Optimization of Quadrotor Route Planning with Time and Energy Priority in Windy Environments

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Abstract: *Route planning studies are of great importance for quadrotors, which are widely used in military and civil fields, to perform their duties autonomously and efficiently. In the study, a method is proposed that enables Quadrotor Route Planning (QRP) to be optimized with time priority and energy priority by using Genetic Algorithm (GA). For the proposed method, the Wind Effected QRP-App (WEQRP-App) desktop software was developed with the Visual Studio C# programming language. In the developed WEQRP-App, real location information from GMAP.Net map plugin and real wind data from the website of the General Directorate of Meteorology were used. Using Wind Effected Quadrotor Route Planning (WEQRP) method, more realistic planning was made before the flight and the flight efficiency was increased in terms of time and energy priority. Thus, it is foreseen that safer and less costly autonomous flights will take place when compared to the Standard QRP (SQRP) created without taking into account the wind effect, by avoiding the problems that arise due to unexpected energy consumption during the flight mission. When the results obtained from the proposed method were examined, it has been observed that WEQRP provides the improvements up to 13,5% in flight times and up to 27,4% in energy consumption according to SQRP.*

Keywords: *Unmanned aerial vehicles, quadrotors, quadrotor route planning, windy environments, optimization.*

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1. Introduction

An Unmanned Aerial Vehicle (UAV) is an aircraft that does not have a pilot on it and can fly autonomously on a pre-planned flight route by being remotely controlled with its automation and communication technologies [25]. Today, UAVs are produced in many different sizes, shapes and features. Especially rotary-wing UAVs, which can perform Vertical Take-Off and Landing (VTOL) from the ground without the need for any airfield, are preferred due to their advantages such as small size, hanging in the air, low cost, practical use and better maneuverability [5].

In recent years, quadrotors, a type of rotary-wing UAV, are widely used in civil and military areas. Quadrotors are used in many fields such as aerial imaging, search and rescue, exploration, scientific research [19, 37]. Route planning is one of the areas that need to be emphasized in order for quadrotors to perform the mentioned tasks autonomously [5]. Quadrotor Route Planning (QRP) is the determination of the most optimal route plan that will enable you to visit the determined locations with the least cost (distance, time, energy) starting from a certain starting point (home) and return to the starting point again [24]. The creation of the optimum QRP depends on the environmental conditions as well as the cost. The most important of these environmental conditions is the wind effect (wind speed, wind angle), which directly affects the flight time and energy consumption [35]. Factors such as the constant change of wind speed and wind angle, the presence of many path options between locations, and the limited amount of energy in QRP make it difficult to optimize QRP [13]. With the optimum implementation of QRP, significant time and energy savings are achieved [36].

In order to create the optimum QRP, heuristic solution methods are preferred instead of exact solution methods where the solution time increases exponentially with the number of locations [4]. In the study, a solution to Wind-Effected QRP (WEQRP) was sought with the Genetic Algorithm (GA), which is a nature-inspired metaheuristic solution method. In the application of the GA to WEQRP, the chromosome structure and the creation of the initial population were performed differently from the Classical GA (CGA). While permutation coding was preferred in the chromosome structure, the close neighborhood algorithm was used to create the initial population [28].

In this study, the WEQRP method which enables the time and energy priority optimization of QRP based on the wind effect, using by GA which is one of the metaheuristic solution methods, has been proposed. For the proposed method, WEQRP-App desktop software was developed with Visual Studio C# programming language. In the proposed method, real position information and wind data entered by using the WEQRP-App interface are used to create WEQRP. The GMAP. Net plugin was used to display the real location information and the generated QRPs on the map. Current wind data were obtained from the online website of the General Directorate of Meteorology (GDM). With the method proposed in this study, it is ensured that flight efficiency is increased according to time or energy priority by making more realistic planning before the flight. Thus, it is predicted that less costly and more reliable autonomous flights will be realized by avoiding the problems caused by unexpected energy consumption during the flight.

2. Literature Review

In the literature, it is seen that studies on UAV route planning in windy environments focus on fixed-wing UAVs [7, 26, 31, 33]. When the studies on QRP are examined considering the wind effect, it is seen that there are studies on estimation of wind speed and wind angle [21, 36], examination of suitable control methods against wind effect in route tracking [1], compensation of trajectory deviations caused by wind effect in quadrotor flight control [8], examination of battery performance and energy consumption under wind [11, 14], quadrotor modeling and control considering wind disturbance [3, 23, 30]. Moreover, most of the existing studies are on minimizing distance or flight time [12, 27].

Luo *et al*. [17] reposed a method which calculates the flight time between targets of a fixed-wing UAV by considering the vector relationship between UAV speed, airspeed and ground speed. Thibbotuwawa *et al*. [32] presented the current state of energy consumption in UAVs and a general classification of the factors affecting energy consumption. Pinto *et al*. [22] discussed the mission planning problem of a UAV squadron that must visit a set of fixed crossing points under flight time constraint. Consequently, they proposed a model that solves the mission planning problem for multiple UAVs in the presence of wind field.

3. Quadrotor Route Planning

The problems that deal with the distribution of goods between the warehouse and the customers are called the Vehicle Routing Problem (VRP) [34]. VRP is an optimization problem that aims to generate the best route sets for all destinations under certain constraints [6]. QRP differs from VRP for reasons such as quadrotors do not have a fixed road network as in land vehicles, have many road options between locations, have limited energy, are more affected by environmental conditions, and are more unstable [9].

Today, quadrotors are used in many civil and military fields such as aerial imaging, search and rescue, reconnaissance, surveillance, security, cargo handling, emergency, scientific research, mapping, agricultural applications [19]. In order for quadrotors to perform these tasks autonomously, efficiently and economically, route planning studies emerge as an area that needs to be focused on. QRP is the determination of the most optimum route plan that will enable you to return to the starting point by visiting the determined locations with the least cost (distance, time, energy) starting from a certain starting point (home) [5, 24].

With the optimal QRP, it is aimed to find the route plan where the distance, time or energy cost of the quadrotor is minimized [34]. QRP aims to determine the route plan with the least total distance to be covered by the quadrotor by minimizing the distance cost, to determine the route plan with the least flight time by minimizing the time (flight time) cost and to determine the route plan with the lowest energy consumption by minimizing the energy cost.

The following constraints should be considered in the solution of QRP:

- Quadrotor ends the flight in the location where it starts.
- Each location is visited only once.
- Quadrotor must complete a route.
- Maximum flight time and maximum energy amount of a quadrotor should be determined.

The QRP mathematical model is a generalization of the VRP mathematical model created by Laporte [15].

The QRP formulation can be given on a graph as *L={0,1,2,...,n}* where the set of locations the starting point (home) is 0 and E is the set of links (paths) between these locations. *G=(L,E)*

The main purpose of QRP is to stop by all the determined locations and while doing this, to minimize the cost by complying with the determined constraints. For this purpose, the QRP mathematical model can be formulated as follows.

Parameters:

$L=\{0,1,2,\ldots,n\}: \textit{Set of locations}$

$t(i,j): \textit{Flight time between i and j locations}$

$e(i,j): \textit{Energy consumption between i and j locations}$

$$x(i,j):\begin{cases}1, \textit{If you are going from point i to point j}\\ 0, \textit{If you are not going from point i to point j}\end{cases}$$

Objective functions

$$\min \sum_{i=0}^{n} \sum_{j=0}^{n} x(i,j)\,t(i,j) \qquad (1)$$

$$\min \sum_{i=0}^{n} \sum_{j=0}^{n} x(i,j)\,e(i,j) \qquad (2)$$

Constraints:

$$\sum_{j=1}^{n} x(0,j) = \sum_{j=1}^{n} x(j,0) \le 1 \qquad (3)$$

$$\sum_{i=0, i\neq j}^{n} x(i,j) = 1, \ \forall j \in L \qquad (4)$$

$$\sum_{j=0,\, j\neq i}^{n} x(i,j)=1,\ \forall i\in L \tag{5}$$

$$\sum_{i,\, j\in S,\ i\neq j}^{n} x(i,j)\leq |S|-1,\ \forall S\in(1,2,\ldots,n),\ |S|\geq 2 \tag{6}$$

The objective function that minimizes the total flight time is given in Equation (1), and the objective function that minimizes the total energy consumption is given in Equation (2). Equation (3) states that each route starts from 0 (home) and ends at home. Equation (4) indicates that each point will be left only once, while Equation (5) means that each point will be visited only once. Equation (6) is the sub-round elimination constraint to get rid of any sub-rounds that may occur in order to limit viable solutions to a single round.

Including real environmental conditions in the QRP enables more realistic planning before a flight. Moreover, by considering these conditions, it is predicted that quadrotors will be able to perform safer and more reliable autonomous flights.

3.1. The Proposed Wind-Effected Quadrotor Route Planning

Environmental conditions must be taken into account in order to obtain the optimum QRP. Wind effect (wind speed, wind angle) comes first among these environmental conditions [35]. Depending on the wind effect, the speed, flight time and energy consumption of a quadrotor change [16, 31].

In order to create WEQRP in which the distance cost is minimized, the coordinate information of the locations and the distance information between the locations are sufficient, while the quadrotor speed and wind vector must also be known in order to create the WEQRP in which the time and energy costs are minimized. In the creation of WEQRP, where the distance cost is minimized, the wind vector is not used and there is no change in the route plan depending on the wind effect. However, the wind vector is used to create WEQRP in which energy and time costs are minimized, and there may be changes in route plans depending on the wind effect. Therefore, in this study, WEQRP, in which changing energy and time costs depending on the wind effect are minimized is emphasized.

The wind vector acting on the quadrotor causes a change in the quadrotor ground speed vector [31].

$$\overrightarrow{Vw}=(vw,\ aw) \tag{7}$$

$$\overrightarrow{Va}=(va,\ aa) \tag{8}$$

$$\overrightarrow{Vg}=(vg,\ ag) \tag{9}$$

In the $\overrightarrow{Vw}$ wind vector in the Equation (7), vw is the wind speed and aw is the wind angle. While vw represents the distance traveled by the wind relative to the ground in unit time, aw represents the direction of the wind. Wind speed and wind angle data are instantaneous weather forecast data from GDM online website. The airspeed vector ($\overrightarrow{Va}$) in Equation (8) is the speed of the quadrotor in the air. While va shows the airspeed, aa shows the airspeed direction angle. Airspeed has certain lower and upper limits according to weather conditions and quadrotor characteristics. The ground speed vector in Equation (9) ($\overrightarrow{Vg}$) is the speed of the quadrotor's projection on the earth under the influence of the wind at the time of flight. While vg represents the ground speed, ag represents the route angle.

The relationship between wind speed, airspeed and ground speed vectors is shown in Figure 1.

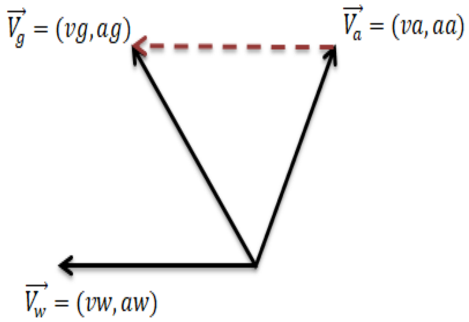


Figure 1. The relationship between wind speed, airspeed and ground speed vectors.

There are two basic methods for obtaining the speed vector used in the calculations of flight time and energy consumption between locations [17, 31, 32]. These methods are the constant ground speed method and the constant airspeed method. In the constant ground speed method, the ground speed is $vg_{i,j}=|\overrightarrow{Vg_{i,j}}|$ assumed to be constant and the airspeed vector is calculated according to the change in the wind speed vector. In the constant airspeed method, the airspeed $va_{i,j}=|\overrightarrow{Va_{i,j}}|$ is assumed to be constant and the ground speed vector is calculated according to the change in the wind speed vector.

In the constant ground speed method, the ground speed is $vg_{i,j}$ is assumed to be constant and the airspeed $va_{i,j}$ is calculated with the formula in Equation (10).

$$va_{i,j}=\sqrt{\begin{array}{l}(vg_{i,j}\times\cos ag_{i,j}-vw\times\cos aw)^2+\\(vg_{i,j}\times\sin ag_{i,j}-vw\times\sin aw)^2\end{array}} \tag{10}$$

In Equation (10), i and j represent locations. The tilt angle of the ground speed vector is $ag_{i,j}$. The tilt angle of the wind speed vector is aw. Wind speed and wind angle at the time of WEQRP creation are taken from the GDM website and WEQRP is created according to the wind data received [20]. Once WEQRP is created, wind effect is considered constant throughout the flight.

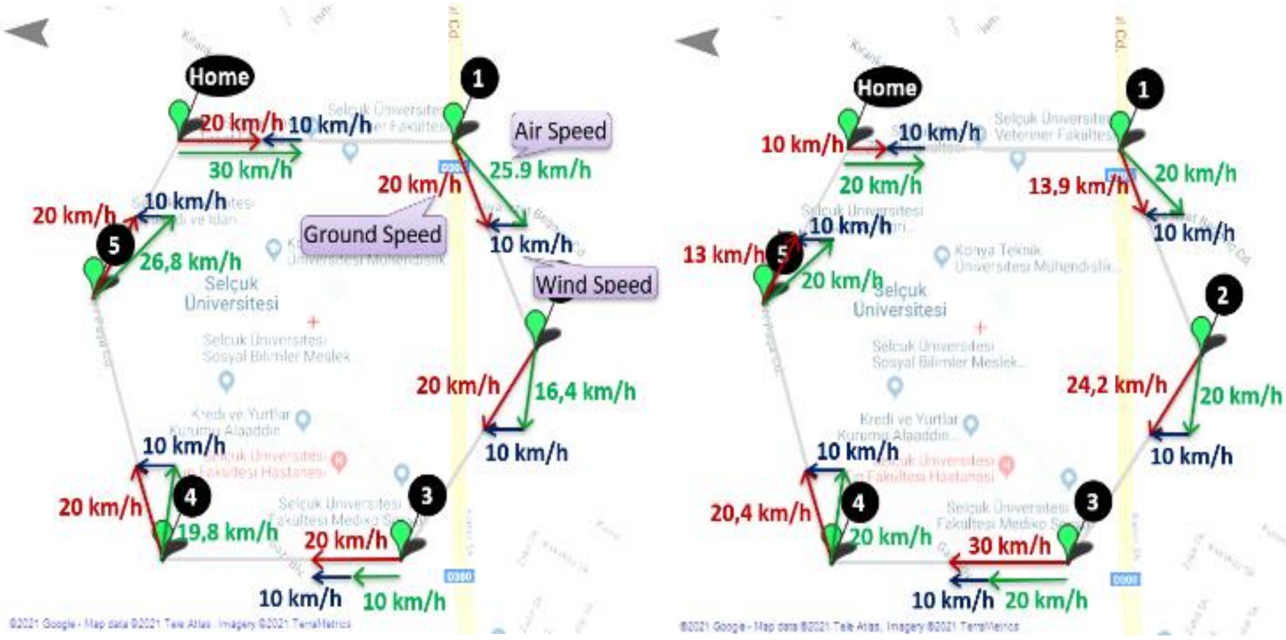
In the constant airspeed method, the airspeed $va_{i,j}$ is considered constant and the ground speed $vg_{i,j}$ is calculated with the formula in Equation (11).

$$vg_{i,j} = \sqrt{\begin{aligned}&(va_{i,j} \times \cos aa_{i,j} + vw \times \cos aw)^2 + \\ &(va_{i,j} \times \sin aa_{i,j} + vw \times \sin aw)^2\end{aligned}} \qquad (11)$$

$$aa_{i,j} = ag_{i,j} - \sin^{-1}\left(\frac{vw}{va_{i,j}} \sin\left(aw - ag_{i,j}\right)\right) \qquad (12)$$

The tilt angle of the airspeed vector $aa_{i,j}$ is obtained by the formula in Equation (12).

The change in ground speed and airspeed vectors when the constant ground speed and constant airspeed methods are used is shown in Figure 2 on a 6 locations route plan.



a) Constant ground speed method.

b) Constant airspeed method.

Figure 2. Speed vectors.

In the constant ground speed method Figure 2-a), it is assumed that the quadrotor is traveling at $vg_{i,j}=20km/h$ constant ground speed. In an environment where the quadrotor's wind speed is $vw=10km/h$ and wind angle is $aw=90°$, to travel at ground speed $vg_{i,j}=20km/h$ between all locations, it should produce the appropriate airspeed vector ($\overrightarrow{Va_{i,j}}$) depending on the wind vector ($\overrightarrow{Vw}$).

In the constant airspeed method Figure 2-b), it is assumed that the quadrotor is traveling at $vg_{i,j}=20km/h$ constant airspeed. In an environment where the quadrotor's wind speed is $vw=10km/h$ and wind angle is $aw=90°$, by traveling at airspeed between all locations, the ground speed vector ($\overrightarrow{Vg_{i,j}}$) is obtained depending on the wind vector ($\overrightarrow{Vw}$).

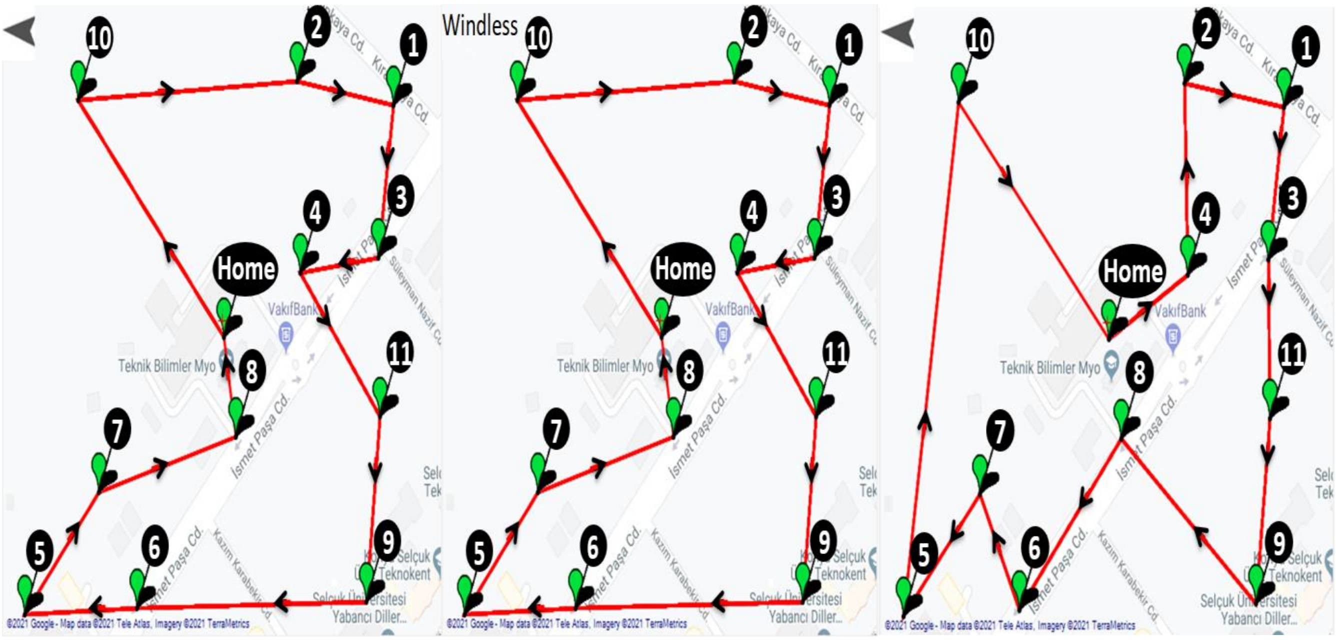
Since the wind effect is assumed to be zero (no) for all weather conditions in Standard QRP (SQRP), the ground speed vector becomes the same as the airspeed vector as shown in Equation (13). Since the speed vectors do not change depending on the wind effect, the route plans created by minimizing the distance, time or energy costs do not change either.

$$\overrightarrow{Vg} = \overrightarrow{Va} \qquad (13)$$

In WEQRP, flight times and energy consumptions also change as the speed vectors between locations change depending on the preferred method at different wind speeds and wind angles. Therefore, in windy environments, the optimum WEQRP can be found by minimizing time or energy consumption costs. WEQRP can vary depending on wind speed and wind angle, as well as in cases where time or energy consumption cost is a priority.

For flights operated with SQRP in windy conditions, flight time and energy consumption will differ from the flight time and energy consumption calculated before the flight. However, for flights operated with WEQRP, flight time and energy consumption will be close to the flight time and energy consumption calculated before the flight, since route planning is made by considering the wind effect at the time of flight.

For 12 locations for flight planning, the display of flight routes of SQRP obtained when wind speed=20 km/h, WEQRP obtained when wind speed=0 km/h and WEQRP obtained when the wind speed=20 km/h is shown in Figure 3.



a) SQRP (*vw=20km/h*). b) WEQRP (*vw=0km/h*). c) WEQRP (*vw=20km/h*).

Figure 3. Flight plans for 12 locations.

Quadrotor speed=25km/h in all route plans shown in Figure 3. In Figure 3-a) and c), the wind angle=90°. The SQRP obtained when wind speed=20km/h in Figure 3-a), the WEQRP obtained when wind speed=0 km/h in Figure 3-b), and the WEQRP obtained when wind speed=20 km/h in Figure 3-c) are shown. In SQRP, cost values and route plan do not change depending on the wind effect. In cases where the wind speed is =0 km/h in WEQRP, the same cost values as SQRP occur. However, when the wind speed is >0, the cost (time, energy) values change, and if a more cost-effective route is found, the route plan also changes. Accordingly, since wind speed=0 in the WEQRP shown in Figure 3-b), while it has the same cost values and route plan as the SQRP in Figure 3-a), since the wind speed is >0 in the WEQRP shown in Figure 3-c), it has different cost values and different route plan.

Considering the wind effect in the study, Time Priority WEQRP (TPWEQRP) where the total flight time cost is minimized and Energy Priority WEQRP (EPWEQRP) where the total energy consumption cost is minimized are emphasized. Depending on the user requirements, the nature of the flight mission, the constraints in the flight area and the environmental conditions, the route plan to be created according to whether TPWEQRP or EPWEQRP is determined.

3.1.1. Time Priority WEQRP

Minimizing the arrival time from one location to another is an important consideration in time-critical flights [31]. With TPWEQRP, İt is aimed to find the optimum route plan where the minimum flight time Equation (15) is obtained after calculating the flight times between the locations determined for flight planning. In order to calculate flight times between locations in TPWEQRP, quadrotor speed vector, wind vector and distance between locations must be known. Depending on the change in wind speed or wind angle acting on the quadrotor, the flight times will also change as the quadrotor speed vectors between locations will change. If a different, more cost-effective route plan is found with the change of flight times between locations, the new route found will be the optimum TPWEQRP. The maximum flight time T_{max} is entered through the developed program and TPWEQRP is created taking into account the entered flight time. If a route plan is created above the maximum flight time entered, the user is warned that the flight cannot be performed safely.

The flight times between locations used in obtaining TPWEQRP are calculated with the formula in Equation (14).

$$t_{i,j} = \frac{d_{i,j}}{vg_{i,j}} \tag{14}$$

$$\min \sum_{i=0}^{n} \sum_{j=0}^{n} x(i,j) \times t(i,j) \le T_{\max} \tag{15}$$

$$hav(Q) = sin^2\left(\frac{Q}{2}\right)$$

$$d_{i,j} = 2r\,arcsin\left(\sqrt{hav(\varphi_j - \varphi_i) + \cos(\varphi_i)\cos(\varphi_j)hav(\lambda_j - \lambda_i)}\right)$$

$$d_{i,j} = 2r\,arcsin\left(\sqrt{\begin{matrix} sin^2\left(\frac{\varphi_j - \varphi_i}{2}\right) + \\ \cos(\varphi_i)\cos(\varphi_j)sin^2\left(\frac{\lambda_j - \lambda_i}{2}\right)\end{matrix}}\right) \tag{16}$$

Ground speed in Equation (14) ($vg_{i,j}$) is calculated with the formula in Equation (11). Distance calculation between locations ($d_{i,j}$) is made with the haversine formula given in Equation (16).

In Equation (16), while φ_i, φ_j *i* and *j* represent latitude values of the locations, λ_i, λ_j represent the longitude values of *i* and *j* locations.

3.1.2. Energy Priority WEQRP

In energy-critical flights, it is aimed to minimize the amount of energy spent traveling from one location to another. Depending on the wind, the speed vector of the quadrotor and the amount of energy consumed change [14]. The change in energy consumption affects the endurance of the quadrotor. With EPWEQRP, it is aimed to find the optimum route plan with the lowest energy consumption Equation (18) by minimizing energy consumption.

Considering the wind effect, the energy consumption between locations is calculated with the formula given in Equation (17) [32, 38]. The total amount of power required to complete the route plan in obtaining EPWEQRP cannot exceed the maximum capacity of the lipo battery on the quadrotor. Through the developed program P_{Max} maximum battery capacity is entered and EPWEQRP is created taking into account the entered battery capacity. If a route plan is formed above the maximum battery capacity entered, the user is warned that the flight cannot be performed safely.

$$P_{i,j} = \frac{1}{2} C_D \times A \times D \times (va_{i,j})^3 + \frac{W^2}{D \times b^2 \times va_{i,j}} \tag{17}$$

$$\min \sum_{i=0}^{n} \sum_{j=0}^{n} x(i,j) \times t(i,j) \times P_{i,j} \leq P_{\max} \tag{18}$$

In Equation (17), C_D aerodynamic drag coefficient, *A* represents the front surface area of the quadrotor as m^2, *D* represents the air density in kg/m^3, *W* represents the weight of quadrotor in *kg*, *b* represents the width of quadrotor in meters and *v* represents the relative speed of the quadrotor in air in *m/sn*. *v* varies depending on the method used.

3.2. WEQRP with Genetic Algorithm

The Genetic Algorithm (GA), developed by John Holland in 1975, is a population-based metaheuristic method that is frequently used in solving optimization problems [10]. In GA, instead of looking for a single solution to the problem, a set of solutions is studied. With GA, it is aimed to find better solutions based on the rule of survival of the best in nature in order to find solutions to problems that are difficult to solve with classical methods. In classical solution methods, the computation time increases also exponentially as the number of positions (n) increases. This makes it impossible to solve problems with multiple locations. The solution costs of GA are low and it reaches the solution faster [18]. In this study, the computational time of the GA varies depending on the population size (P_s) and the number of iterations (I_n). When the time complexity is O(2^n) in classical methods, in GA the time complexity is O($P_s I_n$).

In GA, the number of iterations, population size, crossover size, crossover and mutation probability parameters are used to solve the problem. In addition to these parameters, additional parameters can be used according to the nature of the problem. An example of this is the quadrotor's return to the starting point in WEQRP.

In GA, the possible solution set is called the population. Populations, on the other hand, are composed of individuals whose building blocks are genes or structures defined as chromosomes. Appropriate modeling of the problem and its conversion into gene-chromosome structure are important for finding the optimum solution. In the initial population, genetic variation is achieved by genetic operators called crossover and mutation [29].

The algorithm for solving WEQRP with GA is given below.

Algorithm 1: WEQRP with GA.

```
İnput: $v, T_{max}$, $P_{Max}$, $vw$, $aw$, $I_n$, $P_s$ number of locations(n), Crossover rate ($C_r$), Mutation rate ($M_r$), Current solution($S_c$), The best solution ($S_b$), Close location number($L_n$), Close location probability ($L_p$), The fitness value ($F_c$), The best fitness value ($F_b$)
Begin
Load input parameters
Set iteration counter $I_c=0$
Set population counter $P_c=0$
Define objective function:
$\min \sum_{i=0}^{n} \sum_{j=0}^{n} x(i,j) t(i,j)$   $\min \sum_{i=0}^{n} \sum_{j=0}^{n} x(i,j) e(i,j)$
Generate initial populations
Calculate velocity vectors $v_a$, $v_g$ between locations
Calculate $F_c$ for each route in the initial population:
    If (objective function= TPWEQRP)
        $F_C = \sum_{i=0}^{n} \sum_{j=0}^{n} x(i,j) \times t(i,j)$
    else if (objective function= EPWEQRP)
        $F_C = \sum_{i=0}^{n} \sum_{j=0}^{n} x(i,j) \times t(i,j) \times P_{i,j}$
    End If
While ($I_c < I_n$)
    Select parents from population
    Apply crossover operation on selected parents with $C_r$
    Apply mutation operation with $M_r$
    Calculate the $F_c$ of the children created
    If ( $F_c$ ($S_c$) $\leq F_b$ )
        $F_b = F_c$ ($S_c$)
    End if
End While
End
```

3.2.1. Chromosome Structure

A sequence formed by the combination of more than one gene is called a chromosome. In CGA, the binary coding method is generally used in the creation of chromosomes. In binary coding, each chromosome is expressed as a sequence of 0s and 1s. Permutation coding was preferred in WEQRP. In permutation coding, each chromosome represents a sequence of its constituent characters [2]. In WEQRP, the quadrotor exits the 0 (home) location and returns to the 0 (home) location after visiting the locations it needs to go. Figure 4 shows the chromosome structure of a route plan with 12 locations Figure 3-a).

10 2 1 3 4 11 9 6 5 7 8 0

Figure 4. Permutation coding example chromosome structure.

In Figure 4, each gene shows the locations to be visited in turn.

3.2.2. Establishing the Initial Population

An initial population is created from which new generations will be derived as much as the population size determined in GA. Each chromosome in the population represents possible solutions. In CGA, the initial population is usually randomly generated. Unlike CGA, the initial population in WEQRP was created using the nearest neighbor algorithm instead of being randomly generated. Since the start and end locations must be the same and each location must be visited once in WEQRP, the initial population WAS created by taking these constraints into account.

In the first step of the nearest neighbor algorithm, the closest location to the home location is selected, and in the next steps, the next closest location is selected and finally the starting point is returned [28]. In WEQRP, adding the nearest neighbor to the route is performed as long as it does not violate time or energy constraints. If the constraints are violated, a new route plan is started.

3.2.3. Fitness Function

After the initial population is created, a fitness value is calculated for the chromosomes in the population according to the nature of the problem. The chromosomes with a high fitness value will be more likely to be selected and passed on to the next generation. In WEQRP, the fitness value is obtained by summing the distances, flight times or energy consumption amounts of the locations to be visited in accordance with the order in the chromosome. Thus, the lowest cost chromosome (route) represents the most optimal solution in WEQRP.

3.2.4. Selection and Crossover

In order to produce new chromosomes in GA, two parents must be selected from the initial population. Roulette wheel, tournament and ranked selection are the most used selection methods in GA. In the roulette wheel method, the chance of each chromosome being selected is the ratio of the sum of the fitness values of all individuals in the population to its fitness value. In tournament selection, n individuals are randomly selected from the population and the selected individuals compete with each other. In the sequential selection method, individuals in the population are ranked from smallest to largest according to their fitness values by giving each individual a sequence number, and the roulette wheel method is applied to these numbers.

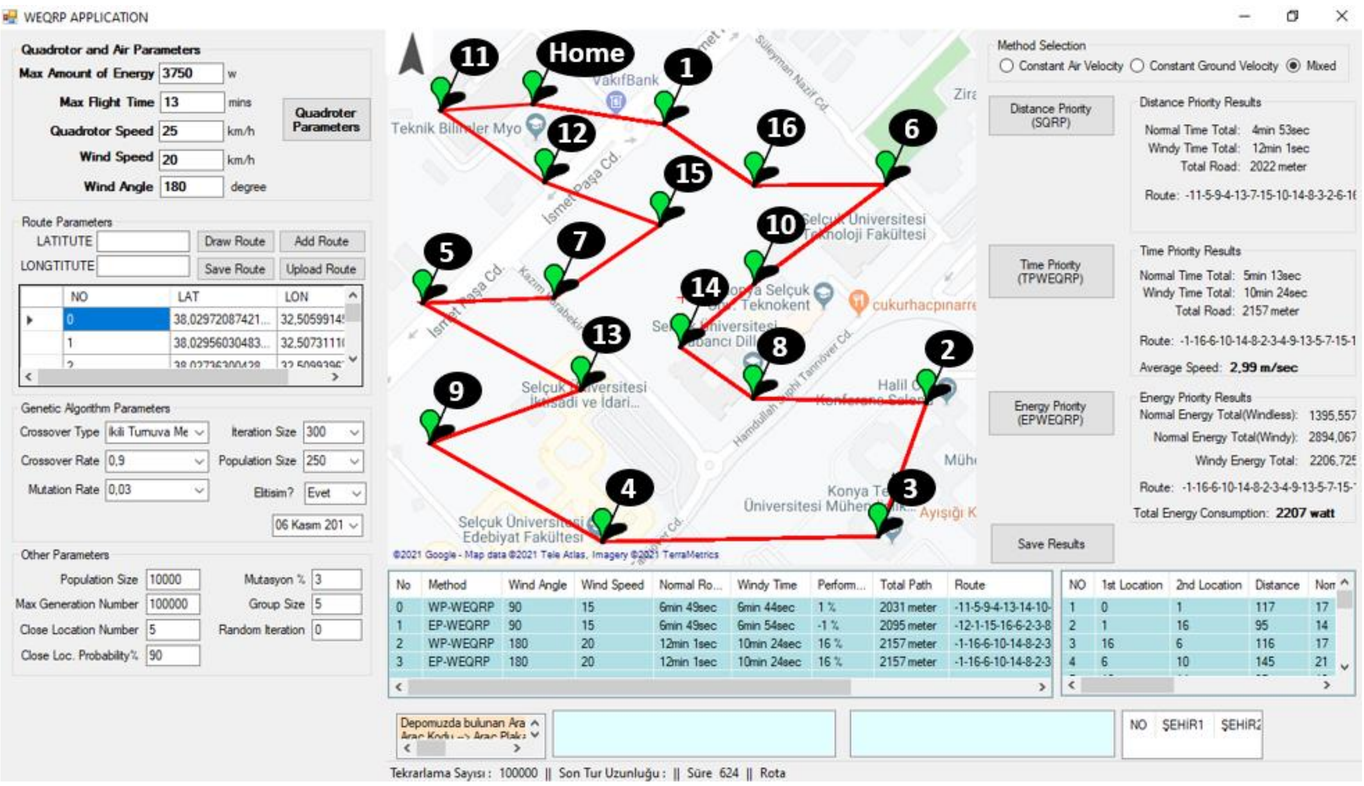
New individuals are formed by crossing the parents obtained at the end of the selection process. A new individual is created by using the genes taken from two individuals according to the selected crossover method in the crossover process. In WEQRP, the start and end locations were fixed and excluded from the crossover.

3.2.5. Mutation

Individuals obtained at the end of the crossover process may not provide the desired diversity. In such a case, by changing one or a few genes of an individual in the population with mutation, new individuals are created to create diversity in the population. Mutation can cause the obtained solutions to get better or worse. The important thing is the appropriate selection of the mutation probability.

4. Application of the Proposed WEQRP

With the developed WEQRP-App, it is aimed to create optimum TPWEQRP and EPWEQRP by using GA, one of the metaheuristic solution methods. Real location information and current wind data were used to create TPWEQRP and EPWEQRP. The GMAP. Net plugin was used to display the real location information on the map and to display the routes to be followed in the route plans created. Current wind data is obtained instantly from the MGM online website when WEQRP will create and it is assumed that the wind effect does not change during the flight period. The developed WEQRP-App interface is shown in Figure 5.



Quadrotor and Air Parameters

Max Amount of Energy 3750 w

Max Flight Time 13 mins

Quadrotor Speed 25 km/h

Wind Speed 20 km/h

Wind Angle 180 degree

Route Parameters

LATITUTE

LONGTITUTE

	NO	LAT	LON
▸	0	38,02972087421...	32,5059914
	1	38,02956030483...	32,5073111
	2	38,02736300428	32,5099396

Genetic Algorithm Parameters

Crossover Type: Ikili Tumuva Me

Iteration Size: 300

Crossover Rate: 0,9

Population Size: 250

Mutation Rate: 0,03

Eltisim?: Evet

06 Kasım 201

Other Parameters

Population Size: 10000

Mutasyon %: 3

Max Generation Number: 100000

Group Size: 5

Close Location Number: 5

Random Iteration: 0

Close Loc. Probability%: 90

Method Selection

○ Constant Air Velocity ○ Constant Ground Velocity ● Mixed

Distance Priority Results

Normal Time Total: 4min 53sec
Windy Time Total: 12min 1sec
Total Road: 2022 meter

Route: -11-5-9-4-13-7-15-10-14-8-3-2-6-16

Time Priority Results

Normal Time Total: 5min 13sec
Windy Time Total: 10min 24sec
Total Road: 2157 meter

Route: -1-16-6-10-14-8-2-3-4-9-13-5-7-15-1

Average Speed: **2,99 m/sec**

Energy Priority Results

Normal Energy Total(Windless): 1395,557
Normal Energy Total(Windy): 2894,067
Windy Energy Total: 2206,725

Route: -1-16-6-10-14-8-2-3-4-9-13-5-7-15-

Total Energy Consumption: **2207 watt**

No	Method	Wind Angle	Wind Speed	Normal Ro...	Windy Time	Perform...	Total Path	Route
0	WP-WEQRP	90	15	6min 49sec	6min 44sec	1 %	2031 meter	-11-5-9-4-13-14-10-
1	EP-WEQRP	90	15	6min 49sec	6min 54sec	-1 %	2095 meter	-12-1-15-16-6-2-3-8
2	WP-WEQRP	180	20	12min 1sec	10min 24sec	16 %	2157 meter	-1-16-6-10-14-8-2-3
3	EP-WEQRP	180	20	12min 1sec	10min 24sec	16 %	2157 meter	-1-16-6-10-14-8-2-3

NO	1st Location	2nd Location	Distance	Nor
1	0	1	117	17
2	1	16	95	14
3	16	6	116	17
4	6	10	145	21

Depomuzda bulunan Ara
Arac Kodu --> Arac Plak

NO	ŞEHİR1	ŞEHİR2

Tekrarlama Sayısı : 100000 || Son Tur Uzunluğu : || Süre 624 || Rota

Figure 5. Developed WEQRP-app interface.

In WEQRP-App, route planning is made according to the maximum flight time and maximum energy amount entered by the user. Moreover, with the application, QRP is created at quadrotor speeds in the ranges determined depending on the quadrotor characteristics and at all wind speeds with an angle value between 0°-360°. If the entered quadrotor speed or wind speed is not within the appropriate ranges, or if the cost of the route plan obtained exceeds the maximum flight time or energy amount, the user is warned that a safe route plan cannot be created.

In TPWEQRP and EPWEQRP, the quadrotor starts from a certain starting location (home) and returns to its starting location after visiting all locations. Figure 6 shows 17 locations determined for route planning through the application displayed on the GMAP. Net map plugin.

Figure 6. Locations determined for route planning.

As in Figure 6, SQRP, TPWEQRP and EPWEQRP can be created for the locations determined on the application.

Since the ground speed vector does not change depending on the wind effect in SQRP, time and energy costs do not change either. The route plans created by minimizing the time or energy cost in SQRP in a windy environment are the same as the route plan created by minimizing the distance cost. Therefore, while SQRP can be optimized by minimizing distance costs, it cannot be optimized by minimizing time or energy costs. In Figure 7, SQRPs obtained at different wind speeds and wind angles for 17 locations selected over the application is shown.

a) *vw=10km/h, aw=90°*.

b) *vw=10km/h, aw=180°*.

c) *vw=20km/h, aw=90°*.

d) *vw=20km/h, aw=180°*.

Figure 7. SQRPs obtained at different wind speeds and wind angles.

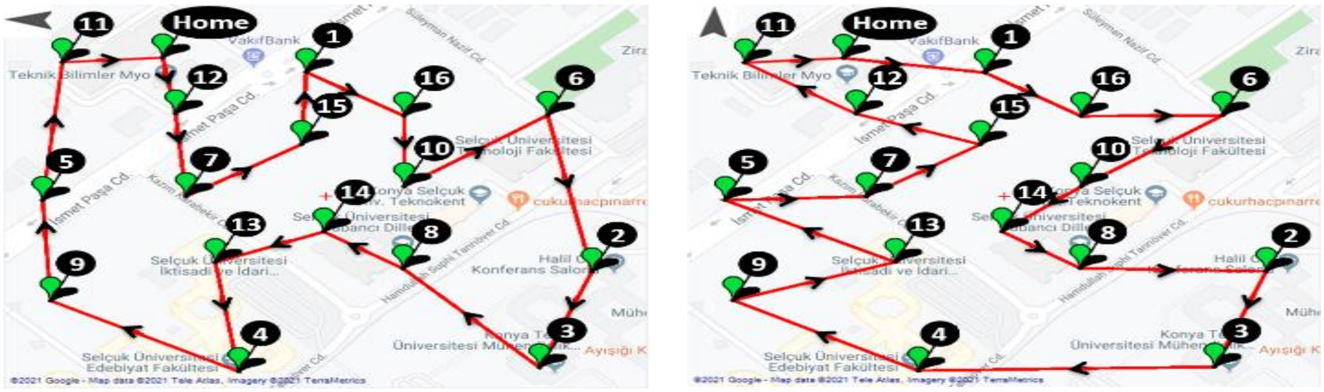
Quadrotor speed=25 km/h was determined in Figure 7. The SQRPs obtained at different wind speeds and wind angles were the same as the quadrotor speed vector did not change depending on the wind effect. In the obtained SQRPs, the quadrotor stops by the locations (Home-11-5-9-4-13-7-15-10-14-8-3-2-6-16-1-12) respectively, and completes its flight mission at Home. For SQRPs, the distance cost was calculated as 2022 meters, the time cost was calculated as 4 minutes 53 seconds, and the energy cost was calculated as 1395 watts.

The route plan and cost values of WEQRP, which is created by minimizing the distance cost, will be the same as SQRP. However, in TPWEQRP and EPWEQRP, time and energy costs vary depending on wind speed and wind angle. If a different, more cost-effective route plan is found with the change in time and energy costs, the new route found becomes the optimum route.

The TPWEQRPs obtained at different wind speeds and wind angles in flight missions where flight time is important are shown in Figure 8.

In Figure 8, the changes in TPWEQRP with the changing time cost depending on the wind effect are shown. In obtaining TPWEQRPs, the quadrotor speed=25 km/h was determined. As the wind speed and wind angle change, the ground speed between locations also changes. Depending on the change in ground speed, the time cost changes and if a different route that can be completed in less time is found, the new route found is accepted as the optimum TPWEQRP.

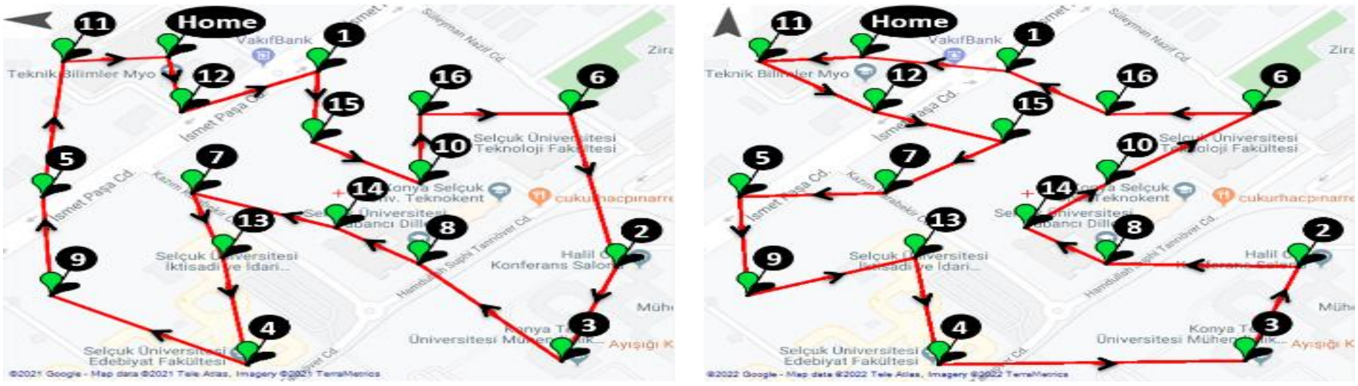
a) *vw=10km/h, aw=90°.* b) *vw=10km/h, aw=180°.*



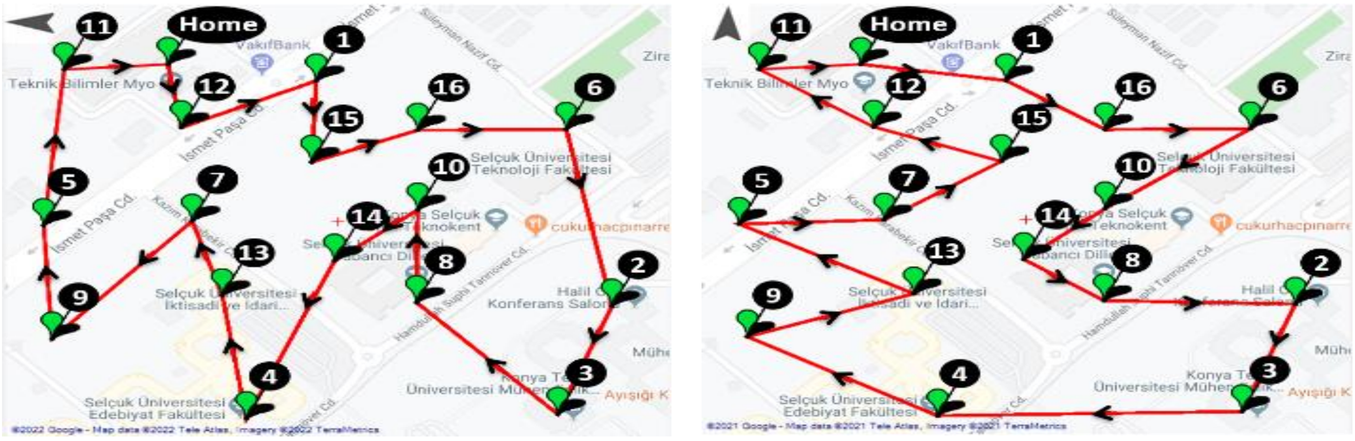
c) *vw=20km/h, aw=90°.* d) *vw=20km/h, aw=180°.*

Figure 8. TPWEQRPs obtained at different wind speeds and wind angles.

EPWEQRPs obtained at different wind speeds and wind angles in flight missions where the amount of energy consumption is important are shown in Figure 9.



a) *vw=10km/h, aw=90°.* b) *vw=10km/h, aw=180°.*



c) *vw=20km/h, aw=90°.* d) *vw=20km/h, aw=180°.*

Figure 9. EPWEQRPs obtained at different wind speeds and wind angles.

Figure 9 shows the changes in EPWEQRPs with the changing energy cost depending on the wind effect. In obtaining EPWEQRPs, the quadrotor speed=25 km/h was determined. As the wind speed and wind angle change, the inter-locations quadrotor speed vector also changes. Depending on the change in the quadrotor speed vector, the energy cost changes and if a different route with less energy consumption is found, the new route is accepted as the optimum EPWEQRP.

5. Results

For the locations determined by the developed application, SQRP, TPWEQRP or EPWEQRP were created with the GA method. The SQRP data given in the tables below are the distance, time and energy data obtained when flying with SQRP taking into account the wind effect.

The flight data of SQRP and TPWEQRP obtained at different wind speeds and different wind angles for 12 locations and 17 locations flight missions via the application are given in Table 1. Quadrotor speed=25km/h in the flight performed.

In Table 1, Number of Locations: the number of locations selected to create a route plan, Wind Speed: different wind speeds, Wind Angle: different wind angle values, Distance: the total flight distance of the route plan, Time: the total flight time of the route plan, Achievement: Comparison of the time data obtained when flying under the influence of wind in route plans obtained with SQRP and TPWEQRP as a percentage, and Is the Rute OK?: whether the route plan created is within the limits determined according to the entered cost values and parameters.

Table 1. SQRP and TPWEQRP flight data.

			SQRP		**TPWEQRP**			
Number of Locations	**Wind Speed (km/h)**	**Wind Angle (°)**	**Distance (m)**	**Time (sec)**	**Distance (m)**	**Time (sec)**	**Achievement (%)**	**Is the route OK? (Y/N)**
12 Locations (Figure 3)	10	0(360)	1882	308	1883	308	**0**	Y
		90	1882	318	1901	312	**1,9**	Y
		180	1882	309	1883	308	**0,3**	Y
		270	1882	318	1901	312	**1,9**	Y
	20	0(360)	1882	580	1883	580	**0**	Y
		90	1882	699	1962	605	**13,4**	Y
		180	1882	583	1883	580	**0,5**	Y
		270	1882	699	1962	605	**13,4**	Y
17 Locations (Figure 8)	10	0(360)	2022	338	2022	337	**0,3**	Y
		90	2022	335	2005	332	**0,9**	Y
		180	2022	337	2022	337	**0**	Y
		270	2022	335	2023	333	**0,6**	Y
	20	0(360)	2022	718	2157	624	**13,1**	Y
		90	2022	660	2039	635	**3,8**	Y
		180	2022	721	2157	624	**13,5**	Y
		270	2022	661	2039	635	**3,9**	Y

The flight data of SQRP and EPWEQRP obtained at different wind speeds and different wind angles for 12 locations and 17 locations flight missions are given in Table 2. Quadrotor speed=25km/h in the flight performed.

Table 2. SQRP and EPWEQRP flight data.

			SQRP		**EPWEQRP**			
Number of Locations	**Wind Speed (km/h)**	**Wind Angle (°)**	**Distance (m)**	**Energy (watt)**	**Distance (m)**	**Energy (watt)**	**Achievement (%)**	**Is the route OK? (Y/N)**
12 Locations (Figure 3)	10	0(360)	1882	1499	1883	1484	**1**	Y
		90	1882	1606	1906	1526	**5**	Y
		180	1882	1484	1883	1484	**0**	Y
		270	1882	1607	1906	1526	**5**	Y
	20	0(360)	1882	2315	1913	2097	**9,4**	Y
		90	1882	2934	1962	2129	**27,4**	Y
		180	1882	2101	1913	2097	**0,2**	Y
		270	1882	2855	1962	2129	**25,4**	Y
17 Locations (Figure 9)	10	0(360)	2022	1683	2096	1634	**2,9**	Y
		90	2022	1638	2023	1625	**0,8**	Y
		180	2022	1708	2083	1638	**4,1**	Y
		270	2022	1632	2023	1625	**0,4**	Y
	20	0(360)	2022	2747	2157	2207	**19,7**	Y
		90	2022	2568	2103	2243	**12,7**	Y
		180	2022	2894	2157	2207	**23,7**	Y
		270	2022	2327	2095	2239	**3,8**	Y

In Table 2, Energy: the amount of energy consumption realized in the route plan, Achievement: Comparing the percentage of energy consumed when flying under the influence of wind in route plans obtained with SQRP and EPWEQRP.

In Table 3, flight data of TPWEQRP and EPWEQRP obtained at different wind speeds and different wind angles for the 12 locations and 17 locations flight missions of the quadrotor flying at 25 km/h are given.

Table 3. TPWEQRP and EPWEQRP flight data.

			TPWEQRP				**EPWEQRP**			
Number of Locations	**Wind Speed (km/h)**	**Wind Angle (°)**	**Distance (m)**	**Time (sec)**	**Energy (watt)**	**Energy Achievement(%)**	**Distance (m)**	**Time (sec)**	**Energy (watt)**	**Time Achievement(%)**
12 Locations	10	0(360)	1883	308	1499	**0**	1883	309	1484	**-0,3**
		90	1901	312	1531	**4,7**	1906	314	1526	**1,3**
		180	1883	308	1499	**-1**	1883	309	1484	**0**
		270	1901	312	1531	**4,7**	1906	314	1526	**1,3**
	20	0(360)	1883	580	2315	**0**	1913	589	2097	**-1,6**
		90	1962	605	2262	**22,9**	1962	605	2129	**13,4**
		180	1883	580	2315	**-10,2**	1913	589	2097	**-1**
		270	1962	605	2129	**25,4**	1962	605	2129	**13,4**
17 Locations	10	0(360)	2022	337	1708	**-1,5**	2096	342	1634	**-1,2**
		90	2005	332	1661	**-1,4**	2023	333	1625	**0,6**
		180	2022	337	1708	**0**	2083	340	1638	**-0,9**
		270	2023	333	1625	**0,4**	2023	333	1625	**0,6**
	20	0(360)	2157	624	2207	**19,7**	2157	624	2207	**13**
		90	2039	635	2297	**10,6**	2103	639	2243	**3,2**
		180	2157	624	2207	**23,7**	2157	624	2207	**14,3**
		270	2039	635	2297	**1,3**	2095	639	2239	**3,3**

The data given in Table 3 provides a comparison of the methods selected in TPWEQRP and EPWEQRP at different wind speeds and wind angles. In Table 3, Time Achievement: Comparison of the flight times obtained with EPWEQRP as a percentage with SQRP under the same wind effect and at the same locations, Energy Achievement: Comparison of the energy consumptions obtained with TPWEQRP as a percentage with SQRP under the same wind effect and at the same locations

6. Discussion

In this study, it was aimed to improve flight missions in terms of flight time and energy consumption by optimizing TPWEQRP and EPWEQRP with GA, one of the metaheuristic methods. For this purpose, a software was developed and permutation coding was preferred in the chromosome structure of GA, while the close neighborhood algorithm was used to create the initial population. Thus, the use of GA in a structure more suitable for WEQRP is provided.

In WEQRP, the cost is always changing depending on the wind effect. However, if a more suitable route plan cannot be found despite the changing costs, the route plan remains unchanged. If a less costly route is found with varying costs depending on the wind effect, the route plan also changes and the obtained route plan is accepted as the new optimum route plan depending on the current wind data.

In order to benefit positively from the quadrotor wind effect with WEQRP, it is tried to find route plans in which upwind situations are minimized and tail winds are maximized. Therefore, although the distance in the obtained WEQRPs generally increases, the quadrotor takes less time and energy to complete the route compared to the SQRP as it receives more tailwind. The data obtained from TPWEQRP and EPWEQRP may be different when compared to the situations Table 3 when the wind speed, wind angle and route plans are the same. Since the route plan with the lowest flight time is sought in TPWEQRP, the distance and energy consumption amount are not taken into account. Therefore, in some cases, although the distance and the amount of energy consumption increase in TPWEQRP, the flight time may decrease. Since the route plan with the lowest energy consumption amount is searched in EPWEQRP, in some cases, although the distance and flight time increase, energy consumption can decrease.

With the study, it was observed that the flights performed with TPWEQRP, which was created at the moment the quadrotor would start flying, taking into account the wind effect, provides up to 13,5% improvement in total flight times when compared to flights with SQRP. It was observed that flights with EPWEQRP provided up to 27,4% improvement in total energy consumption compared to flights with SQRP.

For flights operated with WEQRP, the flight costs calculated before the flight will be close to the actual flight costs. In this way, problems caused by changes in weather conditions will be minimized. Moreover, safer and more stable flights will be provided with WEQRP, which is created taking into account the wind effect, compared to SQRP created without considering the wind effect. Thus, it is considered that the overall operating cost of the system will decrease and the vehicle/load safety will increase further.

With WEQRP, which is created at the moment the Quadrotor starts to fly, more realistic flight time and energy consumption can be obtained. In the study, WEQRPs are obtained by using the weather data at the time of the flight mission. However, with WEQRP, future route plans can be obtained for future flight missions. In instant WEQRP, route planning is made by using the wind data at the time the quadrotor will start flying, while in future WEQRP, route planning can be made according to the wind forecasts at a future date when the flight will take place. Thus, it is thought that an advantage over SQRP can be achieved by creating a future-dated WEQRP in environments where current wind data cannot be obtained or where the wind effect is at certain intervals.

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We commemorate our naive teacher, the late Murat Selek, with longing and mercy.

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