with numerous benefits such as a short delivery time, easy movement (e.g. less traffic congestion), lower energy costs and reduced operational costs. It was also noticed that such solutions had no adverse effect on the environment and enables sustainable logistics operations (Chiang, Li, Shang & Urban, 2019).

The use of UAVs for transportation tasks, however, gives rise to new challenges related to the organization of transport. Typical limitations of air transport systems that use UAVs include the need for periodical (frequent) battery replacement, a pre-determined distance range limited by battery capacity, a limited payload capacity, the possibility of collision between UAVs performing their missions, etc. (Bocewicz, Nielsen, Banaszak & Thibbotuwawa, 2019).

Viewed in this way, the problem under consideration is an extension of the classical VRP that takes into account the weather-related changeable energy consumption (Adbelhafiz, Mostafa & Girard, 2010). In general, this type of problem belongs to the class of NP-hard problems (Bocewicz, Nielsen, Banaszak & Thibbotuwawa, 2019). The model of the VRP developed in this study, which is implemented in a constraint programming environment (IBM ILOG) assumes that energy consumption is a non-linear function that depends on weather conditions, carrying payload, UAVs' "geometry" (Thibbotuwawa, Nielsen, Zbigniew & Bocewicz, 2018a) and the flight trajectory (route) (Guerriero, Surace, Loscrí & Natalizio, 2014). The goal is to find flight mission plans (routings and schedules) which are collision-free and allow to maximize the quantity of goods delivered to customers by a fleet of UAVs with energy capacity limit flying in a given weather condition.

The paper is organized as follows: Section 2 discusses the state-of-the-art on the subject. Section 3 provides an example illustrating the UAV routing problem. Sections 4 and 5 present the proposed model and formulation of the problem. Section 6 reports experiments, which were conducted to verify the correctness of the model. The experiments were carried out in the IBM ILOG declarative programming environment. This illustrate the possibilities of practical application of the proposed solution. The key conclusions are formulated and the main directions of future research are suggested in Section 7.

2. LITERATURE REVIEW

The problem of transporting goods by UAVs is an extension of VRP. In the simplest version, the VRP assumes that one type of product is delivered using one mode of transport. Solutions are sought to minimize the total cost of travel (Golden, Raghavan & Wasil, 2011). The VRP extended to include the assumption that goods should be delivered to customers within specific time intervals is called the Vehicle Routing Problem with Time Windows (VRPTW). It is this type of problem that is most commonly encountered in practice. VRPTW for UAVs are used in both military and civilian settings (Adbelhafiz, Mostafa & Girard, 2010; Yakıcı, 2016; Ullah, et al., 2019).

According to the literature (Bocewicz, Nielsen, Banaszak & Thibbotuwawa, 2019; Chauhan, Unnikrishnan & Figliozzi, 2019; Dai, Fotedar, Radmanesh & Kumar, 2018), the UAV routing problem is usually modeled as a standard VRP with additional constraints reflecting the specific applications of this type of vehicle. The first studies on the UAV routing problem were focused on developing methods that would allow to obtain acceptable solutions within a given time interval. Apart from minimizing the cost of travel, other criteria that must also be considered include: reducing the individual UAVs operation costs (battery consumption), shortening the operation time, and increasing the safety of operations (Enright, Frazzoli, Pavone & Savla, 2014). Another aspect that distinguishes a VRP with UAVs from the standard version of the VRP is the environment in which routes are planned. For surface transport, routes are designed in 2D space (Karpenko, Konovalenko, Miller, Miller & Nikolaev, 2015). By contrast, routes for UAV must be planned in 3D space (Goerzen, Kong & Mettler, 2009). Article (Guerriero, Surace, Loscrí & Natalizio, 2014) presents a mathematical model of routing of UAV in three-dimensional space. It should be noted that the UAV routing approaches found in the literature fail to take into account the variability of weather conditions and the associated non-linearity of energy consumption (Wang, Poikonen & Golden, 2016). Routes established using those methods must be continuously adjusted as the flight progresses. The process of adjustment is very complex and does not protect the mission plan against potential failure due to battery depletion or other causes (Bocewicz, Nielsen, Banaszak & Thibbotuwawa, 2019). Certain studies has formulated the mission planning problem for a fleet of unmanned aerial vehicles (UAVs) as a mixed-integer nonlinear programming problem (MINLP) but approximating the problem of MINLP by a mixed-integer linear program (MILP), and used a solver (GUROBI) (Fügenschuh & Müllenstedt, 2015). They have considered energy limitations of UAVs but has not considered the effects of weather conditions in deriving the energy consumptions and used linier approximations of the energy consumption of UAVs which not realistic in practical context.

An alternative solution is to take into account the uncertainty/variability of weather conditions and the related level of energy consumption already at the stage of planning flight missions. This type of problem is an extension of the VRPTW that incorporates elements related to weather and route-dependent energy consumption (Guerriero, Surace, Loscrí & Natalizio, 2014). Studies (Thibbotuwawa, Nielsen, Zbigniew & Bocewicz, 2018a, 2018b) propose preliminary heuristics that allow to find such solutions. The present paper expands on these studies by using a declarative programming environment (IBM ILOG).

3. A MOTIVATION EXAMPLE

The problem studied can be described as follows: Given is a company that provides air transport services using a fleet of UAVs. In the case under consideration, the fleet consists of three UAVs with identical technical parameters (Tab. 1). The UAVs deliver goods to six customers located in an area covering 10 km^2 – the network of connections is shown in Fig. 1. Vertex N_1 marks the location of the company (the base which the UAVs take off from/land at) and vertices N_2–N_7 mark the locations of the individual customers. It is assumed that UAVs travel at a constant speed v = 20 m/s. The flight times along edge $\{N_i,N_j\}$ of the graph are shown in Fig. 1. For example, the flight time between node N_6 and node N_2 is 185 seconds.

Known is the demand of the individual customers for the goods transported by the UAVs (Tab. 2). It is assumed that the UAVs must deliver the exact quantity of goods demanded by a given customer.

Tab. 1. Technical parameters of UAVs

Technical parameters of UAVs	Value	Unit
Payload capacity Q	100	kg
Battery capacity CAP	6000	kJ
Flight speed v	20	m/s
Drag coefficient C_D	0.54	–
Front surface of UAV A	1.2	m
UAV width b	8.7	m

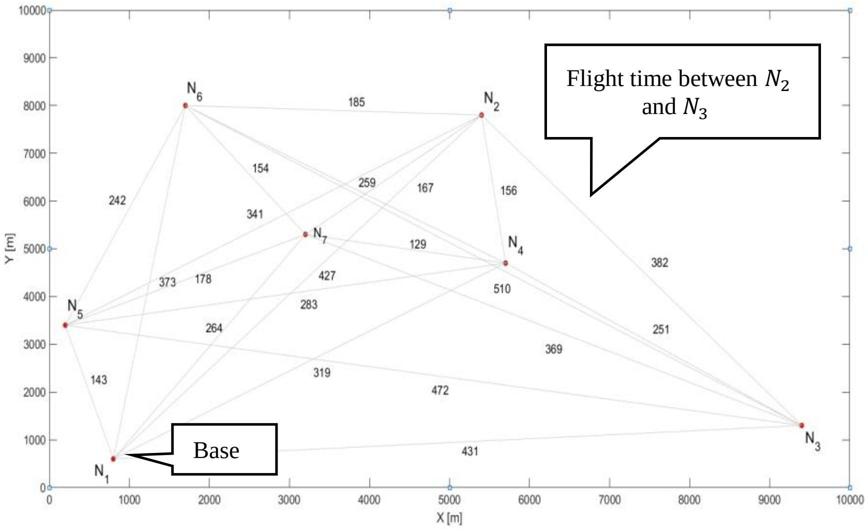

Fig.1. Map of drop-off locations

Tab. 2. Customer demand for transported goods

Node	Demand for goods [kg]
N1	0
N2	60
N3	70
N4	30
N5	40
N6	20
N7	30

Tab. 3. Weather conditions

Weather conditions	**Value**	**Unit**
Wind speed v_w	10	m/s
Wind direction Θ	30	°
Air density D	1.225	kg/m^3

It is additionally assumed that goods are transported in various weather conditions which affect the rate of battery discharge (the speed and direction of wind are both taken into account – Tab. 3). It is assumed that each of the UAVs must travel at the given constant flight speed (v = 20 m/s) regardless of atmospheric conditions. This means that the adoption of fixed, time-invariable delivery plans (that include UAV routes and flight schedules) may result in varying degrees of battery utilization and, in special cases, complete battery depletion. Fig. 2 presents an example of UAV flight routings and schedule that guarantee that the requested goods are delivered to customers (100% customer satisfaction) in the given weather conditions (Tab. 3). As it is easy to see, in this set-up, the freight will be delivered in under 2000 s.

In this set-up, UAVs move along routes Π: Π_1 = (N_1, N_3, N_1), Π_2 = (N_1, N_6, N_2, N_5, N_1), Π_3 = (N_1, N_5, N_7, N_4, N_3, N_1). For example, UAV D_1 (route marked by the blue line) moves from the base N_1 to node N_3, to which it delivers 52 kg of goods and then returns to the base. UAV one D_2 (route marked by the red line) travels from the base N_1 through vertices N_6, N_2 and N_5, at which it drops off 20, 60 and 18 kg of goods, respectively, and then flies back to the base N_1. UAV D_3 (route marked by the green line) delivers goods to customers at the following nodes: N_5 – 22 kg, N_7 – 30 kg, N_4 – 30 kg, N_3 – 18 kg, and then returns to the base.

a)

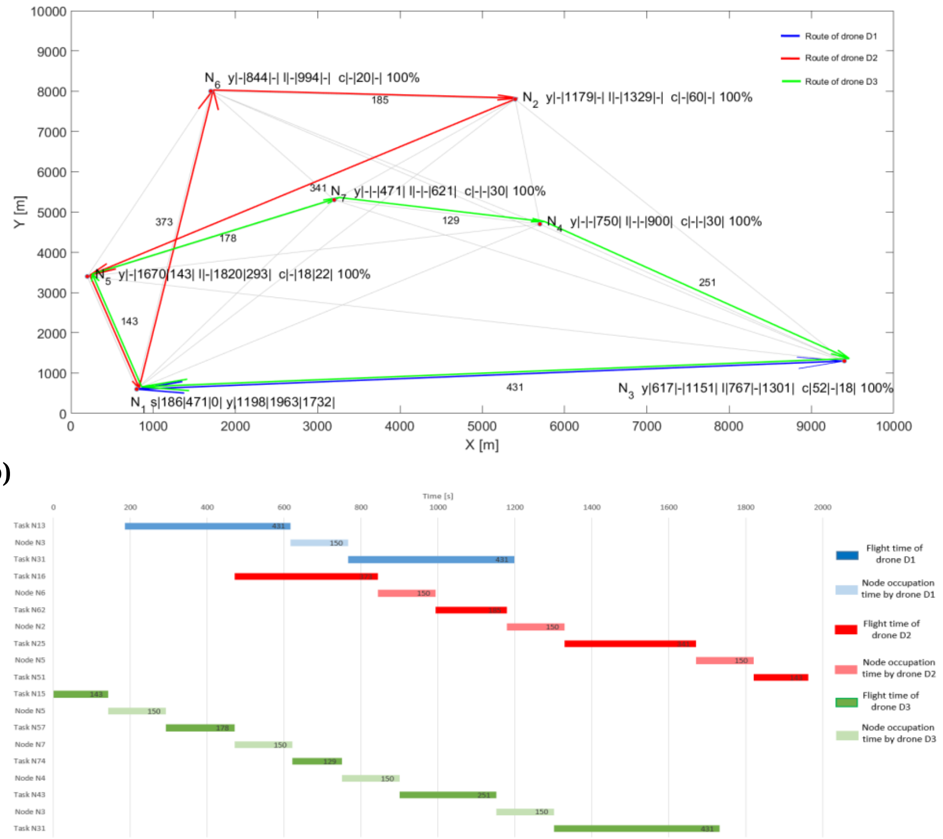

Fig. 2. Routes (a) and flight schedule (b) for a UAV fleet that guarantee delivery of requested goods to customers (weather conditions: wind speed = 10 m/s, wind direction = 30°)

A flight plan like this does not lead to collisions (the UAVs do not use shared edges at the same time – for example, the edge that connects vertices N_3 and N_1) and guarantees that the battery is still charged at the end of the mission. The battery utilization level for the UAVs is 77.58%, 88.93% and 97.53% respectively.

Unfortunately, this set-up cannot be used in all weather conditions. For example, when the wind direction changes from 30° to 60° and the wind speed changes from 10 m/s to 12 m/s, the use of the flight plan from Fig. 2 will lead to the complete depletion of the batteries of UAVs D_2 and D_3 before they return to the base. This situation is illustrated in Fig. 3. As it is easy to notice, UAV D_2 will end its flight while flying from vertex N_5 to N_1 and UAV D_3 will have to land while moving from node N_3 to N_1. This means that flight plans must be tailored to given weather conditions.

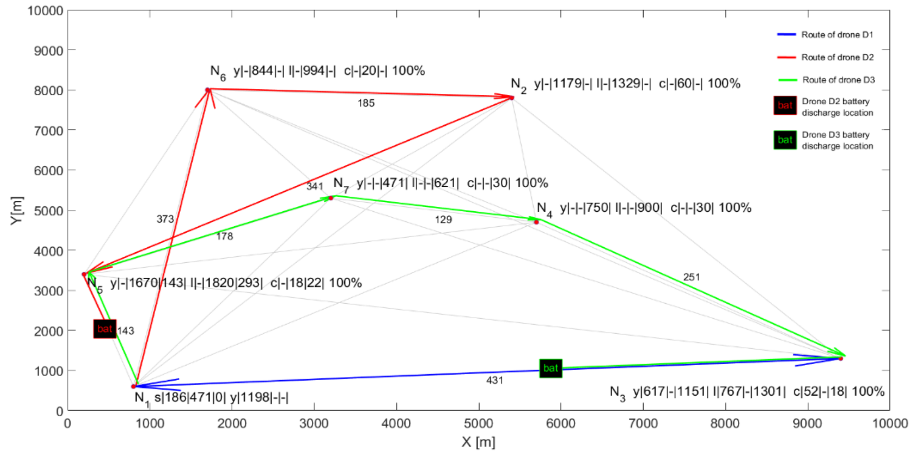

Fig. 3. Simulation results for wind speed = 12 m/s and wind direction = 60°

Taking into account the fact that the adopted weather conditions may affect the possibility of implementing the given flight plan, the problem under consideration boils down to seeking the answer to the following question: *Is the given fleet of UAVs sufficient to meet customer needs (deliver the required quantity of goods) in the given transport network under the specific weather conditions?*

To put it differently, the problem discussed can be considered as a problem of routing and scheduling a fleet of UAVs subject to variable weather conditions (wind speed and direction). Solutions are sought that will maximize customer satisfaction (a function that describes the degree to which customers' needs are satisfied) under the specific weather conditions and given the limited battery life.

4. DECLARATIVE MODEL

The problem discussed in the present paper assumes that the structure of the goods distribution network (number and location of customers and customer demand) is known. The goods are transported by UAVs. Also known is the time horizon in which all flights should be completed. In this context, the following assumptions are taken into account:

- The weather conditions are known (wind speed v_w and wind direction θ),
- The weather conditions are constant over the entire time horizon,
- All UAVs are in the base before the start of the delivery mission,
- The same type of freight is delivered to all customers,
- During the flight, the total weight of the UAV remains constant (i.e. no reduction in weight due to leaving part of the load at a drop-off location is planned for),

– The UAVs travel at a constant speed v = 20 m/s,
– The goal is to find collision-free flight plans and routes that guarantee the highest level of customer satisfaction.

The model is defined as follows:

Parameters

Network:

I – number of nodes,
$t_{i,j}$ – flight time between nodes N_i and N_j,
m_i – demand for goods at the i-th node $i = 1..I$, $m_1 = 0$,
w_i – priority of the i-th node $i = 1..I$, $w_1 = 0$,
TN – node occupation time (unloading time),
TS – time interval at which UAVs can start from the base,
$block_{\{i,j\};\{a,b\}}$ – binary variable corresponding to intersecting edges:

$$block_{\{i,j\};\{a,b\}} = \begin{cases} 1 \; when\ edges\ \{i,j\}\ and\ \{a,b\}\ intersect \\ 0 \qquad otherwise \end{cases}.$$

Technical parameters of the UAV fleet:

K – size of the UAV fleet,
Q – payload capacity of a UAV,
CAP – UAV battery capacity,
$e_{i,j}$ – energy consumed by a UAV during a flight from node N_i to node N_j,
C_D − drag coefficient
A − front surface of UAV,
b − UAV width,
W − total weight of UAV,
$va_{i,j}$ − motor thrust speed.

Environmental parameters:

H – planning horizon $H = [0, t_{max}]$,
D − air density,
v_w − wind speed,
Θ − wind direction.

Decision variables

$x_{i,j}^k$ – a binary variable describing whether the k-th UAV travels from node N_i to node N_j,

$$x_{i,j}^k = \begin{cases} 1 \; when\ k-th\ drone\ travels\ from\ node\ N_i to\ node\ N_j \\ 0 \qquad otherwise \end{cases}.$$

s^k – take-off time of the k-th UAV,

y_i^k – time at which the k-th UAV arrives at node N_i,
c_i^k – weight of freight delivered to node N_i by the k-th UAV,
cp_i – total weight of freight delivered to node N_i,
bat^k – battery level of the k-th UAV.

Sets

$Y^k -$ set of times y_i^k – schedule of the k-th UAV,
$Y -$ family $Y^k -$ schedule of the UAV fleet,
$C^k -$ set $c_i^k -$ weight of freight delivered by the k-th UAV,
$C -$ family C^k,
$\Pi -$ set of UAV fleet routes.

Constraints

Routing. Relationships between variables describing start times and task order.

$$s^k \geq 0 , k = 1 \dots K \tag{1}$$

$$(k \neq q) \Rightarrow \left(\left|s^k - s^q\right| \geq TS\right) , k, q = 1 \dots K \tag{2}$$

$$\sum_{j=1}^{I} x_{1,j}^k = 1 , k = 1 \dots K \tag{3}$$

$$\left(x_{1,j}^k = 1\right) \Rightarrow y_j^k = s^k + t_{1,j} , j = 1 \dots I, k = 1 \dots K \tag{4}$$

$$\left(k \neq q \ \wedge y_i^k \neq 0 \ \wedge y_i^q \neq 0 \right) \Rightarrow \left(\left|y_i^k - y_i^k\right| \geq TN\right) , i = 1 \dots I, k, q = 1 \dots K \tag{5}$$

$$\left(x_{i,j}^k = 1\right) \Rightarrow y_j^k = y_i^k + t_{i,j} + TN, \quad j = 1 \dots I, i = 2 .. I, k = 1 \dots K \tag{6}$$

$$y_i^k \geq 0, i = 1 \dots I, k = 1 \dots K \tag{7}$$

$$\sum_{j=1}^{I} x_{i,j}^k = \sum_{j=1}^{I} x_{j,i}^k , i = 1 \dots I, k = 1 \dots K \tag{8}$$

$$y_i^k \leq H * \sum_{j=1}^{I} x_{i,j}^k \ \ \forall i \in I, \forall k \in K \tag{9}$$

Collision avoidance. Intersecting edges $(b_{\{i,j\};\{a,b\}} = 1)$ cannot be occupied at the same time by UAVs $(x_{i,j}^k = 1, x_{i,j}^q = 1)$

$$\left(block_{\{i,j\}\{a,b\}} \wedge \ x_{i,j}^k = 1 \ \wedge x_{a,b}^q = 1\right) \Rightarrow \left(y_b^q \leq y_j^k - t_{i,j}\right) \vee \left(y_j^k \leq y_b^q - t_{a,b}\right) \quad i, j = 1 \dots I, , k, q = 1 \dots K, k \neq q \tag{10}$$

Delivery of freight. Relationships between variables describing the amount of freight delivered to nodes by UAVs and the demand for goods at a given node.

$$c_i^k \geq 0, i = 1 \dots I, k = 1 \dots K \tag{11}$$

$$c_i^k \leq Q * \sum_{j=1}^{I} x_{i,j}^k, i = 1 \dots I, k = 1 \dots K \tag{12}$$

$$\sum_{i=1}^{I} c_i^k \leq Q, k = 1 \dots K \tag{13}$$

$$\left(x_{i,j}^k = 1\right) \Rightarrow c_j^k \geq 1, k = 1 \dots K, i = 1 \dots I, j = 2 \dots I \tag{14}$$

$$x_{i,i}^k = 0, i = 1 \dots I, k = 1 \dots K \tag{15}$$

$$cp_i \leq m_i, i = 1 \dots I \tag{16}$$

$$\sum_{k=1}^{K} c_i^k = cp_i, i = 1 \dots I \tag{17}$$

$$\sum_{j=1}^{I} x_{1,j}^k = 1, k = 1 \dots K \tag{18}$$

Battery consumption. The amount of energy needed to complete a task may not exceed the maximum battery capacity of the UAV.

$$bat^k \leq CAP, k = 1 \dots K \tag{19}$$

$$\sum_{i=0}^{I} \sum_{j=0}^{I} x_{i,j}^k * t_{i,j} * e_{i,j}, k = 1 \dots K \tag{20}$$

$$e_{i,j} = \frac{1}{2} C_D A D \left(va_{i,j}\right)^3 + \frac{W^2}{D b^2 va_{i,j}}, i,j = 1 \dots I \tag{21}$$

$$va_{i,j} = \sqrt{(vcos\vartheta - v_{\mathrm{w}} cos\theta)^2 + (vsin\vartheta - v_w sin\theta)^2}, i,j = 1 \dots I \tag{22}$$

Objective function. Maximization of customer satisfaction. Customer satisfaction is expressed as the sum of the product of the variables w_i and cp_i. Customer satisfaction should be understood as the ratio of the amount of goods delivered to the demand for goods at a given node expressed as a percentage.

$$CS = \max \sum_{i=0}^{I} w_i * cp_i \tag{23}$$

5. PROBLEM FORMULATION

In the context of the proposed model, the problem under consideration can be formulated as follows: *Given is a fleet of K UAVs moving in a transport network consisting of I vertices. Do there exist routes Π in that network that guarantee maximum customer satisfaction CS while satisfying the constraints associated with collision avoidance (10), delivery of the required quantity of goods (11)–(18) and energy consumption (19)–(22)?*

This problem can be considered as a *Constraint Optimization Problem* (COP) [12]:

$$COP = (\mathcal{V}, \mathcal{D}, \mathcal{C}, \text{CS}) \quad (24)$$

where: $\mathcal{V}$ = {Π, Y, C} – a set of decision variables: Π – variables describing UAV routes, Y – variables describing the schedule of UAV fleet tasks, C – variables describing the quantity of goods delivered by UAVs,
$\mathcal{D}$ − a finite set of descriptions of decision variables,
$\mathcal{C}$ − a set of constraints describing the relationship between routes, the flight schedule and the transported loads (1)–(22),
CS − an objective function representing the level of customer satisfaction.

To solve the *COP*, one has to determine the values of the decision variables for which all constraints are satisfied and for which the objective function reaches a maximum. By implementing the *COP* in a constraint programming environment, such as IBM ILOG, one can build a computational engine for use in decision support systems (DSS).

6. COMPUTATIONAL EXPERIMENTS

In Section 3, it was noted that in the considered delivery network, the route from Fig. 2, cannot be used under weather conditions v_w = 12 m/s ; Θ = 60°, as it leads to battery depletion in UAVs D_2 and D_3 before the completion of their missions. The model developed in this study can be used to determine a flight mission that would guarantee the return of all UAVs to the base under the given weather conditions, while maximizing the level of customer satisfaction. To put it differently, what is sought is the answer to the following question: *Given a fleet of 3-UAVs moving in the transport network from Fig. 1, do there exist routes Π that can ensure the maximum level of customer satisfaction in the given weather conditions ($v_w = 12\frac{m}{s}$; $\Theta = 60°$)?*

To answer this question one must solve problem (23). This problem was implemented and solved in the declarative programming environment IBM ILOG (Intel Core i7-M4800MQ 2.7 GHz, 32 GB RAM). The solution was obtained in 5.14 s.

Fig. 4 shows the computed routes and flight schedule. A set-up like this guarantees that the demanded quantity of goods are delivered to customers in the given weather conditions. Customer satisfaction at all nodes is 100%. Battery consumption for the UAVs traveling along these routes under the given weather conditions is 94.86%, 98.12%, 30%, and 99.5%, respectively.

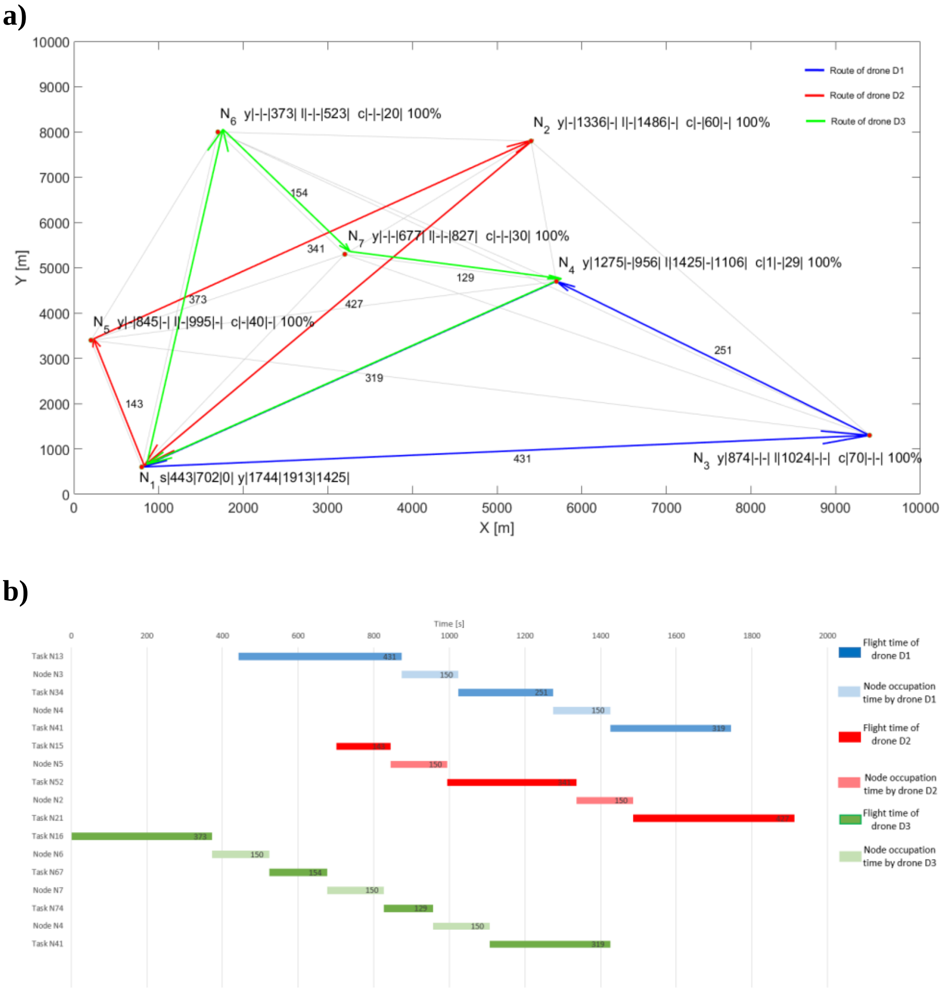

Fig. 4. UAV routes (a) and a flight schedule (b) that guarantee delivery of the requested quantity of goods to customers (weather conditions: wind speed = 12 m/s, wind direction = 60°)

The model we developed was used in a series of experiments performed to assess the effect of weather on the solutions obtained and the scale of problems that could be effectively solved online at a calculation time < 300s.

In the first case, missions were determined for the given network (Fig. 1) and a fixed fleet of 3 UAVs (Tab. 1) for variable weather conditions, i.e. v_w = 5–15 m/s; Θ = 30°–360°. The results are shown in Tab. 4 and 5.

Tab.4. Simulation results for a constant wind speed = 10 m/s and variable wind direction

Wind direction [°]	Customer satisfaction [%]	Simulation time [s]
30	100	6.03
60	100	5.33
90	100	6.39
120	100	6.27
150	100	6.52
180	100	6.82
210	100	5.47
240	100	5.31
270	100	6.32
300	100	5.29
330	100	5.3
360	100	6.33

Tab.5. Simulation results for a variable wind speed and a constant wind direction = 30°

Wind speed [m/s]	Customer satisfaction [%]	Simulation time [s]
5	100	5.91
6	100	6.25
7	100	26.83
8	100	6.42
9	100	6.11
11	100	7.62
12	100	5.02
13	83.3	21.73
14	66.6	23.59
15	66.6	12.03

Tab. 4 clearly shows that at wind speed v_w = 10 m/s and a wind direction in the range 30°–360°, it is possible to designate routes that guarantee 100% customer satisfaction. When the wind direction is constant and the value of wind speed changes as indicated in Tab. 5. then, at wind speeds greater than 13 m/s it is no longer possible to find a solution that guarantees 100% customer satisfaction. In other words, the given UAV fleet allows to meet all customer needs only when the wind speed does not exceed 12 m/s .

In the next stage of our research, we assessed the effectiveness of the proposed approach. During the experiments, it was assumed that a UAV's payload capacity Q was balanced against the total weight of goods to be delivered to all nodes. The results are shown in Tab. 6. As it is easy to see, getting an answer to the question posed, in under 300 s is only possible for networks in which the number of UAVs is lower than or equal to 4 and the number of customers is lower than or equal to 8.

Tab.6. Results of the search for maximum network complexity, for wind speed = 10 m/s and wind direction = 30°

No.	No. customers	No. UAVs	Customer satisfaction = 100%	Calculation time [s]
1	6	2	Yes	7.46
2	6	3	Yes	6.03
3	6	4	Yes	10.18
4	6	5	Yes	113.93
5	6	6	No solution	300
6	7	2	Yes	5.6
7	7	3	Yes	11.05
8	7	4	Yes	187.57
9	7	5	No	300
10	7	6	No	300
11	8	2	Yes	15.82
12	8	3	No	28.81
13	8	4	Yes	253.22
14	8	5	No solution	300
15	8	6	No	300
16	9	2	No	300
17	9	3	No solution	300
18	9	4	No	300
19	9	5	No solution	300
20	9	6	No solution	300

7. CONCLUSION

The proposed declarative model (implemented in the IBM ILOG environment) allows to design UAV flight routes that guarantee the maximum level of customer satisfaction for various weather conditions. As the results of the experiments show, the admissible size of the network for which this type of solution is possible is 8 nodes for a fleet of 4 UAVs. This means that the proposed approach can be used with methods in which a network is partitioned into many small clusters. From this perspective, the approach developed in this study can be used as an element of the heuristics presented in (Thibbotuwawa, Nielsen, Zbigniew, & Bocewicz, 2018a) and (Thibbotuwawa, Nielsen, Zbigniew, & Bocewicz, 2018b).

In our future research, we plan to extend the model so that it can take into account the variable weight of a UAV and allow to search for routes that are robust to given weather conditions.

REFERENCES

Adbelhafiz, M., Mostafa, A., & Girard, A. (2010). Vehicle Routing Problem Instances: Application to Multi-UAV Mission Planning. In *AIAA Guidance, Navigation, and Control Conference*. Toronto, Canada. doi:10.2514/6.2010-8435

Bocewicz, G., Nielsen, P., Banaszak, Z., & Thibbotuwawa, A. (2019). Routing and Scheduling of Unmanned Aerial Vehicles Subject to Cyclic Production Flow Constraints. In *Advances in Intelligent Systems and Computing Distributed Computing and Artificial Intelligence, Special Sessions, 15th International Conference* (pp. 75–86, vol. 801). doi:10.1007/978-3-319-99608-0_9

Chauhan, D., Unnikrishnan, A., & Figliozzi, M. (2019). Maximum coverage capacitated facility location problem with range constrained drones. *Transportation Research Part C: Emerging Technologies*, *99*, 1-18. doi:10.1016/j.trc.2018.12.001

Chiang, W., Li, Y., Shang, J., & Urban, T. L. (2019). Impact of drone delivery on sustainability and cost: Realizing the UAV potential through vehicle routing optimization. *Applied Energy, 242*, 1164–1175. doi:10.1016/j.apenergy.2019.03.117

Dai, R., Fotedar, S., Radmanesh, M., & Kumar, M. (2018). Quality-aware UAV coverage and path planning in geometrically complex environments. *Ad Hoc Networks, 73*, 95–105. doi:10.1016/j.adhoc.2018.02.008

Enright, J. J., Frazzoli, E., Pavone, M., & Savla, K. (2014). UAV Routing and Coordination in Stochastic, Dynamic Environments. *Handbook of Unmanned Aerial Vehicles*, 2079–2109. doi:10.1007/978-90-481-9707-1_28

Fügenschuh, A., & Müllenstedt, D. (2015). *Flight planning for unmanned aerial vehicles*. Hamburg: Professur für Angewandte Mathematik, Helmut-Schmidt-Universität/Universität der Bundeswehr Hamburg, Fachbereich Maschinenbau.

Goerzen, C., Kong, Z., & Mettler, B. (2009). A Survey of Motion Planning Algorithms from the Perspective of Autonomous UAV Guidance. *Journal of Intelligent and Robotic Systems, 57*(1–4), 65–100. doi:10.1007/s10846-009-9383-1

Golden, B. L., Raghavan, S., & Wasil, E. A. (2011). *The vehicle routing problem: Latest advances and new challenges* (Ser. 43). New York, USA: Springer. doi:10.1007/978-0-387-77778-8

Guerriero, F., Surace, R., Loscrí, V., & Natalizio, E. (2014). A multi-objective approach for unmanned aerial vehicle routing problem with soft time windows constraints. *Applied Mathematical Modelling, 38*(3), 839–852. doi:10.1016/j.apm.2013.07.002

Karpenko, S., Konovalenko, I., Miller, A., Miller, B., & Nikolaev, D. (2015). UAV Control on the Basis of 3D Landmark Bearing-Only Observations. *Sensors, 15*(12), 29802–29820. doi:10.3390/s151229768

Thibbotuwawa, A., Nielsen, P., Zbigniew, B., & Bocewicz, G. (2018a). Energy Consumption in Unmanned Aerial Vehicles: A Review of Energy Consumption Models and Their Relation to the UAV Routing. *Advances in Intelligent Systems and Computing Information Systems Architecture and Technology: Proceedings of 39th International Conference on Information Systems Architecture and Technology – ISAT 2018* (pp. 173–184). doi:10.1007/978-3-319-99996-8_16

Thibbotuwawa, A., Nielsen, P., Zbigniew, B., & Bocewicz, G. (2018b). Factors Affecting Energy Consumption of Unmanned Aerial Vehicles: An Analysis of How Energy Consumption Changes in Relation to UAV Routing. *Advances in Intelligent Systems and Computing Information Systems Architecture and Technology: Proceedings of 39th International Conference on Information Systems Architecture and Technology – ISAT 2018* (pp. 228–238). doi:10.1007/978-3-319-99996-8_21

Ullah, S., Kim, K., Kim, K. H., Imran, M., Khan, P., Tovar, E., & Ali, F. (2019). UAV-enabled healthcare architecture: Issues and challenges. *Future Generation Computer Systems, 97*, 425–432. doi:10.1016/j.future.2019.01.028

Wang, X., Poikonen, S., & Golden, B. (2016). The vehicle routing problem with drones: Several worst-case results. *Optimization Letters, 11*(4), 679–697. doi:10.1007/s11590-016-1035-3

Yakıcı, E. (2016). Solving location and routing problem for UAVs. *Computers & Industrial Engineering, 102*, 294-301. doi:10.1016/j.cie.2016.10.029