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Unmanned Aerial Vehicle hub-location and routing for monitoring geographic borders

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ABSTRACT

Recently, hub location problems have become more common with successful applications in air transportation. In this paper, we consider a hub-location and routing problem for border (Borders in this work refer to land borders, unless otherwise stated.) security in Turkey. Security is currently one of the most important issues. Countries are spending large amounts to prevent threats that may come from neighboring countries. Land borders are required to be monitored because of illegal border crossing activities and terrorist attacks. Various geographical restrictions at the borders can cause difficulties in monitoring and gathering the required data. We focus on selecting hubs among the airports run by the General Directorate of State Airports Authority of Turkey, the assignment of demand points to hubs and determining optimal routes for each hub. The study consists of two stages. First, the single allocation p-hub median problem is solved to determine the locations of the hubs for unmanned aircraft. To select hubs, the decision model uses an appropriateness parameter that is obtained by using ELECTRE, a multi-criteria decision-making tool. Five criteria are considered: The type of airport, the remoteness from threats, the proximity to a land border, the aerodrome traffic density and the time that the possible hubs are open to the air traffic. In the second stage, optimal routes are determined for each hub by using two mathematical models. The first model is cost-oriented and there is one vehicle per hub. In the second mathematical model for routing, the monitoring frequency parameters which means the priority of monitoring of the demand nodes obtained by using ELECTRE are used to maximize the monitoring frequency of the demand nodes. The criteria for demand nodes are (1) the need for UAVs, (2) illegal border crossing, and (3) the number of the illegal border activities and attacks. There are three vehicles per hub in the second model. The results of two mathematical models for routing problem are evaluated.

1. Introduction

Border security has become one of the most important issues for countries at the present time. Many countries are investigating new technologies to protect their borders from potential threats. It is critical that countries should foresee and take measures to address threats from neighboring countries. Currently, developed countries use state-of-the-art technologies to protect their borders, such as Unmanned Aerial Vehicles (UAVs), satellite-based surveillance systems, and sensors. UAVs are

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remotely piloted or self-piloted aircrafts that can carry cameras, sensors, communications equipment or other payloads. According to Federation of American Scientists, they have been used in a reconnaissance and intelligence-gathering role since the 1950s, and more challenging roles are envisioned to include including combat missions such as situation development, battle management, and battle damage assessment. The UAV becomes especially important when the geological structure of the region has areas with very steep cliffs (read as [www.global security]").

Events, wars, and various political disputes in neighboring countries highlight how important it is to provide security at a country's borders. Various geographical restrictions at the borders can cause difficulties in tracking and taking action. The motivations behind the work is to address the monitoring of movements along the land borders of Turkey by unmanned aircraft. The cities on the borders have been taken as demand points. Existing airports in Turkey are chosen as possible hubs. This problem is related to "location-routing" and "transportation–location" problems in the literature, which have been active areas of research since 1970 [1–8]. These authors presented different problems and valuable models. Our study focused on the UAV location and routing problem for land border security. The first phase of the study is to address which airports will be chosen as a hub for UAVs. The model in this phase is the revised version of the model which is used for single allocation p-hub median problem to monitor land borders in our earlier work [9]. In this paper, the objective function of the decision model uses the appropriateness parameter to select hubs which will be used. In the second phase, it is determined which routes are optimal for each hub. In this study, three sub-problems have been addressed. First, the single allocation p-hub median problem is solved to determine the locations of the hubs. To reflect the regional features of possible hubs in the mathematical model, we determined an appropriateness parameter for these hubs. Within the scope of the problem, appropriateness parameter for possible hubs are determined with ELECTRE (ELimination Et Choix Traduisant la REalité – ELimination and Choice Expressing the REality) method, a multi-criteria decision making tool. In many areas, ELECTRE methods have been applied. The environmental management, agriculture and forest, energy, water management, finance, calls for tender, transportation and military are certain areas [10]. To obtain appropriateness parameter, five criteria are considered: The type of airport, the remoteness from threats, the proximity to a land border, the aerodrome traffic density and the time that the possible hubs are open to the air traffic. To decide the hub locations, a mathematical model is built and solved. The second sub-problem is the routing problem of the UAVs to minimize cost by considering flight restrictions. The third sub-problem is the routing problem of the UAVs to maximize the surveillance frequency of demand locations based on the monitoring frequency parameters obtained by the ELECTRE method. The multiple-trips case is considered as well. In this phase, for determining the optimal routes for each hub, two mathematical models are built and the results are evaluated.

The remainder of this paper is organized as follows. Section 2 introduces the basic concepts of hub location problem. Single allocation p-hub median problem for monitoring land borders is given in Section 3. Section 4 demonstrates the application of the model for monitoring land border. Our results are summarized in Section 5.

2. Hub location problem

Hubs facilities serve as switching or transshipment points in transportation and communication systems. Networks with hubs concentrate traffic flows on the hub-to-hub links and economies of scale for interhub movement provide a major incentive for hub systems [11].

Hub location problems are concerned with locating hub facilities and discounted transportation links, allocating origin and destinations nodes (e.g., cities) to hubs, and routing flows through the network. There are particular models such as hub center, hub median, hub covering in the literature [12]. Campbell's study gives formulations for four types of discrete hub location problems: the p-hub median problem, the uncapacitated hub location problem, p-hub center problems and hub covering problems [13]. The p-hub median problems focus on minimizing the total transportation cost (time, distance, etc.) needed to serve the given set of flows, given n demand nodes, flow between origin–destination pairs and the number of hubs [14]. The studies considering the p-hub median problem are analyzed in two different types (Fig. 1). The difference of hub networks is in how non-hub nodes are allocated to hubs. All the incoming and outgoing traffic of every demand center is routed through a single hub in single type while each demand center can receive and send flow through more than one hub in multiple allocation [14,15].

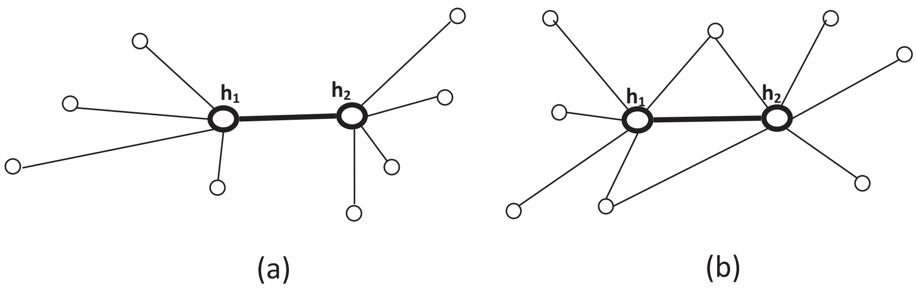

Fig. 1. (a) Single allocation type and (b) multiple allocation type.

In Fig. 1(a) each demand point is assigned to exactly one hub while two demand points are allocated to two hubs (h_1 and h_2) in Fig1(b).

This paper focuses on single allocation p-hub median in unmanned aircraft system in order to monitor the movement at the land borders of Turkey. The first mathematical formulation on the p-hub median problem with single assignment was proposed by O'Kelly, with a nonlinear objective function [16]. Campbell [13] produced the linear integer programming formulation for the single allocation p-hub median problem. Ernst and Krishnamoorthy [17] proposed a 0–1 mixed integer programming formulation which requires fewer variables and constraints to solve larger problems. They employed a simulated annealing upper bound to develop an LP-based branch and bound algorithm. Sohn and Park transformed the quadratic 0–1 integer program for the single allocation problem in the fixed two hub system into a linear program and solved it in polynomial time when the hub locations were fixed [18]. Ebery presented a formulation for solving large single allocation p-hub median problems with two or three hubs [19]. Related studies in hub location research are reviewed in Alumur and Kara, 2008 [14] and Campbell and O'Kelly, 2012 [20].

3. Single allocation p-hub median problem for monitoring land border

The Republic of Turkey has two European and six Asian countries for neighbors along its borders, 2573 km in total length. The border to the northwest with Greece is 212 km long and that with Bulgaria is 269 km. The borders of Turkey with Syria (877 km long), Iran (454 km long) and Iraq (331 km long) are especially important. There is no physical security system at these borders except the one with Syria. Monitoring land borders has become an important issue because of Turkey's geostrategic location, complex relations with its neighboring states, closeness to the energy resources in the Middle East, international transportation, and terrorist incidents in the east and the southeast [9].

Each region has specific features. The features of all the possible hubs and demand nodes are not assumed to be the same to provide a realistic model. Parameters that present the regional features are defined and used to reflect the differences between the regions. The hubs are selected among these possible choices using a mathematical model for the single allocation p-hub median problem [9]. Moreover, the appropriateness parameters of these hubs are obtained with ELECTRE and are used in the model to reflect the regional features of the possible hubs. ELECTRE is well suited to our problem, where we impose extremely diverse quantitative and qualitative criteria that cannot be converted to a common unit. Similarly, we obtain the monitoring frequency parameters to determine the priority of monitoring of the demand nodes by using this method. To maximize the monitoring frequency of the demand nodes, they are used in the mathematical model for routing. The criteria for the demand nodes are (1) the need for UAVs, (2) illegal border crossing, and (3) the number of the illegal border activities or attacks.

3.1. Determining appropriateness parameter of the Hubs

To reflect the regional features of the possible hubs in the mathematical model for the single allocation p-hub median problem, we determine an appropriateness parameter for each hub. These parameters are obtained by using ELECTRE which is a multi-criteria decision-making tool [21]. It is a popular and proven Multiple Attribute Decision Making method in Europe. The basic concept of the ELECTRE method is to deal with "outranking relations" by using pair-wise comparisons among alternatives. This method examines both the degree to which the preference weights are in agreement with pair wise outranking relationships and the degree to which the weighted evaluations differ from each other. This stage is based on a 'concordance and discordance' set.

ELECTRE methods are relevant when the performances of the criteria are expressed different units [10]. There are different versions of ELECTRE (I, II, III, IV and TRI) in the literature. All these versions are based on the same fundamental concepts but differ operationally. ELECTRE I is designed for selection problems while ELECTRE TRI is designed for assignment problems. ELECTRE II, III and IV are used when problem involves ranking [22]. This paper concentrates on ELECTRE III, since the current problem involves ranking of possible airports in Turkey to obtain appropriateness parameters which are used in the mathematical model. The steps to be followed in ELECTRE III are discussed as we move along the current problem [22]:

Step 1. Define the problem and determine the objective. In this case, the problem is to obtain appropriateness parameters of possible hubs (existing airports in Turkey).

Step 2. Identify the alternatives (a_i) available. The alternatives are existing airports in Turkey (Fig. 2). They have been coded as ADANA, ADIYAMAN, ..., VAN according to their location. In this study, 34 possible hubs are considered.

Step 3. Determine the attributes/criteria/performance indicators (b_j) that govern the problem. Our criteria are the type of the airport, the remoteness from threats, proximity to a border, the aerodrome traffic density, the time that the hubs are open to the air traffic. The aerodrome traffic density means the number of aircraft movements in the mean busy hour. Either a take-off or a landing constitutes a movement.

Step 4. Classify the attributes/criteria/performance indicators into direct (performance grows while measure increases) and indirect categories (performance grows while measure decreases).

Step 5. Form the performance matrix. i.e., obtain the coefficient related to the attributes ($j = 1, 2, \ldots, n$) and the alternative a_i ($i = 1, 2, \ldots, m$) (see Table 1).

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Fig. 2. Airports – potential hubs.

Table 1
Performance matrix for the hub selection.

Number	Possible hubs	Type of the airport	Remoteness from threats	Having land border	Aerodrome traffic density (movements)	Time being open to the air traffic (hours/day)
1	ADANA	Civil	Medium	No	19527	24
2	ADIYAMAN	Civil	Medium	No	692	8.5
3	AĞRI	Civil	Low	Yes	485	8
4	ANKARA	Civil	Medium	No	47379	24
5	ANTALYA	Civil	Medium	No	105828	24
6	BALIKESİR	Civil-military	Medium	No	81	8
7	ÇANAKKALE	Civil-military	Medium	No	1050	10.5
8	DENİZLİ	Civil-military	High	No	1314	24
9	DİYARBAKIR	Civil-military	Low	No	5762	14
10	ELAZIĞ	Civil-military	Medium	No	1404	9.5
11	ERZİNCAN	Civil-military	Low	No	1141	8.5
12	ERZURUM	Civil-military	Medium	No	3624	15.5
13	GAZİANTEP	Civil	Low	Yes	5134	24
14	ISPARTA	Civil	High	No	1458	8.5
15	İSTANBUL	Civil	Medium	No	208601	24
16	İZMİR	Civil	Medium	No	40321	24
17	KARS	Civil	Medium	Yes	1712	9
18	KAYSERİ	Civil-military	High	No	4798	24
19	KONYA	Civil-military	Medium	No	2086	17
20	MALATYA	Civil-military	Medium	No	3112	24
21	MARDİN	Civil	Low	Yes	1212	8
22	KAHRAMANMARAŞ	Civil	Medium	No	740	9
23	MUĞLA	Civil	Medium	No	20059	24
24	MUŞ	Civil-military	Low	No	556	8
25	NEVŞEHİR	Civil	Medium	No	1331	15.5
26	SAMSUN	Civil	High	No	4055	24
27	SİİRT	Civil	Low	no	248	8
28	SİNOP	Civil	High	No	109	9
29	SİVAS	Civil	Medium	No	1021	9
30	TEKİRDAĞ	Civil-military	Medium	No	7383	24
31	TRABZON	Civil	High	No	11282	24
32	ŞANLIURFA	Civil	Low	Yes	1081	12.5
33	UŞAK	Civil-military	High	No	358	8
34	VAN	Civil	Low	Yes	4206	8.5

Table 2
The weights and thresholds of the criteria for the hub selection.

Criteria	Weights	Indifference thresholds (q_j)	Preference thresholds (p_j)	Veto thresholds (v_j)
The type of the airport	0.14	1	2	–
The remoteness from threats	0.27	1	2	4
Having land border	0.14	1	2	–
The aerodrome traffic density (movements)	0.18	100	200	100000
Time that the hubs are open to the air traffic (hours/day)	0.27	1	4	24

Step 6. Quantify the qualitative attributes using the scale of 1–10, where 1 mean very low, 3 means low, 5 means medium, 7 means high, and 9 means very high.

Step 7. Absolute weight values on a suitable scale are assigned for each attribute/criterion/performance indicator reflecting the normative judgment of the decision maker.

Step 8. Form the threshold matrix using the strong preference threshold value (p_j), indifference threshold value (q_j) and veto threshold value (v_j) for each attributes/criteria/performance indicators.
The preference threshold indicates the largest difference between the performances of the alternatives such that one is preferred over the other on the criterion considered. The indifference threshold indicates the largest difference between the performances of the alternatives on the criterion considered such that they remain indifferent for the decision maker. The veto threshold is a limit beyond which the credibility of the outranking relation two alternatives is refused.
The strong preference threshold value (p_j), indifference threshold value (q_j) and veto threshold value (v_j) for each criterion are given in Table 2.

Step 9. Evaluate the concordance index for each criterion 'j' for every pair of alternatives. Performances are to be maximized on some criteria and minimized on some other criteria. In maximization, the concordance index is calculated as below:

$$C_j(a_1, a_2) = \left\{ \begin{array}{ll} 1 & if g_j(a_1) - q_j \le g_j(a_2) \\ 0 & if g_j(a_1) - p_j \ge g_j(a_2) \\ \left[\frac{p_j - g_j(a_2) + g_j(a_1)}{p_j - q_j}\right] & \text{otherwise} \end{array} \right\}.$$

Step 10. Compute the measure of concordance for every pair of alternatives taking into account the relative importance (w_j) of each criterion to construct the concordance matrix as follows:

$$C(a_1, a_2) = \frac{\sum_{j=1}^{n} w_j c_j(a_1, a_2)}{\sum_{j=1}^{n} w_j}.$$

Step 11. Evaluate the discordance index for each criterion for every pair of alternatives. In maximization, the discordance index is calculated as below:

$$d_j(a_1, a_2) = \left\{ \begin{array}{ll} 0 & \text{if } g_j(a_1) + p_j \ge g_j(a_2) \\ 1 & if\ g_j(a_1) + v_j \le g_j(a_2) \\ \left[\frac{g_j(a_2) - g_j(a_1) + p_j}{v_j - p_j}\right] & \text{otherwise} \end{array} \right\}.$$

Step 12. Evaluate the credibility degree/index for every pair of alternatives to construct the credibility matrix using the following equation.

$$S(a_1, a_2) = \left\{ \begin{array}{ll} C(a_1, a_2) & \text{if} d_j(a_1, a_2) \le C(a_1, a_2) \forall j = 1, \ldots, n \\ C(a_1, a_2) \prod\limits_{j \in j(a_1, a_2)} \frac{1 - d_j(a_1, a_2)}{1 - C(a_1, a_2)} & \text{otherwise} \end{array} \right\}.$$

Step 13. Evaluate the ranking exploitation index T for every pair of alternatives to construct the ranking exploitation matrix.

$$T(a_1, a_2) = \left\{ \begin{array}{ll} 1 & \text{if } S(a_1, a_2) > \lambda - S(\lambda) \\ 0 & otherwise \end{array} \right\}.$$

where $\lambda = max\, S(a_1, a_2)$ and $S(\lambda)$ is given by the user. λ is the hightest degree of credibility in the credibility matrix, and $S(\lambda)$ is the discrimination threshold.

$$S(\lambda) = \alpha + \beta\, \lambda.$$

In this formula, α and β are technical parameters that Roy and Bouyssou [23] suggest setting to $\alpha = 0.3$ and $\beta = -0.15$. $T(a1, a2)$ takes both the concordance indices and discordance indices into consideration to show how much a_i outranks a_k. Then the degrees of credibility are gathered in a credibility matrix.

Step 14. Use the descending distillation process and construct the pre-orders (Z1) of the alternatives.
Step 15. Use the ascending distillation process and construct the pre-orders (Z2) of the alternatives.
Step 16. Obtain final ranking by combining the results of (Z1) and (Z2).

Considering both the concordance dominance and the discordance dominance matrices, ranking exploitation matrix for alternatives is obtained in Step 13. $T(a1, a2)$ takes both the concordance indices and discordance indices into consideration to show how much a_i outranks a_k. In this study, this matrix has been evaluated with the Copeland method. The Copeland method is used as distillation process. We want to use Copeland method to obtain appropriateness parameters of alternatives. It considers not only how many "wins" an alternative has (C) but also explicitly includes the "losses" for an alternative (R). The Copeland score is determined by subtracting the losses for an alternative from its wins (C − R) [24]. In the Copeland's method, candidates are ordered by the number of pairwise victories, minus the number of pairwise defeats [25]. The Copeland score ranking methodology, effective and stable tool for ranking objects, is also applied outside of its usual political environment (voting). The results show that the Copeland method has the advantage of facilitating the analysis of large partially ordered sets, which were practically impossible to handle using existing methods [26].

In the mathematical model, we need appropriateness parameters on 0–1 scale for possible hubs. For this reason, the scores in the (C − R) column are normalized by means of $(X - X_{min})/(X_{max} - X_{min})$ formula which converts data on any scale to data on 0–1 scale. X_{min} and X_{max} are minimum and maximum values of the Copeland scores, respectively. After the scores (X) are normalized, appropriateness parameters of hubs are obtained. The appropriateness parameters for hub alternatives are given in Table 3.

In Table 3, the total number of "1"s in the column of Adana is 15. It means that Adana has 15 losses. Similarly, the total number of "1"s in the row of Adana is 17. It shows the wins of Adana. The column (C − R) presents the Copeland scores. In the table, the Copeland score of Ankara is 13 (20-7 = 13). The appropriateness parameter of Ankara is 0.7 obtained by normalization.

The appropriateness parameters determined through the ELECTRE and Copeland method in this section are used in the mathematical model for hub selection.

3.2. Mathematical model

The formulation of the single allocation p-hub median problem is used to determine the locations of the hubs for unmanned aircraft. The model is revised version of the model in our previous work [9]. In this paper, the decision model uses an appropriateness parameter to select hubs which will be used. Existing airports in Turkey are chosen as possible hubs. Therefore, the fixed cost of opening a facility is disregarded [9]. The primary assumptions are listed below.

Assumptions

- The aircraft altitudes are constant.
- There is always a site available.
- The models of all the aircraft are the same.
- The speeds of the aircraft are constant (220 km/h).
- The speed of the aircraft during observation operations is 110 km/h.
- Observation diameter is 15 km.
- The communication range of all aircrafts is 300 km.
- Aircrafts return to the same hubs from which they depart.
- Operations are performed in good weather conditions.
- There is no threat to the aircraft
- The potential hubs are controlled by the General Directorate of State Airports Authority of Turkey, Airport (DHMI).

Parameters

The following notation is used to model and formulate the hub-location problem:

H: $\{1, \ldots, m\}$ is the set of the possible hubs
N: $\{1, \ldots, n\}$ is the set of the demand nodes.
i: Demand node $i = 1, 2, \ldots, 16$
j: Possible hub $j = 1, 2, \ldots, 34$
β_j: The appropriateness parameter of the jth possible hub determined through the ELECTRE and Copeland method
d_{ij}: Distance between ith demand node and jth hub
S: The range (the maximum distance between two stopping places) of the aircraft
p: Total number of the hubs ($p \leqslant$ the number of the demand nodes)

Table 3
Ranking exploitation matrix and normalized Copeland scores (appropriateness parameters) for hub alternatives.

Possible hubs	Adana	Adıyaman	Ağrı	Ankara	Antalya	Balıkesir		Sivas	Tekirdağ	Trabzon	Şanlıurfa	Uşak	Van	∑C	C-R	Normalized Copeland scores
Adana	–	1	1	0	0	1	…	1	0	0	1	0	1	17	2	0.5
Adıyaman	0		1	0	0	0	…	0	0	0	0	0	1	6	−15	0.2
Ağrı	0	0		0	0	0	…	0	0	0	0	0	0	0	−30	0
Ankara	1	1	1		0	1	…	1	0	0	1	0	1	20	13	0.7
Antalya	0	1	1	0		1	…	1	0	0	1	0	1	17	3	0.5
Balıkesir	0	0	1	0	0		…	0	0	0	0	0	0	6	−15	0.2
Çanakkale	0	1	1	0	0	1	…	1	0	0	0	0	1	13	−2	0.5
Denizli	1	1	1	1	1	1	…	1	1	0	1	0	1	29	27	0.9
Diyarbakır	0	0	1	0	0	0	…	0	0	0	1	0	1	6	−14	0.3
Elazığ	0	1	1	0	0	0	…	0	0	0	0	0	1	8	−7	0.4
Erzincan	0	0	1	0	0	0	…	0	0	0	0	0	0	3	−24	0.1
Erzurum	0	1	1	0	0	1	…	1	0	0	1	0	1	15	1	0.5
Gaziantep	0	0	1	0	0	0	…	0	0	0	1	0	1	7	−7	0.4
Isparta	1	1	1	1	1	1	…	0	0	0	0	0	1	14	9	0.6
İstanbul	1	1	1	0	1	1	…	1	0	0	1	0	1	21	14	0.7
İzmir	1	1	1	0	1	1	…	1	0	0	1	0	1	21	14	0.7
Kars	0	1	1	0	0	1	…	0	0	0	0	0	1	9	−8	0.4
Kayseri	1	1	1	1	1	1	…	1	1	0	1	0	1	27	23	0.9
Konya	1	1	1	0	1	1	…	1	0	0	1	0	1	18	7	0.6
Malatya	1	1	1	0	1	1	…	1	0	0	1	0	1	20	15	0.7
Mardin	0	0	0	0	0	0	…	0	0	0	0	0	0	1	−26	0.1
Kahramanmaraş	0	1	1	0	0	1	…	0	0	0	0	1	0	6	−10	0.3
Muğla	1	1	1	0	1	1	…	1	0	0	1	0	1	20	13	0.7
Muş	0	0	1	0	0	0	…	0	0	0	0	0	0	5	−18	0.2
Nevşehir	1	1	1	0	1	1	…	1	0	0	1	0	1	18	5	0.6
Samsun	1	1	1	1	1	1	…	1	1	1	1	1	1	31	31	1
Siirt	0	0	0	0	0	0	…	0	0	0	0	0	0	0	−28	0
Sinop	1	1	1	1	1	1	…	1	0	1	0	1	1	21	20	0.8
Sivas	0	1	1	0	0	1	…		0	0	0	0	1	8	−8	0.4
Tekirdağ	1	1	1	0	1	1	…	1		0	1	0	1	21	16	0.8
Trabzon	1	1	1	1	1	1	…	1	1		1	0	1	29	26	0.9
Şanlıurfa	0	0	1	0	0	0	...	0	0	0		0	1	7	−9	0.3
Uşak	1	0	1	1	1	1	…	0	1	1	0		0	24	21	0.8
Van	0	0	1	0	0	0	…	0	0	0	0	0		2	−22	0.1
∑R	15	21	30	7	14	21	…	16	5	3	16	3	24			

$$a_{ij} = \begin{cases} 1, & \text{if } d_{ij} < S \\ 0, & \text{otherwise.} \end{cases}$$

Decision variables

$$Y_j = \left\{ \begin{array}{ll} 1, & \text{if the } j^{\text{th}} \text{ possible hub is selected to be a main hub} \\ 0, & \text{otherwise} \end{array} \right\},$$

$$X_{ij} = \left\{ \begin{array}{ll} 1, & \text{if the } i^{\text{th}} \text{ demand node has been assigned to the } j^{\text{th}} \text{ main hub} \\ 0, & \text{otherwise} \end{array} \right\}.$$

Model:

$$\max \sum_{j}^{m} \beta_j \cdot Y_j \text{s.t.,} \tag{1}$$

$$\sum_{j}^{m} X_{ij} = 1 \quad \forall i \in N, \tag{2}$$

$$X_{ij} \leqslant Y_j \quad \forall i \in N \quad \forall j \in H, \tag{3}$$

$$\sum_{j}^{m} Y_j = p, \tag{4}$$

$$X_{ij} \leqslant a_{ij} \quad \forall i \in N \quad \forall j \in H, \tag{5}$$

$$X_{ij} \in \{0,1\} \quad \forall i \in N \quad \forall j \in H. \tag{6}$$

Eq. (1) defines the objective function. This function gives which hub will be activated for maximum benefit. Eq. (2) assigns a demand node for each hub using Eq. (3). The maximum number of active hubs is limited to p with Eq. (4). Eq. (5) performs the hub selection and assignment using the maximum range of the aircraft. Hub location model does not consider roundtrip. It considers only distance between demand node and hub. To assign a demand node to a hub, the distance must not exceed the maximum distance between two stopping places of aircraft. According to results of hub location model, the routing model is established. The roundtrip and observation times of aircraft are considered in routing model.

3.3. The solution of the model

The CPLEX solver of the GAMS program is used to select hubs among possible airports. The parameter p shows the number of selected hub in the mathematical model. The model can be solved for different p values where $p \leqslant 16$ since there are 16 demand nodes [9]. In this study we assume that the decision maker wants to select four main hubs since there are four UAVs. Because of this reason, p is set to 4 in the mathematical model. The results are given in Table 4.

The objective function of the mathematical model gives maximum benefit. On the basis of the results of our model, the airports at Gaziantep, Tekirdag, Trabzon and Van are selected to be used for the UAV system. The reasons for recommending an airport as a hub are that it is close to the border, it has a current airport, and it has a low volume of traffic. The appropriateness parameters of all possible hubs are have a role in the decision.

4. Section-2: UAVs' routing problem

4.1. The monitoring frequency parameters for demand nodes

The cities on the borders are taken as demand points: Hatay, Kilis, Gaziantep, Urfa, Mardin, Şırnak, Hakkari (Iran and Iraq borders), Van, Ağrı, Iğdır, Kars, Ardahan, Artvin, Edirne, and Kırıkkale. Demand points (cities on a border with a neighboring country) are weighted and used in the model to determine the monitoring frequency of the demand locations. The criteria used to rank the demand nodes are as follows:

(1) The need for UAVs,
(2) The number of the illegal border crossing, and
(3) The number of the illegal border activities or attacks.

Table 5 shows the demand nodes and their scales using the criteria.

Illegal border crossing activities and the intensity of terrorist incidents taking place on the borders are the reasons for monitoring the demand locations. The relevant data are obtained from the Internet site of the Turkish Armed Forces General Staff.

The process used for obtaining appropriateness parameters for possible hubs is also used for obtaining monitoring frequency parameters to determine the surveillance frequency of demand nodes/locations in routing problem. The parameters are obtained by using ELECTRE and Copeland method. They are used in the mathematical models in routing problem as the monitoring frequency parameters of demand nodes. The weights and thresholds of the criteria which assigned in steps 7 and 8 in ELECTRE III are given Table 6.

It can be observed that the "the number of the illegal border crossing" is the most important criterion.

Similar to Section 3.1, the monitoring frequency parameters are formed using the ELECTRE and Copeland method. Then they are normalized by means of the formula $(X - X_{min})/(X_{max} - X_{min})$, and the corresponding values are used in the mathematical models in the routing problem. Ranking exploitation matrix and normalized Copeland scores for the demand nodes alternatives are presented in Table 7.

It can be observed that the demand nodes Edirne, Iğdır and Van have the highest values, in descending order.

The monitoring frequency parameters for the demand nodes are used in the routing problem to maximize the monitoring frequency.

Table 4
Hubs and their demand nodes for $p = 4$.

Number of hubs	Recommended hubs	Related demand nodes
$p = 4$	(13) Gaziantep	1, 2, 3, 4
	(30) Tekirdağ	15, 16
	(31) Trabzon	13, 14
	(34) Van	5, 6, 7, 8, 9, 10, 11, 12

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Table 5
Performance matrix for routing.

	Demand nodes	The need for UAV	The number of the illegal border crossing[a]	The number of the illegal border activities[a]
1	Hatay	Little	31	4
2	Kilis	Little	3	0
3	G.Antep	Little	1	0
4	Urfa	Little	3	1
5	Mardin	Little	5	23
6	Şirnak	Much	4	83
7	Hakkari-İran	Much	19	60
8	Hakkari-Iraq	Much	19	60
9	Van	Much	43	12
10	Ağri	Much	15	1
11	Iğdir	Medium	42	2
12	Kars	Medium	1	0
13	Ardahan	Medium	4	1
14	Artvin	Medium	11	0
15	Edirne	Medium	193	0
16	Kirikkale	Medium	7	0

[a] Data are taken from the official website of the Turkish General Staff.

Table 6
The weights and thresholds of the criteria for routing.

Criteria	Weights	Indifference thresholds (q_j)	Preference thresholds (p_j)	Veto thresholds (v_j)
The need for UAV	0.18	1	2	–
The number of the illegal border crossing	0.55	1	2	50
The number of the illegal border activities	0.27	1	2	80

4.2. Mathematical model for routing

A review of the relevant literature generally notes two limitations. First, flights are assigned to a specific type of fleet rather than certain types of aircrafts. Second, an aircraft performs just one flight per day in operations where flights are assigned to certain aircraft. Therefore, the routing problem for the UAVs examined in this study is additionally modeled to include the following features:

(1) Flights are assigned to a specific aircraft instead of fleets.
(2) An aircraft can be assigned multiple flights in one day.

We formulated and solved the routing problem using our mathematical model, permitting the assignment of more than one flight to a particular UAV per day and the assignment of flights to particular UAVs instead of fleets. The goals of these assignments include profit maximization, cost minimization and the optimal utilization of a particular UAV.

The assignment models in which a specific aircraft performs just one flight a day are among the fundamental problems taken into consideration in preparing this study. In studies where airline companies assign each of their aircraft to just one flight a day, the number of flights that could actually be performed in a day is limited by the number of aircraft owned by that airline company. Nevertheless, the aircraft belonging to an airline company in fact do perform multiple flights within a day. For airline companies to be able to maximize their profits, their aircraft should remain active as much as possible. The reasons are that airline companies are charged per hour when their aircraft occupy airports and they cannot generate any income during that time, the aircraft should be airborne as much as possible. Moreover, it should be noted that the reviewed situations in the relevant literature in which an aircraft is assigned to just one flight occur only in intercontinental flights, which compose only a small proportion of the total number of flights. For the aforementioned reasons, it is irrational to expect that airline companies assign their aircraft to just one flight a day. Therefore, this study investigated this problem, and each aircraft is allowed to perform multiple flights in a day, depending on the durations of their flights.

In this study, the routing problem of UAVs is investigated based on two dimensions. The first model is designed to minimize cost, while the second one is designed to maximize the surveillance frequency of the demand locations based on the monitoring frequency parameters obtained through the ELECTRE method.

Both models are constructed using the following assumptions:

Table 7
Ranking exploitation matrix and normalized Copeland scores (monitoring frequency parameters) for the demand nodes alternatives.

	Hatay	Kilis	G.Antep	Urfa	Mardin	Şirnak	Hakkari İran	Hakkari-Iraq	Van	Ağri	Iğdir	Kars	Ardahan	Artvin	Edirne	Kirikkale	∑C	C-R	Normalized Copeland scores
Hatay	–	1	1	1	1	1	1	1	0	1	0	1	1	1	0	1	12	9	0.8
Kilis	0		1	0	0	0	0	0	0	0	0	1	0	0	0	0	2	−9	0.1
G.Antep	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	−13	0
Urfa	0	0	1		0	0	0	0	0	0	0	1	0	0	0	0	2	−9	0.1
Mardin	0	1	1	1		1	0	0	0	0	0	1	1	0	0	0	6	−2	0.4
Şirnak	0	1	1	1	0		0	0	0	0	0	1	0	0	0	0	4	−5	0.3
Hakkari–İran	0	1	1	1	1	1		0	0	1	0	1	1	1	0	1	10	7	0.7
Hakkari–Iraq	0	1	1	1	1	1	0		0	1	0	1	1	1	0	1	10	7	0.7
Van	1	1	1	1	1	1	1	1		1	1	1	1	1	0	1	14	13	0.9
Ağri	0	1	1	1	1	1	0	0	0		0	1	1	1	0	1	9	4	0.6
Iğdir	1	1	1	1	1	1	1	1	0	1		1	1	1	0	1	13	11	0.9
Kars	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	−13	0
Ardahan	0	1	1	1	0	0	0	0	0	0	0	1		0	0	0	4	−5	0.3
Artvin	0	1	1	1	1	1	0	0	0	0	0	1	1		0	1	8	2	0.5
Edirne	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	15	15	1
Kirikkale	0	1	1	1	1	1	0	0	0	0	0	1	1	0	0		7	0	0.5
∑R	3	11	13	11	8	9	3	3	1	5	2	13	9	6	0	7			

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Assumptions

- All aircraft are of the same type.
- The camcorder records and sends the data to the center throughout the entire flight.
- Aircraft have a specific duration of flight.
- An aircraft that has returned from an operation has a preparation time (time for charging/fuel).
- Each route starts and ends at the same main hub.
- Each hub is assigned to 3 UAVs.
- Each demand node is visited by only one route.
- Each UAV has a time window with a maximum length T.
- Each UAV may be assigned to more than one route.
- Energy consumption is distributed uniformly.
- The normal flight speed of an aircraft is 120 knots (220 km/h).
- The flight speed during monitoring is 60 knots (110 km/h).

It is assumed that all aircrafts are the same type in order to assure the normal flight speed. Otherwise the mathematical model would be modified for different flight speeds. It is also assumed that there is uniform energy consumption while the aircraft is going demand nodes and monitoring demand nodes. There is no data in the literature in order to consider the energy consumption in the mathematical model.

Parameters

R_p: $\{1, \ldots, r\}$ is set of routes for pth hub
V_p: $\{1, \ldots, v\}$ is set of vehicles for pth hub
N_p: $\{1, \ldots, n\}$ is the set of the demand nodes for pth hub
t_r: Time of route r
a_{nr}: A parameter which takes the value 1 if the route r ($r \in R_p$) includes node n.

$$a_{nr} = \left\{ \begin{array}{ll} 1; & \text{if} \cdot \text{route} \cdot r \cdot \text{includes} \cdot \text{demand} \cdot \text{location} \cdot n \\ 0; & \text{otherwise} \end{array} \right\}.$$

C_v: The constant cost of an aircraft
C_o: The cost of routing an aircraft
L_v: The greatest time capacity of aircraft v, (the maximum time that an aircraft can remain airborne)
$\gamma(n)$: The monitoring frequency parameter of demand location n determined through the ELECTRE and Copeland method

Decision variables

$$h_v = \left\{ \begin{array}{ll} 1; & \text{if} \cdot \text{aircraft} \cdot v \cdot \text{is} \cdot \text{used} \\ 0; & \text{otherwise} \end{array} \right\},$$

$$y_{rv} = \left\{ \begin{array}{ll} 1; & \text{if} \cdot \text{route} \cdot r \cdot \text{is} \cdot \text{assigned} \cdot \text{to} \cdot \text{aircraft} \cdot v \\ 0; & \text{otherwise} \end{array} \right\}.$$

The cost-oriented model is presented below. The model is solved for each $p = \{1, \ldots, 4\}$

$$\begin{aligned} &\min C_v \sum_v h_v + C_0 \sum_v \sum_r t_r \cdot y_{rv}, \\ &\text{s.t.,} \end{aligned} \tag{7}$$

$$\sum_r t_r \cdot y_{rv} - L_v \cdot h_v \leqslant 0 \quad \forall v \in V_p, \tag{8}$$

$$\sum_v \sum_r a_{nr} \cdot y_{rv} = 1 \quad \forall n \in N_p, \tag{9}$$

$$y_{rv} \in \{0, 1\} \quad \forall r \in R_p \quad \forall v \in V_p, \tag{10}$$

$$h_v \in \{0, 1\} \quad \forall v \in V_p. \tag{11}$$

Eq. (7) is the objective function, which aims to minimize the total cost, including the aircraft constant costs and operational costs. Constraint (8) refers to the total time limit; an aircraft can remain in the air for a maximum of 24 h. Therefore, they should use their time in the most efficient way. Constraint (9) ensures that the demand locations are included within the selected routes only once. Constraints (10) and (11) restrict y_{rv} and h_v to have a value of either 0 or 1.

The strategic weighting-oriented model is as follows:

$$\max \sum_v \sum_r \sum_n \gamma_n . a_{nr} . y_{rv}, \quad \text{s.t.} \tag{12}$$

$$\sum_r t_r \cdot y_{rv} - L_v \cdot h_v \leqslant 0 \quad \forall v \in V_p, \tag{8}$$

$$\sum_v \sum_r a_{nr} \cdot y_{rv} \geqslant 1 \quad \forall n \in N_p, \tag{13}$$

$$\sum_v \sum_r a_{nr} \cdot y_{rv} \leqslant 3 \quad \forall n \in N_p, \tag{14}$$

$$y_{rv} \in \{0,1\} \quad \forall r \in R_p \quad \forall v \in V_p, \tag{10}$$

$$h_v \in \{0,1\} \quad \forall v \in V_p. \tag{11}$$

Eq. (12) is the objective function and aims to increase the surveillance frequency of the demand locations based on the monitoring frequency parameters obtained through the ELECTRE and Copeland method. Constraints (13) and (14) ensure that the demand locations are included within the selected routes for 1–3 times.

4.3. Solution of aircraft routing problem

After the hubs and the demand locations to which they would provide service are determined, the durations for the hub-to-demand-location and the demand-location-to-demand-location portions of the flights are calculated, along with the time spent by the aircraft in the demand locations (processing time). The normal speed for aircraft departing from and returning to the hubs is assumed to be 220 km/h, and their flight speed during surveillance between two demand locations is taken as 110 km/h. The corresponding durations are estimated by dividing the flight distances between the locations by the aircraft speed. Table 8 shows the hub-to-demand-location durations, Table 9 shows the demand-location-to-demand-location durations, and Table 10 shows the times spent by aircraft in the demand locations.

Durations (hour) in the table are the proportion of air distances between demand locations of the same hub to aircraft speed (220 km/h).

Processing times (hour) in Table 10 are the proportion of air distances of the borders with demand locations to aircraft speed during surveillance (110 km/h).

After the durations are determined, a set of routes is formed. All the routes are calculated through multiplying the number of demand locations with the permutation of the number of demand locations and the number of locations that can be established within the route [$n^*(n,m)$]. Those options among the determined routes which exceeded 24 h are not regarded legible for evaluation since they exceed aircrafts' flight durations and possible routes are determined for each hub. Those routes taking more than 24 h among the total 109672 routes– 4 routes for Tekirdağ, 4 for Trabzon, 64 for Gaziantep and 109600 for Van – are excluded and the resulting number is 44696 routes. After the routes are determined, they are solved

Table 8
Hub-to-demand location durations.

From/to	Hatay	Kilis	Gaziantep	Şanlıurfa
(a)				
Gaziantep	0.69	0.18	0.29	1.03

From/to	Mardin	Şirnak	Hakkari (Iraq border)	Hakkari (İran border)	Van	Ağrı	Iğdır	Kars
(b)								
Van	1.11	0.61	0.82	0.68	0.37	0.67	0.83	1.16

From/to	Edirne	Kırklareli
(c)		
Tekirdağ	0.27	0.51

From/to	Ardahan	Artvin
(d)		
Trabzon	1.31	0.90

Table 9
Demand location-to-demand location durations.

From/to	Hatay	Kilis	Gaziantep	Şanlıurfa
(a)				
Hatay	–	1.27	1.89	3.27
Kilis	1.27	–	0.68	1.73
Gaziantep	1.89	0.68	–	1.18
Şanlıurfa	3.27	1.73	1.18	–

From/to	Mardin	Şirnak	Hakkari (Irak border)	Hakkari (İran border)	Van	Ağri	Iğdir	Kars
(b)								
Mardin	–	1.68	2.77	3.09	3.05	3.75	4.00	4.31
Şirnak	1.68	–	1.44	1.72	2.05	2.85	3.23	3.76
Hakkari (Iraq border)	2.77	1.44	–	0.68	1.68	2.60	3.08	3.71
Hakkari (İran border)	3.09	1.72	0.68	–	1.23	2.04	2.65	3.32
Van	3.05	2.05	1.68	1.23	–	1.18	1.65	2.42
Ağri	3.75	2.85	2.60	2.04	1.18	–	0.56	1.33
Iğdir	4.00	3.23	3.08	2.65	1.65	0.56	–	0.73
Kars	4.31	3.76	3.71	3.32	2.42	1.33	0.73	–

From/to	Edirne	Kırklareli
(c)		
Edirne	–	1.18
Kırklareli	1.18	–

From/to	Ardahan	Artvin
(b)		
Ardahan	–	0.82
Artvin	0.82	–

Table 10
Time spent by the aircraft in the demand locations (monitoring times).

Demand points	*t* (hour)	Demand points	*t* (hour)
Hatay	1.50	Van	1.83
Kilis	0.72	Ağrı	0.52
Gaziantep	0.48	Iğdır	1.41
Urfa	1.83	Kars	1.04
Mardin	1.22	Ardahan	1.15
Şirnak	1.64	Artvin	0.75
Hakkari (Iraq border)	1.57	Edirne	1.83
Hakkari (Iran border)	0.81	Kırlareli	0.88

Table 11
The routes for each hub (first model-one vehicle per hub).

Route number	Routes for Hub-Van	Route times (hour)
(a)		
9	Hub-Van, Kars, Iğdır, Ağrı, Hub-Van	5.42
22149	Hub-Van, Hakkari(Iran border), Hakkari (Iraq border), Hub-Van	4.56
33054	Hub-Van, Şırnak, Van, Hub-Van	2.86
38669	Hub-Van, Mardin, Hub-Van	3.44
(b)		
1	Hub-Tekirdağ, Edine, Hub-Tekirdağ	2.37
2	Hub-Tekirdağ, Kırklareli, Hub-Tekirdağ	1.9
(c)		
4	Hub-Trabzon, Ardağan, Artvin, Hub-Trabzon	4.52
(d)		
1	Hub-Gaziantep, Hatay, Hub-Gaziantep	2.88
26	Hub-Gaziantep, Kilis, Gaziantep, Urfa, Hub-Gaziantep	6.1

Table 12
The routes for each hub (second model-3 vehicles per hub).

Route number	Routes for Hub-Van	Route times (hour)
(a)		
436	Hub-Van, Kars, Van, Ağrı, Hakkari (Iraq border), Hakkari (İran border), Iğdır, Şırnak, Hub-Van	14.6
40587	Hub-Van, Mardin, Hakkari (Iran border), Ağrı, , Iğdır, Van, Hub-Van	14.61
(b)		
1	Hub-Tekirdağ, Edirne, Hub-Tekirdağ	2.37
2	Hub-Tekirdağ, Kırklareli, Hub-Tekirdağ	1.9
(c)		
1	Hub-Trabzon, Artvin, Hub-Trabzon	2.96
2	Hub-Trabzon, Ardağan, Hub-Trabzon -	3.36
(d)		
1	Hub-Gaziantep, Hatay, Hub-Gaziantep	2.88
3	Hub-Gaziantep, Gaziantep, Hub-Gaziantep	1.06
4	Hub-Gaziantep, Urfa- Hub- Gaziantep	3.89
8	Hub-Gaziantep, Kilis, Hatay, Hub-Gaziantep	3.86
10	Hub-Gaziantep, Kilis, Urfa, Hub-Gaziantep	5.49

with CPLEX solver in GAMS program. The vehicles and routes for each hub according to the first model are summarized in Table 11.

The table demonstrates the routes and route information gained by means of solving the cost-oriented model with GAMS program. The vehicle chosen for Van took off from the hub, monitored Kars, Iğdır and Ağrı demand locations and turned back to the hub. The vehicle then departed from the hub again, monitored Iran and Iraq demand locations and turned back to the hub. Since the remaining energy of the same vehicle would be sufficient, it performed routes 33054 and 38669 and turned back to the hub.

The vehicles and routes for each hub according to the second model are summarized in Table 12.

The table includes the routes and route information gained by means of solving the strategic weights-oriented model determining surveillance frequency of the demand locations with GAMS program. Three vehicles are assigned to Tekirdağ. Since a demand location is allowed to be monitored more than once unlike the first model, all the vehicles monitored all the locations and turned back to the hub.

5. Conclusion

The aim of the study is to examine the security system within Turkey land borders and to monitor the border activity by means of Unmanned Aerial Vehicles. The study focused on selecting hubs among the airports run by the General Directorate of State Airports Authority of Turkey and determining optimal routes for each hub. The study consisted of two stages.

The first stage focused on determining the appropriateness parameters of possible hubs with ELECTRE, a multi-criteria technique, and choosing hubs. The appropriateness parameters and UAV's range are used in hub selection model and the most convenient airports are chosen among the present ones to establish the UAV system. At the end of the first stage, Tekirdağ, Trabzon, Gaziantep and Van airports are recommended for establishing UAV system. Tekirdağ hub is suggested because in comparison with İstanbul airport, another alternative in northwest region, it is closer to land border, it had less traffic and it possessed a military airport. Other hubs are opened due to their superior features when compared to other candidate hubs in their area. All in all, it is demonstrated that using the appropriateness parameters determined by the multiple criteria method in choosing a hub requiring multiple considerations would be beneficial.

The second stage focused on determining the monitoring frequency parameters for demand locations and routing the UAVs from the four opened hubs depending on the first stage. A total 109672 routes are first established for demand locations determined for the hubs. This number is reduced down to 44696 by eliminating those flights with durations over the flight duration of UAVs. Two models that make it possible to assign multiple routes to a single aircraft are developed. The first model aimed to minimize cost while the second one is designed in order to maximize the surveillance frequency of demand locations based on the monitoring frequency parameters obtained by the ELECTRE method. As a result of the second stage, in the cost-oriented model, a single vehicle monitored two different routes for Tekirdağ hub, a single vehicle monitored a single route for Trabzon hub, a single vehicle monitored four different routes for Van hub, and a single vehicle monitored two different routes for Gaziantep. In the model using the monitoring frequency parameters, on the other hand, three vehicles monitored two different routes for Tekirdağ hub, three vehicles monitored two different routes for Trabzon hub, three vehicles monitored two different routes for Van hub, and three vehicles monitored five different routes for Gaziantep hub. Each demand location is monitored once as a result of the first model. In the second model, the surveillance frequency of the demand locations with greater the monitoring frequency parameters increased. In conclusion, the monitoring frequency parameters turned out to be significant in aircraft routing model aimed at maximizing the surveillance frequency of demand locations.

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In future studies, solution could be achieved by adding cost data to hub determination model as well. Also, the model could be solved in UAV routing and scheduling problem by including aircraft altitude. There are trade-off between the cost minimization and surveillance optimization. Two mathematical models for routing can be combined by using multi objective modeling.

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